Sustainable food design via fermentation of plant-based matrices

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Abstract

Introduction. Climate change and food security challenges have increased interest in plant-based diets; however, matrix complexity often limits nutrient bioavailability and functionality. Fermentation offers a targeted strategy to overcome these constraints.

Materials and methods. The study analyzed peer-reviewed scientific publications on the fermentation of plant-based food matrices and their nutritional, functional, and technological implications, based on literature searches conducted in PubMed, Scopus, Web of Science, ScienceDirect, and open-access sources, focusing primarily on publications from 2005 to 2026 using relevant keywords.

Results and discussion. Fermentation induces targeted biochemical changes in plant-based food matrices, leading to reported increases in protein digestibility of approximately 10–25%, improvements in mineral bioaccessibility of 15–50%, and reductions in antinutritional factors of up to 60–80%, together with enhanced techno-functional and sensory properties. In addition, fermentation promotes partial proteolysis and the release of free amino acids and bioactive peptides, contributing to improved nutritional value and potential bioactivity. It also facilitates the redistribution of phenolic compounds, increasing the proportion of soluble fractions and associated antioxidant capacity. Moreover, fermentation can modify carbohydrate structures, including partial hydrolysis of complex polysaccharides, which may improve digestibility and reduce gastrointestinal discomfort.

It also contributes to the development of desirable flavor compounds through microbial metabolism, enhancing consumer acceptability of plant-based products. The magnitude of these effects is strongly matrix-dependent and influenced by raw material composition, microbial strains, and processing conditions, while integration with technologies such as extrusion, baking, and drying supports the development of functional foods and plant-based meat analogues; however, variability among studies, lack of standardized protocols, and limited industrial-scale validation remain important challenges.

Conclusions. Fermentation is a versatile, low-energy approach that enables matrix-level optimization of the nutritional, functional, and sensory properties of plant-based foods, while requiring standardized and scalable evaluation for effective implementation.

Introduction

Global drivers for the transformation of food systems

In international and regional policy issues, the global transformation of food systems has emerged as a strategic priority because of challenges such as climate change, the growth of global populations, and food security. The Food and Agriculture Organization of the United Nations (FAO), the World Health Organization (WHO), and the European Union highlight the urgent challenge of developing sustainable food systems. Through policy frameworks such as the European Green Deal and the Farm to Fork Strategy, the EU specifically addresses the need to meet growing food demand without compromising nutritional quality for an expanding population (Cotta, 2025; FAO, 2022). One constant issue highlighted in these frameworks is the ever-widening gap between the requirements for international protein and supply in sustainable animal-based proteins in low- and middle-income regions. For this reason, plant-based diets are progressively established as a cornerstone of future diets in addition to animal products as a means of substituting for animal food in the modern world and as resilient and sustainable systems of food production (Prócel and Padilla, 2025; Verni et al., 2022).

Protein gap and the role of plant-based foods

International reports consistently highlight a growing mismatch between global protein demand and the availability of sustainable protein sources. Animal-based proteins, while nutritionally valuable, are associated with high environmental costs and limited scalability. As a result, plant-based protein systems are increasingly promoted not only as alternatives but as essential components of future resilient food systems, particularly in regions facing nutritional and economic constraints (Capcanari et al., 2025).

Plant sources, in particular cereals and legumes, shape the bulk of this transition, because they are widely produced, have a relatively low environmental impact, and offer complementary nutritional profiles. In combination, cereal-legume systems improve the quality of protein via optimized essential amino acid composition, and dietary fiber, minerals, and bioactive nutrients that are biologically significant to human health.

From a food system perspective, cereals and legumes are attractive raw materials because they:

– are widely produced and globally available;
– have a relatively low environmental footprint (Plaza-Bonilla et al., 2018);
– provide complementary amino acid profiles when combined (Han et al., 2021);
– represent suitable substrates for bioprocessing and functional optimization (Machida et al., 2022).

However, the application of cereals and legumes in food systems is limited by the inherent complexity of their food matrices, where interactions between proteins, starch, minerals, and antinutritional factors reduce nutrient bioavailability, impair techno-functional performance, and negatively affect sensory quality.

Therefore, this review aims to provide a structured and comprehensive synthesis of current knowledge on fermentation-induced biochemical transformations in cereal, legume-, and mixed plant-based food matrices, with a particular emphasis on their nutritional, functional, and technological implications. Special attention is given to matrix-dependent effects, fermentation strategies, integration with complementary processing technologies, and current limitations relevant to sustainable food design.

Materials and methods

This review relies on an analysis of various relevant scientific publications about the fermentation of plant-based food matrices with respect to their nutritional, functional, and technological effects. All the studies were peer-reviewed articles and review papers published by several authors worldwide with a focus on cereals, legumes, mixed cereal–legume systems, and selected plant-derived matrices. The search for literature was conducted using PubMed, Scopus, Web of Science, and ScienceDirect, along with relevant open-access sources, focusing on studies published mainly from 2005 to 2025. Keyword combinations on plant-based foods, fermentation, food matrix, nutritional quality, functional properties, antinutritional factors, sensory attributes, and sustainable food design were employed. Publications were included in the review due to their significance for fermentation-induced biochemical transformations and reported influence on nutritional quality, techno-functional performance, and product-related properties. In view of variability in experimental design and methodology, the results were compared according to commonality of trends, technological relevance, and limitations of the study from a matrix-oriented and design-driven approach.

Results and discussion

Plant-based food matrices as targets for fermentation

Concept of food matrix in plant-based foods. Food matrix is the concept of the three-dimensional organization of nutrients and non-nutritive components within a food (the physical structure and chemical interactions involved) used in food science. Instead of a reductionist mentality that views nutrients as having their own function, a food matrix perspective suggests that the interaction relationship among macromolecules (proteins, carbohydrates, and lipids), micronutrients, and bioactive compounds found present in the matrix determines nutritional, functional, and physiological activities. This organization is very complicated in plant-based foods, where cell walls, storage organelles, as well as a large number of structurally bound compounds exist (Alrosan et al., 2023; Nkhata et al., 2018). And in that sense, there is a significant differentiation between an ingredient and a food matrix. Ingredients (e.g., protein isolates, starches, fiber fractions) are commonly derived via intensive fractionation processes that disrupt native interactions and simplify composition. Such ingredients do provide some degree of technological predictability, of course, but they generally do not have the structural complexity or nutritional synergy that results from whole or minimally processed matrices. Plant-based food matrices (whole flours, meals, fermented batters) retain protein–carbohydrate-mineral-phytochemical interactions which strongly influence digestibility, bioaccessibility, and metabolic responses. Excessive fractionation can indeed enhance functionality, but according to the available literature on cereal- and legume-based foods, it may compromise sustainability and nutritional integrity, reinforcing the importance of matrix-oriented processing strategies (Tsafrakidou et al., 2020; Verni et al., 2022).

The protein-carbohydrate-bioactive interactions are fundamental for plant matrices of nutrition. Storage proteins in legumes and cereals are commonly known to have phytic acid, polyphenols, and non-starch polysaccharides that can form insoluble or poorly digestible complexes. The amount of phytic acid in raw legumes and cereals is between 0.5 and 2.5 g/100 g dry matter; condensed tannins (0.2–1.5 g/100 g depending on species and variety) are also expected. Such interactions decrease mineral bioavailability and protein digestibility, resulting in lower nutritional efficiency despite high protein content (Nkhata et al., 2018; Sakandar et al., 2023).

Table 1

Structural organization and interactions within plant-based food matrices

Matrix component	Type of interaction	Structural role in the matrix	References
Proteins	Protein–protein, protein–polyphenol	Network formation, water binding	Alrosan et al., 2022; Wang et al., 2022; Zhang et al., 2021
Starch	Starch–protein, starch–fiber	Viscosity, gelation, texture	Ren et al., 2024; Yildiz et al., 2013; Zhang et al., 2016
Non-starch polysaccharides	Fiber–water interactions	Hydratation, matrix rigidity	Li et al., 2023; Türker et al., 2023
Minerals	Mineral–phytate complexes	Spatial immobilisation within matrix	Lopes et al., 2021; Pragya et al., 2023; Raes et al., 2014
Polyphenols	Polyphenol–protein complexes	Structural stabilisation, sensory impact	Feng et al., 2023; Perez-Gregorio and Simal-Gandara, 2017

Fermentation is therefore particularly relevant, as it targets these matrix-level interactions rather than isolated components, enabling controlled biochemical restructuring of plant-based food matrices.

Types of fermentable plant-based food matrices

Plant-based food matrices used as substrates for fermentation can be classified according to their botanical origin, macronutrient composition, and structural organization. Legumes, cereals, pseudocereals, mixed cereal–legume systems, and plant-derived by-products differ substantially in protein content, carbohydrate profile, presence of antinutritional factors, and matrix complexity, which in turn determines their response to microbial metabolism during fermentation. This classification framework allows a matrix-oriented understanding of fermentation effects, highlighting how different plant substrates exhibit distinct nutritional, functional, and sensory outcomes following bioprocessing.

Legume-based matrices. Legumes represent one of the most intensively studied plant matrices for fermentation-based food development due to their high protein content (typically 18–35 g/100 g dry matter) and their central role in plant-based dietary patterns. Legumes can be characterized by high levels of antinutritional factors, too, including phytates, trypsin inhibitors (up to 20–40 mg/g in raw seeds), raffinose-family oligosaccharides (2–8% dry matter), and saponins, also in the legume matrix. The compounds negatively affect digestibility, mineral absorption, and sensory acceptance (Sakandar et al., 2023; Verni et al., 2022). Beyond conventional soaking and cooking treatments, De Pasquale et al. (2020) demonstrated that lactic acid fermentation is particularly effective in reducing saponins, which are biologically active glycosides known for their antinutritional effects, especially when applied in combination with starch gelatinization. Compared to gelatinization alone, fermentation resulted in a more pronounced degradation of antinutritional factors and contributed to a significant improvement in in vitro protein digestibility of legume flours (De Pasquale et al., 2020). Fermentation of legume matrices has been shown to reduce phytate content by 30–70%, depending on fermentation time, microbial strains, and pH evolution; it decreases trypsin inhibitor activity and oligosaccharide levels as well. Furthermore, proteolysis that is induced by fermentation enhances the free amino acids and small peptides, allowing for improved digestibility and, in some cases, improved umami perception. These effects make legumes ideal candidates for fermentation-driven matrix optimization (Adebo et al., 2022; Garrido-Galand et al., 2021).

Cereal and pseudocereal matrices. The vast majority of cereals and pseudocereals come in the form of carbohydrates with starch contents ranging from 60 to 75%, and protein contents between 7 to 15%. Although they are less protein-rich than legumes, cereals are major sources of dietary energy as well as micronutrients. Similar to legumes, cereal matrices contain phytic acid (typically 0.3–1.5 g/100 g) and phenolic molecules, limiting mineral bioaccessibility (Nkhata et al., 2018; Oboh et al., 2009).

Fermentation of cereal matrices—namely sourdough fermentation—has been shown to reduce phytic acid concentration by 40–90% when optimised, primarily due to endogenous and microbial phytase activity at acidic pH levels. Fermentation also alters starch–protein interactions, which in turn influence viscosity, glycemic response, and dough rheology. Fermentation in these contexts improves texture and flavor complexity, thereby aiding shelf life in breads and cereal-based porridges, giving added value to the aforementioned transformations (Gobbetti et al., 2020; Mykhonik and Hetman, 2022; Wanink et al., 1994).

Mixed cereal–legume matrices. Mixed cereal–legume matrices integrate the complementary nutritional properties of these two groups and are of growing interest as sustainable options other than animal-based protein systems. These matrices generally obtain improved amino acid balance, with legumes counterbalancing lysine deficiency in cereals and cereals providing sulfur-containing amino acids. In blended matrices, protein contents commonly range from 15 to 25 g/100 g depending on formulation (Chinma et al., 2025; Kaleda et al., 2020).

Fermentation of cereal–legume blends introduces additional complexity, as microbial metabolism must adapt to heterogeneous substrates. Experimental evidence supporting these synergistic effects in cereal–legume matrices was provided by Rizzello et al. (2014), who investigated sourdough fermentation of wheat flour enriched with chickpea, lentil, and bean flours at a total replacement level of 15% (w/w). The authors demonstrated that sourdough-fermented wheat–legume bread exhibited significantly higher concentrations of total free amino acids, enhanced phytase and antioxidant activities, and improved in vitro protein digestibility compared to yeast-fermented wheat bread. Moreover, sourdough fermentation contributed to a marked reduction of the starch hydrolysis index, indicating a lower predicted glycaemic response, while maintaining good sensory acceptability and crumb structure (Rizzello et al., 2014).

However, in most investigations synergistic effects are reported, such as increased degradation of phytates, increased digestibility of protein, and a more balanced sensory profile than with single raw material systems. They are of high potential to be used in sustainable food design as nutritionally adequate systems can be processed with moderate intensity and have functional versatility (Garrido-Galand et al., 2021; Patel et al., 2013).

Plant-based by-products and underutilized matrices. Plant-derived by-products, including bran, hulls, and milling fractions, are becoming more widely acknowledged as fermentable matrices loaded with high fiber and polyphenol contents. Although these matrices are usually characterized by lower amounts of protein, they can have significant levels of bound phenolic compounds and minerals. Fermentation has been reported to generate 20–60% augmented free soluble phenolics, combined with improved antioxidant activity, substantiating their valorization in circular food systems (Oboh et al., 2009; Szymandera-Buszka et al., 2021). These matrices are best incorporated at moderate levels into composite formulations due to technological and sensory limitations, rather than used as stand-alone substrates. However, their incorporation is also compatible with sustainability goals and demonstrates fermentation as an essential facilitator of by-product utilization.

Solid-state fermentation (SSF) represents a particularly suitable approach for the valorization of lignocellulosic agro-industrial residues (Stabnikova et al., 2010). In SSF systems, microorganisms grow directly on moist solid substrates that serve simultaneously as physical support and nutrient source. Filamentous fungi such as *Aspergillus* spp. and *Rhizopus* spp. demonstrate strong lignocellulose-degrading potential and organic acid production capacity, enabling structural disruption of plant cell walls and enhanced release of bound nutrients (Vassilev and De Oliveira Mendes, 2018).

Fermentation as a matrix-oriented biochemical tool

Fermentation represents a matrix-oriented biochemical approach that allows for modifiable rearrangement of plant-based food systems by way of microbial metabolism and enzyme activity. In cereal-based fermentations, lactic acid bacteria (LAB), yeasts, and filamentous fungi constitute the principal microbial groups involved, each contributing distinct metabolic pathways and enzymatic systems. LAB may be classified as homofermentative or heterofermentative depending on their metabolic end-products (Stabnikov et al., 2025), while yeasts contribute primarily to carbon dioxide production and flavor formation (Prakash, 2016). Unlike isolated nutrients, fermentation addresses all the interactions in the food matrix, including protein–carbohydrate–mineral and protein–polyphenol complexes, which play an important role in nutritional and functional performance of cereal- and legume-based foods. A clear illustration of this matrix-oriented processing strategy was provided by De Pasquale et al. (2020), who combined starch gelatinization with lactic acid fermentation to enhance the nutritional quality of legume flours. The authors showed that preliminary gelatinization increased substrate accessibility for microbial proteolysis, while subsequent fermentation intensified the degradation of antinutritional factors, particularly saponins, resulting in higher protein digestibility compared to raw or solely fermented flours (De Pasquale et al., 2020). In plant-based matrices, fermentation promotes a limited range of core biochemical events that carry wide relevance: acidification, activation of endogenous and microbial enzymes (e.g., phytases, proteases, amylases), partial hydrolysis of macromolecules, and redistribution of low-molecular-weight compounds. These changes are mainly pH-controlled, substrate availability, and microorganism–matrix specific and together induce adaptation in digestibility, bioaccessibility, and techno-functional properties reported in the following sections. Crucially, the strength and direction of fermentation effects are dependent on the matrix. Diverse results may also be obtained in legume-, cereal-, or mixed-origin matrices where the same fermentation conditions yield divergent outcomes due to differences in protein composition, starch structure, cell wall architecture, and antinutrient profiles. This matrix dependence explains the variability across studies and reinforces the feasibility of integrating fermentation strategies into a food design framework, where biochemical transformations are targeted toward relevant nutritional and functional outcomes rather than implemented as generic processing steps.

While Figure 1 presents a conceptual classification of plant-based matrices as fermentation targets, Table 2 integrates these matrix categories with representative fermentation strategies and reported biochemical transformations described in the literature.

Table 2

Overview of plant-based food matrices, fermentation strategies, and key biochemical targets

Plant-based matrix	Raw material examples	Fermentation type/ microorganisms	Biochemical targets	Key reported outcomes	References
Legumes	Chickpea, lentil, pea, faba bean	Lactic acid fermentation (*Lactiplantibacillus plantarum*, *L. brevis*, *Levilactobacillus fermentum*)	Phytic acid, trypsin inhibitors, raffinose-family oligosaccharides, storage proteins	Decrease in phytate (≈30–70%), reduction of trypsin inhibitor activity, increased protein digestibility, and free amino acids	Karovičová and Kohajdova, 2007; Nkhata et al., 2018; Verni et al., 2022
Cereals	Wheat, rye, oat, barley	Sourdough fermentation (LAB + yeasts)	Phytic acid, starch–protein interactions	Phytate reduction (≈40–90%), improved mineral bioavailability, enhanced dough rheology, and bread quality	Nkhata et al., 2018; Verni et al., 2022
Pseudocereals	Buckwheat, quinoa, amaranth	LAB fermentation	Bound phenolics, protein–polyphenol complexes	Increased free phenolic compounds, enhanced antioxidant activity, improved protein functionality	Oboh et al., 2009; Tsafrakidou et al., 2020
Cereal–legume blends	Wheat–pea, rice–bean, maize–soy	Controlled LAB fermentation	Antinutritional factors, protein–carbohydrate complexes	Improved amino acid balance, reduced antinutrients, more balanced sensory profile	Abdalla et al., 2025; Chinma et al., 2025
Plant-based by-products	Bran, hulls, milling fractions	Solid-state fermentation (LAB, fungi)	Bound phenolics, fiber matrix	Increase in free phenolics (≈20–60%), enhanced antioxidant activity, valorization of by-products	Oboh et al., 2009; Tsafrakidou et al., 2020
Mixed plant matrices	Legume flours, cereal meals	LAB fermentation + extrusion	Protein structure, flavour precursors	Improved texture, reduced beany flavour, enhanced umami perception	Licandro et al., 2020; Tsafrakidou et al., 2020
Legume proteins	Pea, lupin, chickpea proteins	LAB fermentation	Storage proteins, allergenic fractions	Improved solubility and emulsifying properties, reduced allergenicity	Gänzle, 2022
Fermented composite foods	Bread, porridges, extruded snacks	Sourdough / mixed fermentation	Starch–protein network	Improved viscosity control, digestibility, and sensory acceptability	Nout, 2009
Legume flours (pre-treated matrices)	Chickpea, lentil, pea	Starch gelatinization + lactic acid fermentation (LAB)	Saponins, protein–antinutrient complexes, storage proteins	Enhanced degradation of saponins, improved accessibility of storage proteins, increased in vitro protein digestibility, matrix-dependent nutritional optimization	De Pasquale et al., 2020
Cereal–legume composite foods (baked products)	Wheat–chickpea, wheat–lentil, wheat–bean blends	Sourdough fermentation (LAB-dominated)	Phytic acid, starch–protein network, storage proteins	Increased free amino acids, improved protein digestibility, enhanced phytase and antioxidant activity, reduced starch hydrolysis index, improved sensory acceptability	Rizzello et al., 2014
Legume matrices (soybean)	Soybean	LAB fermentation (*Lactobacillus plantarum*, α-galactosidase-producing strains)	Phytates, tannins, trypsin and protease inhibitors, raffinose-family oligosaccharides	Strong reduction of antinutritional factors, enzyme-driven improvement of nutritional quality and gastrointestinal tolerance	Adeyemo and Onilude, 2013
Cereals and pseudocereals	Wheat, maize, buckwheat, amaranth	Lactic acid fermentation (LAB, mixed cultures)	Phytates, enzyme inhibitors, protein–mineral complexes	Consistent reduction of antinutritional factors, improved mineral bioavailability and functional quality across matrices	Liptáková et al., 2017

Beyond botanical classification, the response of plant-based matrices to fermentation is strongly influenced by the metabolic capabilities and enzymatic profiles of the microorganisms involved. Understanding matrix–microorganism specificity is therefore essential for rational fermentation design.

Matrix constraints and fermentation-driven transformations

Strong interactions of proteins, starch, minerals, and phytochemicals, which are often mediated by antinutritional agents such as phytic acid, tannins, protease inhibitors, and α-galactosides, are commonly reported in reviews to restrict nutrient bioavailability, protein digestibility, and technological functionality but also to drive unfavorable sensory characteristics like bitterness, astringency, and legume-derived off-flavours (Nkhata et al., 2018; Sakandar et al., 2023; Verni et al., 2022). The main matrix-level limitations associated with cereal- and legume-based systems and their nutritional and technological implications are summarized in Table 3. These constraints represent key structural and biochemical barriers that justify the application of targeted bioprocessing strategies such as fermentation. These limitations are further illustrated schematically in Figure 1, highlighting the mechanisms of mineral chelation by phytic acid and protein binding by tannins that underpin reduced nutritional performance.

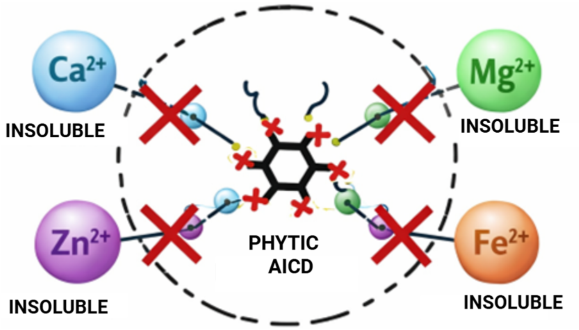
Table 3

Major limitations associated with cereal- and legume-based food matrices

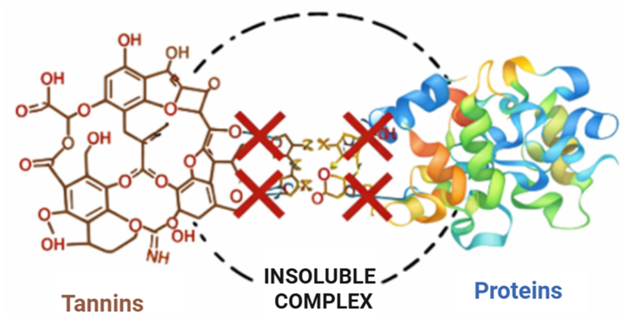
Matrix component	**Limiting factor**	**Consequence**	**References**
Phytic acid	Mineral chelation	Reduced Fe, Zn bioaccessibility	Sarkhel and Roy, 2022; Zhang et al., 2022
Tannins	Protein binding	Lower digestibility	Gilani et al., 2005, 2012; Kumar et al., 2022
Tannins	Iron chelators	Iron absorption inhibition (100 mg can inhibit it by up to 88%)	Okaiyeto et al., 2025
Raffinose-family oligosaccharides	Poor digestion	Gastrointestinal discomfort	Elango et al., 2022; Sanyal and Bishi, 2021
Protein–starch complexes	Structural rigidity	Reduced techno-functionality	Abdel-Aal, 2024; Navneet and Joye, 2025

Addressing these matrix-level constraints requires targeted processing strategies capable of modifying molecular interactions within the food matrix rather than simply altering ingredient composition.

Microbial metabolism, especially that of lactic acid bacteria, induces acidification, activates endogenous and microbial enzymes, and promotes controlled hydrolysis of macromolecules, enabling the degradation of antinutritional compounds, the release of bound minerals and phenolics, and partial proteolysis of storage proteins (Adebo et al., 2022; Alrosan et al., 2023).



Mineral chelation by phytic acid



Protein binding by tannins

Figure 1. Major matrix-level limitations of cereal- and legume-based foods and their implications for nutritional and functional performance
(created by the authors)

Early comprehensive reviews highlighted that legume- and cereal-based fermented foods have been integral components of traditional diets across Asia, Africa, and the Near East for centuries, primarily due to their improved digestibility, enhanced sensory attributes, and increased nutritional value compared to raw materials (Reddy et al., 1983). Building on this traditional knowledge, a growing body of experimental evidence demonstrates that fermentation markedly reduces key antinutritional factors in cereals and legumes, including phytic acid, tannins, trypsin inhibitors, and raffinose-family oligosaccharides, thereby improving mineral bioavailability and gastrointestinal tolerance.

Beyond antinutrient degradation, fermentation induces profound modifications at the protein level, where controlled proteolysis alters macromolecular interactions within the food matrix and directly affects techno-functional properties such as solubility, water-holding capacity, and emulsifying behavior. However, these effects are strongly dependent on the botanical origin of the substrate, the metabolic capacity of the selected microbial strains, and fermentation conditions. Consequently, increasing emphasis is placed on matrix-specific and process-controlled fermentation strategies rather than the application of generalized, one-size-fits-all fermentation approaches (Emkani et al., 2022; Garrido-Galand et al., 2021; Sakandar et al., 2023).

In addition to increasing nutritional quality, fermentation plays a key role in defining the functional and sensory properties of plant-based foods. In cereal-legume systems, fermentation alters the mechanism of interaction between starch and protein and hydration properties, which then influence viscosity, rheology, and texture – variables that are of particular concern to porridges, baked goods, and extruded products. It is well established that sourdough fermentation has proven to be a promising, sustainable means of utilizing the potential of legumes, pseudo-cereals, and milling by-products in baking applications, enabling higher inclusion levels while maintaining acceptable texture, aroma complexity, and shelf life (Chinma et al., 2025; Gobbetti et al., 2020; Rizzello et al., 2014).

Moreover, fermentation also aids in the biotransformation and redistribution of phytochemicals in plant-derived matrices. Studies concerning legumes and underutilized plant species have shown that via fermentation more free soluble phenolic substances are obtained at the expense of bound fractions, leading to an increase in the antioxidant activity. These effects are due to microbial and endogenous enzymatic activity disrupting cell wall structures and phenolic–macromolecule complexes. At the same time, critical assessments underline that increases in antioxidant capacity measured in vitro do not necessarily translate into proven physiological effects, reinforcing the need for cautious interpretation (Oboh et al., 2009; Verni et al., 2019).

In recent years, more and more research has stressed an integrated approach of fermentation together with complementary processing technology as a way for sustainable food design. Hybrid methods, which integrate fermentation with extrusion, baking, or controlled drying techniques, enable any of the biochemical changes seen during fermentation to be converted into tangible changes in texture, flavor development, and product stability. These methods also help to valorize the production of high protein, high fiber plant food items, which are convenient and shelf-stable, while the need for additives or intensive refining is minimized, and are largely consistent with sustainability targets in international food policy frameworks (Patel et al., 2013).

Together, available evidence provides the justification to view fermentation not only as a traditional process, but also as a strategic tool for the sustainable development of plant-based food products. By inducing controlled biochemical transformations within cereal-, legume-, and mixed plant-based food matrices, fermentation can improve nutritional quality, functional performance, sensory acceptance, and product safety. However, the reported effects of fermentation remain highly variable and strongly dependent on matrix composition, microbial strains, and processing conditions, while challenges related to process standardization and industrial scalability persist (Alrosan et al., 2023; Tsafrakidou et al., 2020).

Matrix–microorganism specificity in plant-based fermentation

The biochemical and functional outcomes of plant-based fermentations are determined not merely by the presence of microorganisms, but by the specificity of interactions between microbial enzymatic systems and the structural organization of the plant matrix. This matrix–microorganism specificity is increasingly recognized as a central determinant of fermentation efficiency, metabolic pathways, and nutritional outcomes.

Plant-based matrices differ considerably in macronutrient composition, endogenous enzyme activity, antinutritional factor content, and physical structure. Cereals are typically starch-dominant (60–75%), with moderate protein levels and active endogenous amylases, while legumes contain higher protein concentrations (18–35%) alongside phytates, trypsin inhibitors, raffinose-family oligosaccharides, and phenolic compounds. These compositional differences strongly influence microbial growth dynamics and enzymatic expression profiles (Gupta and Abu-Ghannam, 2012; McFeeters, 2004; Rombouls and Nout, 1995).

Lactic acid bacteria. In cereal fermentations, lactic acid bacteria (LAB), particularly representatives of the genera *Lactobacillus, Leuconostoc, Pediococcus,* and *Lactococcus*, dominate acidification processes. Homofermentative strains primarily convert hexoses into lactic acid, whereas heterofermentative strains produce lactic acid, acetic acid, ethanol, and CO_2, affecting dough rheology and sensory development (Blandino et al., 2003; McFeeters, 2004). The balance between these metabolic pathways influences texture, leavening, and flavor complexity.

In legume matrices, however, LAB performance depends strongly on strain-specific enzymatic systems. Strains of *Lactiplantibacillus plantarum* and *L. casei* exhibit variable proteolytic systems, phytase activity, and α-galactosidase production. These enzymatic differences determine the extent of phytate degradation, protein hydrolysis, and oligosaccharide breakdown (Demirci et al., 1998; Gupta and Abu-Ghannam, 2012; Liu et al., 2018).

Importantly, excessive proteolysis under prolonged fermentation can negatively influence sensory quality due to the accumulation of bitter peptides, highlighting the need for controlled fermentation windows.

Yeasts and symbiotic interactions. In cereal-based sourdough systems, *Saccharomyces cerevisiae* and non-*Saccharomyces* yeasts (e.g., *Candida* spp.) coexist with LAB in stable consortia. Yeasts metabolize maltose and glucose into ethanol and CO_2, contributing to leavening and volatile flavor compounds, while LAB lower pH and modify protein–starch interactions. Symbiotic interactions enhance fermentation stability and product quality (McFeeters, 2004; Mehta et al., 2012). Yeast–LAB interactions are less common in pure legume fermentations but become relevant in cereal–legume blends.

Filamentous fungi. In solid-state fermentations (e.g., tempe-type systems), *Rhizopus oligosporus* restructures dense protein matrices through mycelial penetration, enhancing nutrient accessibility. *Aspergillus oryzae* and *A. sojae* contribute strong proteolytic and amylolytic activities in soybean fermentations (Mehta et al., 2012). These systems differ fundamentally from LAB fermentations in enzyme spectrum and structural impact.

Process environment as modulator. Beyond microbial taxonomy and enzymatic repertoire, fermentation outcomes are strongly modulated by the physicochemical environment of the process. Parameters such as pH evolution, water activity, substrate particle size, oxygen availability, salt concentration, and temperature dynamically influence microbial growth kinetics and metabolic flux distribution (Berenjian, 2019). These variables determine not only the rate of acidification but also the expression and activity of key enzymes involved in phytate degradation, proteolysis, and carbohydrate hydrolysis.

Experimental studies on repeated-batch fermentations with Lactobacillus plantarum and related strains have demonstrated that medium composition and environmental conditions significantly alter lactic acid production rates and metabolic pathways, leading to variability in biochemical transformation efficiency (Singh et al., 2024). Likewise, marked differences have been observed between submerged and solid-state fermentation systems, where oxygen diffusion, moisture gradients, and substrate structure generate distinct enzymatic profiles and structural modifications within plant matrices (Hur et al., 2014; Rombouls and Nout, 1995).

These observations confirm that fermentation performance cannot be generalized across plant-based systems. Rather, it emerges from the coordinated interaction between botanical matrix composition, microbial enzymatic capacity, and tightly controlled process parameters. This matrix-dependent behavior has been experimentally demonstrated in cereal, pseudocereal, and legume substrates co-fermented with *Propionibacterium freudenreichii* and *Levilactobacillus brevis*, where vitamin B12 production varied markedly depending on buffering capacity, pH evolution, and substrate composition (Xie et al., 2021). Recognition of this matrix–microorganism–environment interplay is fundamental for rational fermentation design and for the development of structurally optimized, nutritionally enhanced, and sustainable plant-based food products.

A structured overview of matrix–microorganism interactions across major plant-based fermentation systems is presented in Table 4.

As shown in Table 4, fermentation performance is not uniform across plant matrices. Differences in substrate composition and microbial enzymatic potential result in distinct structural modifications and nutritional responses, reinforcing the importance of matrix-specific fermentation strategies.

Nutritional and functional implications of fermentation-induced biochemical transformations

Biochemical transformation due to fermentation in plant-based food matrices results in greater nutritional quality and increased performance of food, but the effects do vary significantly from raw material to raw material, from microbial cultures to processing conditions. Fermentation results need to be considered at the matrix level, not as isolated nutrient changes, as there is a close interdependence between composition, structure, and processing history (Tsafrakidou et al., 2020).

Protein digestibility and amino acid availability. Digestibility of protein content following fermentation is one of the reported nutritional benefits consistent between cereal-, legume-, and mixed matrices. A series of studies reports in vitro protein digestibility enhancement from 10 to 25 percentage points in fermented legume flours compared with unfermented ones, depending upon the time to ferment and microbial strains used. These enhancements are usually ascribed to partial proteolysis and disentanglement of protein–antinutrient complexes; however, the degree of proteolysis differs significantly between matrices (Tsafrakidou et al., 2020). In addition to digestibility, some authors have found that the availability of free amino acids and low-molecular-weight peptides is promoted after fermentation, with increments in the range of 20–60% relative to the raw materials. Yet reviews have shown that augmented availability of amino acids is not synonymous with sensory acceptance, as excessive proteolysis can cause bitterness or undesirable flavor development in certain legume matrices (Rizzelo et al., 2014).

Mineral bioaccessibility. Fermentation has been extensively studied as a way to enhance mineral bioaccessibility in plant-based foods by reducing phytic acid and other chelating compounds. Several authors have reported reductions in phytic acid content of 30–70% in fermented legume matrices and up to 40–90% in fermented cereal-based systems, particularly under conditions favoring phytase activity.

Table 4

Matrix–microorganism specificity in plant-based fermentation systems

Matrix Type	Dominant microorganisms	Key enzymatic activities	Structural impact	Nutritional outcomes	References
Cereals (wheat, rye)	*Lactobacillus* spp., *Saccharomyces cerevisiae*	Amylases, phytases, proteases	Acidification, starch hydrolysis, gluten network modification	Decrease in phytate content (40–90%), improved rheology	Blandino et al., 2003; McFeeters, 2004
Legumes (chickpea, lentil)	*L. plantarum*, *L. casei*	Proteases, phytases, α-galactosidase	Protein–phytate complex disruption	Increase in digestibility (10–25%), ↓ RFOs	Gupta and Abu-Ghannam, 2012
Cereal–Legume blends	LAB + yeasts	Combined proteolytic and amylolytic activity	Balanced acidification, matrix softening	Improved amino acid balance	Chinma et al., 2025; Patel et al., 2013
Solid-State Fermentation (soy/tempe)	*Rhizopus oligosporus*	Strong proteases, amylases	Mycelial penetration, increased porosity	Improved nutrient accessibility	Mehta et al., 2012
Bran / By-products	LAB, fungi	Esterases, phenolic-degrading enzymes	Cell wall disruption	Increase in free phenolic content (20–60%)	Oboh et al., 2009
Pseudocereals (quinoa, buckwheat)	*L. plantarum*, *Weissella* spp.	Phytases, phenolic esterases	Release of bound phenolics	Improved antioxidant activity	Tsafrakidou et al., 2020
Pea protein isolates	LAB strains (strain-dependent)	Proteolytic systems	Modification of protein solubility	Increase in protein solubility (15–50%), improved emulsification	Aderinola and Duodu, 2022
Fermented soy (koji systems)	*Aspergillus oryzae*	Strong proteases, amylases	Intensive macromolecule hydrolysis	Increase in free amino acids content, flavor compounds	McFeeters, 2004
Repeated-batch LAB systems	*L. plantarum*	Lactic acid production, metabolic flux adaptation	Altered acidification kinetics	Process optimization potential	Demirci et al., 1998
High-moisture cereal fermentation	LAB consortia	Phytase activation	Enhanced mineral release	Increased Fe, Zn bioaccessibility	Nkhata et al., 2018

The direct effect of the fermentation reaction is that the estimated bioaccessibility of mineral sources, including iron, zinc and calcium, has been reported to improve with relative improvements in mineral bioaccessibility usually between 15 and 50%, depending on the matrix and analytical technique (Adebo et al., 2022). However, some studies have noted that reducing phytate does not independently predict mineral uptake, with residual polyphenols and fiber composition in this respect remaining modulating factors for mineral binding (Raes et al., 2014). This highlights the importance of integration of matrix composition assessment, as opposed to dependence on single metrics.

Reduction of antinutritional factors and gastrointestinal tolerance. Other authors mentioned that fermentation leads to enhanced gastrointestinal tolerance of cereal- and legume-based foods due to lower levels of raffinose-family oligosaccharides and protease inhibitors. The reported decreases in α-galactosides are between 20 and 60%, and trypsin inhibitor activity may be reduced by 25–80%, depending on fermentation intensity. These effects are primarily attributed to the activity of microbial α-galactosidases and proteases, which hydrolyze fermentable oligosaccharides and enzyme inhibitors that otherwise contribute to bloating, flatulence, and impaired protein digestion. In this context, fermentation has been described as an ex situ digestion step that improves tolerance of plant-based foods, particularly in cereal- and legume-rich diets, by reducing FODMAPs (fermentable oligosaccharides, disaccharides, monosaccharides, and polyols) and immune-reactive proteins (Gänzle, 2020). These alterations are particularly significant in legume-containing formulations geared towards vulnerable populations or high-consumption scenarios. Consistent with these observations, Adeyemo and Onilude (2013) reported reductions of phytates (from 1.16 to 0.04 mg/g), tannins (from 1.93 to 0.12 mg/g), and trypsin inhibitor activity (from 1.20 to 0.01 mg/g) in soybeans fermented with α-galactosidase-producing *L. plantarum* strains, supporting fermentation as an effective strategy for improving gastrointestinal tolerance in legume-rich formulations (Adeyemo and Onilude, 2013). Similar conclusions were drawn by Gänzle (2020), who emphasized the relevance of fermentation-mediated degradation of raffinose-family oligosaccharides and protease inhibitors for improving digestive tolerance in sensitive individuals consuming plant-based foods.

Functional and technological implications

Hydration and rheological properties. Hydration behavior and rheological properties of plant-based matrices are drastically influenced by fermentation-induced restructuring. These have been attributed to changes in protein unfolding, partial hydrolysis of starch, and fiber structure modification and shown by increases in water absorption capacity of fermented flours in the order of 10–40% by several studies (Emkani et al., 2022). It is known that fermentation achieves a decrease in excessive viscosity of cereal–legume systems at an equivalent solids content, and improves nutrient density without compromising processability (Garrido-Galand et al., 2021). These effects may become an important consideration in all fermented batters, porridges and bakery applications, as viscosity control and water management are important aspects for the quality of the product as well as energy efficiency of the product.

Techno-functional properties of proteins. From a functional perspective, fermentation is said to affect protein solubility, emulsifying capacity, and foaming behaviour (Alrosan et al., 2023). A number of authors showed that protein solubility increased during fermentation by around 15–50%, particularly in legume matrices, with the highest increase in solubility observed, followed by a drop-off under highly acidic conditions. Enhancement of emulsifying activity and stability is most commonly observed within the moderate proteolysis stage, while excessive hydrolysis may impede the formation of networks and the integrity of the structure (De Pasquale et al., 2020). These results indicate that fermentation might benefit protein functionality within a defined processing window and therefore emphasize the optimization of the process.

Sensory-related functional outcomes. While not a primary sensory analysis per se, a combination of studies reported indirect sensory improvements associated with fermentation-induced biochemical alterations. In fermented cereal and pseudocereal products, these biochemical changes have been associated with improved flavor complexity, reduced bitterness, and enhanced consumer acceptance, highlighting the dual nutritional and sensory benefits of fermentation-driven matrix modification (Liptáková et al., 2017).

A reduction of beany or raw legume notes and the emergence of mild acidic and savory characteristics have been observed, especially in cereal–legume blends and fermented dough preparations. Nevertheless, some authors also point to bitter compounds in the fermented products when fermentation is prolonged or poorly controlled, with trade-offs in relation to nutritional enhancement and sensory quality identified.

These biochemical changes undergone by fermentation translate into nutritional and functional improvements at the plant-based food matrix scale, highlighting that fermentation should not be considered merely a preservation method, but rather an aspect of its conceptual design. Both the nutritional and technological effects of fermentation are mediated through the collective transformations of proteins, carbohydrates, minerals, and bioactive constituents of the matrix and are dependent on the composition of the raw materials, microbial consortia, and the environmental conditions of the fermentation process. Improved digestibility of protein across cereal, legume, and mixed-origin matrices is one of the strongest reported nutritional impacts of fermentation.

The digestibility of proteins in fermented legume flours was investigated in experimental studies such as (Nkhata et al., 2018; Verni et al., 2022), and fermented legumes exhibited 10–25 percentage points greater in vitro digestibility than unfermented flours. It is known that the disruption of protein–antinutrient complexes and an increase in enzymatic accessibility occur in the microbial and endogenous proteases-mediated proteolysis. At the same time, several authors present up to 20–60% increase in free amino acids and low-molecular-weight peptides, depending on fermentation duration and strain chosen (Abdalla et al., 2025; Chinma et al., 2025). However, reviews also warn that over-proteolysis is harmful to sensory quality by virtue of the production of bitter peptides in legume-rich matrices, suggesting the importance of fermentation strategy control.

Mineral bioaccessibility is another prominent health benefit of fermentation-induced phytic acid degradation. As indicated in numerous literature studies, phytate-content reductions of 30–70% in legume matrices and 40–90% in cereal-based systems are reported, especially for conditions that maximise phytase activity (Oboh et al., 2009; Verni et al., 2022). Consequently, there has been a reported 15–50% improvement in bioaccessibility of the minerals (iron, zinc, calcium) based on matrix composition and analytical methodology (Nkhata et al., 2018; Tsafrakidou et al., 2020). Importantly, several authors stress that phytate reduction alone does not fully predict mineral uptake. Residual polyphenols, fiber architecture, and protein interactions remain critical modulators of mineral binding. This demonstrates that it is essential to evaluate mineral bioaccessibility within the whole food matrix and not based on isolated compositional indicators alone.

Apart from nutrients alone, fermentation enhances the complete health potential of the nutritional composition of the plant-based matrix with respect to the reduction of the non-nutritional content due to anti-nutritional content to the gastrointestinal problems caused by fermentation. Categorical reductions in raffinose-family oligosaccharides (α-galactosides) have been documented with yields between 20% and 60%, and the action of trypsin inhibitor can be decreased by 25–80%, which is in part due to the fermentation kinetics and substrate (Chakraborty et al., 2022; Karovičová and Kohajdova, 2007; Nkhata et al., 2018). The latter becomes particularly important in legume-containing formulations for high consumption practices or for nutritionally sensitive populations.

Functionally and technologically, fermentation-mediated reorganization of macromolecules also influences hydration properties, rheology, and functionality of proteins. Studies on cereal–legume batters have shown that enzymatic enhancement of starch hydrolysis accelerates microbial metabolism, promotes faster acidification, and significantly modifies viscosity and gas retention behavior (Iyer and Ananthanarayan, 2008). The fermentation process is well-studied in many studies, which showed up to 10-40% increase in water absorption capacity of fermented flours, attributed to protein unfolding and partial starch hydrolysis along with fiber modification (Knez et al., 2023; Verni et al., 2022). These transformations generally lead to decreased viscosity at equal solids content, allowing higher density of nutrients and processability in batter, porridge, and fermented doughs.

Similarly, the solubility and interfacial properties of proteins are also influenced by fermentation. For instance, cereal–legume-based non-dairy probiotic beverages fermented with *Lactobacillus acidophilus* showed increased antioxidant capacity, total phenolic content, and viable cell counts as substrate concentration increased (Chavan et al., 2018). In legume-based systems, protein solubility increased by around 15–50% during moderate fermentation. Before excessive acidification occurred, this was observed as an optimal change (Aderinola and Duodu, 2022; Verni et al., 2022). Comparable improvements in free amino acid availability and protein functionality have been reported in cereal–legume sourdough systems fermented with *Lactobacillus plantarum*, where controlled fermentation enhanced both nutritional and technological properties (Coda et al., 2010).

Enhanced emulsifying performance and foam stability are frequently associated with limited proteolysis, whereas an excessive level of hydrolysis can impair network formation and structural integrity. Together, these results indicate that fermentation can be strategically applied to personalize techno-functional properties in a specified processing window. Finally, fermentation-mediated biochemical modifications also indirectly influence sensory properties such as texture and flavor development. Several authors reported the attenuation of beany or raw legume notes and the emergence of mild acidic and savory properties in cereal–legume blends and fermented dough systems. Still, a long or poorly regulated fermentation might result in the formation of bitter compounds, showing the need for a trade-off between nutritional benefit and sensory reception.

As a whole, these findings suggest that fermentation is indeed a form of matrix-level intervention with the potential to enhance nutritional quality and functional performance at the same time. Once incorporated into a food design system, fermentation facilitates the specific manipulation of biochemical reactions to promote certain nutritional and technological goals, instead of acting as a one-size-fits-all process.

Fermentation as a tool for sustainable food design

Fermentation has been increasingly acknowledged as a crucial enabling technology within sustainable food design, especially in plant-based food systems. Now, far removed from its previous role as a preservation technique, the notion of fermentation is understood in ways that are described as low energy, clean label and functionality-enhancing and is aligned directly to current sustainability targets, in terms of environmental impact reduction, limited list of ingredients and nutritional performance.

Fermentation as a low-energy and clean-label process. Fermentation runs at a less harsh temperature (about 25–40 °C) than conventional thermal or chemical processing, as well as with less mechanical input and lower energy requirements. There are multiple life cycle and process-oriented studies, and fermentation is seen as a resource-efficient technology when included in existing production chains (Verni et al., 2022). Different from enzymatic treatments, which utilize purified enzymes or chemical modifications, fermentation enables in situ enzyme production by microorganisms for use in clean-label formulations without the need for declared additives. Fermentation enables the functional and sensory-enhancing effect through biological transformation rather than ingredient enrichment from a clean-label perspective. A variety of authors emphasize that fermented plant-based products tend to reduce the role of stabilizers, emulsifiers and flavor-masking agents in the formulation of a product, thereby addressing consumer demand for minimally processed foods with recognizable processing histories (Knez et al., 2023; Tsafrakidou et al., 2020).

Relevance for functional foods and plant-based meat analogues. Fermentation also has a particularly strategic role in the development of functional foods and plant-based meat analogues. In protein-rich matrices, controlled fermentation has been observed to allow for improved emulsifying capacity, water-holding ability, and gel formation, all of which are important properties for the structuring of meat analogues. Moderate fermentation tends to improve protein network formation, whereas excessive proteolysis affects texture, thus highlighting the importance of process optimization (Aderinola and Duodu, 2022). Fermentation also plays a role in the development of products with increased protein quality, lower antinutritional content, and better micronutrient bioaccessibility, all within the framework of the functional food paradigm. Meanwhile, flavor complexity obtained through fermentation aids in a decrease of added flavor and salt in plant-based analogues, meeting both sensory and nutritional targets.

The integration of fermentation into plant-based food design results in simultaneous nutritional, functional, and sensory outcomes, as summarized in Table 4.

Integration of fermentation in plant-based product development. Fermentation plays an instrumental role in various growing applications in plant food, such as flours, doughs, beverages, snacks, and protein-rich formulas. Fermentation has been reported to improve protein digestibility (+10–25 percentage points), mineral bioaccessibility (+15–50%) and functional hydration properties (+10–40% water absorption capacity) within cereal–legume matrices, thereby making the matrix more suitable for downstream processes (Chinma et al., 2025; Nkhata et al., 2018). Most importantly, several authors stress the need to promote fermentation upstream in product design, rather than as a corrective step at the final formulation stage. Early fermentation allows the transformation of the food matrix prior to extrusion, baking, or drying, making the processed product easier to process and less complicated to formulate. In legume-rich environments, fermentation attenuates beany flavors and potential antinutritional limitations that impose barriers to inclusion (Karovičová and Kohajdova, 2007; Verni et al., 2019), ensuring the effective application of this approach.

Synergies between fermentation and complementary technologies. Increasing literature indicates the complementary impact of fermentation and various processing technologies like extrusion and baking, as well as drying. Fermented raw materials in extrusion procedures are frequently produced with improved flow behavior, decreased viscosity and enhanced expandability of the obtained ingredients to allow the production of texturized plant proteins and protein-rich snacks. For instance, lactic acid fermentation of pea protein followed by high-moisture extrusion has been shown to increase free glutamate levels, reduce characteristic pea-like off-flavors, and improve structural organization and texture of plant-based sausage analogues in a strain-dependent manner (Valtonen et al., 2023). There is research support that fermentation before extrusion can enhance the solubility of protein by 15–50% and can also decrease shear-induced protein aggregation and thus improve the texture and digestibility of extruded products (Licandro et al., 2020; Tsafrakidou et al., 2020). In baking applications, sourdough fermentation still stands out among the established types of fermentation-based food design. The integration of fermented legume flours into wheat-based doughs has also been demonstrated to significantly enhance nutritional density while still having a satisfactory condition of rheology and sensory profile (Chinma et al., 2025; Verni et al., 2022), including at 15–30% legume. Fermentation in combination with controlled drying practices (e.g., vacuum or low temperature drying) has also been investigated for the design of instant cereal–legume blends and fermented flours that retain functional and nutritional integrity in a package with minimal shelf space (Nkhata et al., 2018).

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Current limitations and research gaps in fermentation-based plant food design

Although the nutritional and functional effects of fermentation have attracted an increasing amount of support from experimental data in relation to plant-based food systems, some drawbacks and unaddressed gaps impair the interpretation, comparability, and application of the published results (Gänzle, 2020; Adebo et al., 2022). Upon further review of the literature, it is found that observed benefits are quite context-dependent and should be regarded in a larger context of matrix composition, processing environment, and product intended use (Gänzle, 2020).

Table 4

Nutritional, functional, and sensory outcomes associated with fermentation-based plant food design (literature synthesis)

Product category	Raw material base	Nutritional outcome (reported trends)	Functional / technological outcome	Sensory outcome	References
Fermented legume flours	Chickpea, lentil, pea	Improved protein digestibility; reduced antinutritional factors	Increased hydration capacity; improved processability	Reduced beany notes	Karovičová and Kohajdova, 2007; Nkhata et al., 2018; Verni et al., 2022
Bakery products (sourdough)	Wheat–legume blends	Enhanced mineral bioaccessibility; improved protein quality	Improved dough rheology and gas retention	Mild acidic and savory notes	Chinma et al., 2025; Verni et al., 2022
Extruded plant-based products	Cereal–legume matrices	Improved protein quality and digestibility	Improved expansion behavior and texture uniformity	Cleaner flavor profile	Licandro et al., 2020; Tsafrakidou et al., 2020
Instant cereal–legume blends	Cereals, legumes	Reduced viscosity at high solids content	Faster rehydration; improved flow properties	Improved mouthfeel	Nkhata et al., 2018; Nout, 2009
Plant-based meat analogues	Legume protein concentrates/ isolates	Enhanced protein functionality	Improved emulsification, gelation, and water retention	Improved juiciness and flavor complexity	Aderinola and Duodu, 2022; Gänzle, 2022
Fermented functional foods	Mixed plant matrices	Increased micronutrient bioaccessibility; reduced antinutrients	Stable matrix structure	Balanced acidity	Chinma et al., 2025; Knez et al., 2023

Reported outcomes reflect general trends described across multiple independent studies and may vary depending on matrix composition, microbial strains, and processing conditions.

The high variability in the experimental design, including the origin of raw material, particle size, pre-treatments, microbial species, fermentation time, temperature, and analytical steps, is among the most serious limitations of the studies in this paper (Adebo et al., 2022). For those reasons, reported enhanced protein digestibility, mineral bioaccessibility, and techno-functional properties are frequently quite broad in range, which complicates cross-study comparisons and meta-analytical interpretation (Adebo et al., 2022; Raes et al., 2014). A few authors have observed that fermentations under the same conditions might produce different results from cereal, legume, or mixed matrices depending on the fundamental protein composition, starch structure, cell wall architecture, and antinutrient profiles of the material (Gänzle, 2020).

This variability is intimately linked to the absence of standardized fermentation protocols optimized for plant-based food matrices (Adebo et al., 2022). Fermentation parameters are often optimized within individual studies, but very few attempts to achieve harmonization of methodologies or create reference conditions that would enable reproducibility and benchmarking across laboratories have been made. This limitation is especially salient in studies assessing protein digestibility and mineral bioaccessibility, where differences in in vitro models, enzyme systems, and extraction protocols can significantly influence reported outcomes (Raes et al., 2014). As a result, the gains made in one experimental setting may not be directly transferable to other contexts.

The other important limitation concerns the lack of generalizing results from laboratory scale to industrial processing conditions (Gobbetti et al., 2020). The majority of the research in fermentation is at bench scale with controlled and simplified systems, while industrial fermentation technology has higher variability of raw material quality, process stability, and energy efficiency. Reasons such as scale-up feasibility, robustness of the process, and integration into existing production lines have not been addressed, especially for extrusion, drying, or high-throughput baking (Gobbetti et al., 2020). This knowledge gap constrains the translation of attractive fermentation strategies into commercial plant-based products.

An application-oriented limitation that recurs and is consistently observed is insufficient incorporation of biochemical, functional, and sensory considerations into the same research. Though these were investigated for individual factors (e.g., phytate reduction, protein solubility, water absorption capacity), fewer investigations systematically link these biochemical reactions to techno-functional performance and consumer-relevant sensory characteristics (Gänzle, 2020; Gobbetti et al., 2020). As discussed in a number of reviews, increases in nutritional quality don’t always translate to acceptable texture, flavor, or overall product quality. Excessive proteolysis or acidification may enhance digestibility while simultaneously impairing sensory acceptance, implying that efficient strategies for balancing these processes are a critical concern.

Lastly, current investigations generally focus on the occurrence of single-strain fermentations in a controlled environment, which may lack the complexity necessary to comprehend the traditional or industrial fermentation environments. Mixed microbial consortia, back-slopping practices, and dynamic microbial succession – common in real-world fermentations – remain insufficiently characterized in relation to matrix restructuring and product performance (Gobbetti et al., 2020). Overcoming these limitations, fermentation can move beyond purely empirical methods to be a predictive, design-driven technology.

Conclusions

Fermentation is an efficient and sustainable bioprocess for the design of plant-based foods, as it enables the modification of food matrices rather than the manipulation of isolated nutrients. At the matrix level, fermentation induces biochemical changes such as phytate degradation, limited proteolysis, and carbohydrate restructuring, which contribute to increased protein digestibility, improved mineral bioaccessibility, and reduced levels of antinutritional factors in cereal-, legume-, and mixed plant-based systems.

These nutritional improvements are closely linked to enhanced functional and technological properties, including protein solubility, water and oil absorption capacity, emulsification, gelation, texture, and flavor development. However, the extent and nature of these effects are highly matrix-dependent and influenced by the composition of raw materials, microbial strains, and processing conditions, highlighting the need for design-led and controlled fermentation strategies.

Furthermore, the integration of fermentation with complementary processes such as extrusion, baking, and drying expands its applicability in the development of functional foods and plant-based meat analogues. Despite significant progress in this field, challenges remain, including high variability among studies, the lack of standardized fermentation protocols, and limited validation at the industrial scale. Therefore, future research should prioritize standardized and scalable approaches, along with comprehensive assessment of biochemical, functional, and sensory outcomes, to fully exploit fermentation as a strategic tool in sustainable food design.

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