

Plant-Based Fermented Beverages: Processing, Nutritional and Quality

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Abstract

Plant-based fermented beverages are gaining attention as non-dairy foods that combine the nutritional diversity of cereals, millets, nuts and seeds with beneficial biochemical changes induced by fermentation. This critical narrative review examines recent advances in the processing, fermentation, nutritional modification and quality of plant-based fermented beverages, focusing primarily on studies published during 2016–2026. Pretreatments such as soaking, germination, cooking, enzymatic hydrolysis, milling and homogenization influence nutrient accessibility, fermentable carbohydrate availability and physical stability. Lactic acid bacteria are widely used for controlled fermentation, although their performance depends on the substrate and strain. Fermentation may improve protein solubility and digestibility, reduce selected antinutritional factors, modify phenolic compounds, generate organic acids and aroma compounds, and enhance texture through exopolysaccharide production. However, these effects vary among substrate–culture combinations. Cereal- and millet-based beverages often face limitations related to protein content and colloidal stability, whereas nut- and seed-based beverages present challenges involving fermentable sugars, lipid oxidation, allergenicity and emulsion stability. Composite cereal–nut and millet–seed formulations may provide nutritional and technological complementarity. Future research should emphasize matrix-specific starter selection, storage stability, sensory validation, micronutrient fortification and strain-resolved functional evidence. Overall, plant-based fermented beverages represent promising food systems requiring matrix-specific formulation and processing strategies.

Keywords: plant-based beverages; lactic acid bacteria; fermentation; cereals; millets; nuts; seeds; dairy alternatives; antinutritional factors; rheology; storage stability

1. Introduction

Demand for plant-based foods has expanded the range of beverages positioned as alternatives to conventional milk and fermented dairy products. The category now includes products prepared from cereals, legumes, nuts, seeds and mixed plant sources. These products are attractive for consumers who avoid lactose or milk proteins, follow vegan diets, seek greater dietary diversity, or prefer plant-derived foods. However, the term “dairy alternative” describes product use and market positioning rather than nutritional equivalence. Commercial plant-based beverages vary substantially in protein, minerals and vitamins, and many require fortification to approach selected micronutrient levels of cow’s milk (Chalupa-Krebzdak et al. 2018; Ramsing et al. 2023; Kulaksız Gunaydı and Cakmak Kafadar 2026).

Fermentation offers a route to improve several limitations of plant matrices. Lactic acid bacteria (LAB) can acidify plant substrates, hydrolyse or transform macromolecules, produce aroma-active metabolites and, in some cases, synthesize exopolysaccharides (EPS) that improve viscosity and water retention. Fermentation may also reduce selected antinutritional compounds and undesirable volatile compounds. These effects are highly dependent on the plant material, pretreatment, starter strain, fermentation conditions and subsequent storage, and should not be generalized across all plant-based products (Montemurro et al. 2021; Horlacher et al. 2023; Erem and Kilic-Akyilmaz 2024).

The technological challenge arises because milk and plant matrices are structurally different. Dairy yogurt develops through acid-induced destabilization and network formation of milk proteins, whereas plant beverages contain combinations of starch granules, plant proteins, cell-wall polysaccharides, oil bodies, insoluble particles and phenolic compounds. As a result, a culture that performs well in milk may acidify a cereal, nut or seed beverage slowly or may generate an unacceptable flavour or texture. Plant-based fermentation therefore requires matrix-specific process design rather than direct transfer of dairy technology (Montemurro et al. 2021; Erem and Kilic-Akyilmaz 2024).

Cereals such as rice, oat and barley are carbohydrate-rich and can provide fermentable substrates after suitable starch modification. Millets and sorghum are increasingly valued for dietary fibre, minerals and phytochemicals, but their antinutritional factors, particulate mouthfeel and characteristic flavours require attention. Nuts contribute unsaturated lipids and protein but often provide limited readily fermentable carbohydrate. Seeds such as pumpkin, sesame, sunflower, flax and hemp can increase protein, minerals and unsaturated lipid content, yet oxidation, bitterness and emulsion instability remain important constraints.

This review critically compares cereal-, millet-, nut- and seed-based fermented beverages from a food-science perspective. Attention is given to processing and pretreatment, starter-culture selection, fermentation mechanisms, nutritional and antinutritional changes, bioactive compounds, physicochemical and rheological quality, sensory acceptance, microbial safety, storage stability and commercialization. The central premise is that successful products require simultaneous optimization of microbial performance, nutritional composition, structure, flavour, safety and shelf stability rather than maximization of a single attribute.

Priority was given to studies that described the plant matrix, microbial culture and fermentation conditions sufficiently to interpret the reported changes. Evidence from chemical antioxidant assays, in-vitro digestion, microbial survival studies and human studies was considered separately because these endpoints represent different levels of biological evidence. The presence of viable LAB was not interpreted as proof of probiotic functionality; the term probiotic requires demonstrated health benefit for adequately characterized live microorganisms (Hill et al. 2014).

2. Raw Materials and Matrix Characteristics

The composition of the raw material determines how a plant beverage behaves during extraction, heat treatment, homogenization and fermentation. Starch-rich matrices generally require gelatinization or hydrolysis to control viscosity and provide fermentable sugars, whereas lipid-rich matrices require attention to emulsion stability and oxidation. Protein concentration and functionality influence buffering capacity, gel formation and mouthfeel. Fibre and insoluble particles can improve nutritional value but may promote sedimentation or grittiness. Phenolic compounds can contribute antioxidant capacity and colour while also producing bitterness or astringency. Consequently, formulation should begin with an understanding of matrix composition rather than with a fixed dairy-derived fermentation protocol (Mäkinen et al. 2016; Montemurro et al. 2021).

2.1 Cereal-based substrates

Rice is a useful base because of its mild flavour, light colour in white varieties and suitability for gluten-free product development. Its high starch content can support fermentation after cooking or hydrolysis, but rice beverages are commonly low in protein and may separate during storage. Pigmented rice can contribute phenolics and colour, although the extent of these components depends strongly on cultivar, milling degree and processing. Germination can activate endogenous enzymes and alter the availability of sugars, amino acids and phytochemicals before fermentation.

Oat is technologically attractive because β -glucan contributes soluble fibre and viscosity. The same polysaccharide–starch system can, however, make process control difficult. Excessive hydrolysis may produce a thin beverage, while insufficient hydrolysis may leave excessive viscosity or ungelatinized particles. Fermentation can modify oat flavour and texture, and selected cultures can generate compounds such as acetoin and diacetyl when metabolic conditions permit (Erem and Kilic-Akyilmaz 2024).

Barley provides starch, β -glucan, protein, minerals and phenolic compounds. Malting or germination can increase endogenous amylolytic activity and facilitate fermentation. Conventional barley contains gluten and is therefore unsuitable for products specifically intended to be gluten-free unless a validated gluten-free source and process are used.

2.2 Millet and sorghum substrates

Millets are increasingly explored because they combine starch with dietary fibre, minerals and diverse phenolic compounds. Finger millet is notable for its mineral-rich composition and phenolic fraction, while pearl millet provides protein, lipids and micronutrients in addition to starch. Their use in beverages is nevertheless constrained by coarse mouthfeel, characteristic cereal aromas, darker colour in some varieties and antinutritional compounds such as phytate and tannins. Soaking, germination, fine milling and fermentation can be combined to address these limitations.

Sorghum is a gluten-free cereal with substantial compositional diversity. Tannin-rich sorghums contain phenolic compounds that can contribute astringency and interact with proteins. Fermentation should therefore aim for controlled biotransformation rather than indiscriminate removal of all phenolics. The desired endpoint is a balance between nutrient accessibility, acceptable sensory properties and retention of useful phytochemicals.

2.3 Nut-based substrates

Almond, cashew, hazelnut, walnut and other nuts provide protein, unsaturated lipids and characteristic flavour. Their higher lipid fraction can improve creaminess but also increases susceptibility to oxidative deterioration. Compared with starch-rich cereals, some nut beverages provide limited readily fermentable carbohydrate, which may restrict acidification by conventional yogurt cultures. Blending with cereal substrates or carefully selected carbohydrate supplementation can improve fermentation performance, but the effect on sweetness, energy density and labelling should be considered (Montemurro et al. 2021; Erem and Kilic-Akyilmaz 2024).

Allergenicity is an additional formulation and regulatory consideration for tree-nut products. Fermentation can hydrolyse proteins and may reduce the immunoreactivity of selected allergens under specific conditions, but it cannot be assumed to eliminate allergenic risk. Products containing allergenic nuts must therefore remain appropriately managed and labelled.

2.4 Seed-based substrates

Pumpkin, sesame, sunflower, flax and hemp seeds are promising ingredients because they provide protein, minerals, unsaturated fatty acids and phytochemicals. Seed-based beverages remain less extensively studied than soy-, oat- and almond-based products, leaving important gaps in starter selection, flavour development and storage stability. Pumpkin seed is particularly attractive for composite formulations because its protein and lipid fractions can complement carbohydrate-rich cereal and millet bases.

The technological disadvantages of seeds include bitterness or seed-like notes, insoluble particles, emulsion instability and lipid oxidation. Fine grinding, filtration, homogenization and appropriate heat treatment are therefore important. For highly unsaturated seed matrices, oxidative stability should be monitored alongside microbial and sensory quality.

Table 1. Matrix-specific opportunities and limitations in fermented plant-based beverages

Matrix	Key components	Advantages	Principal limitations
Rice	Starch; low-moderate protein	Mild flavour; gluten-free potential; easy blending	Low protein density; sedimentation; starch instability
Oat	Starch, β -glucan, protein, lipids	Soluble fibre; viscosity; established beverage use	Hydrolysis control; cereal flavour; phase stability
Barley	Starch, β -glucan, protein, phenolics	Malting potential; fermentable carbohydrate	Gluten; sedimentation
Finger millet	Starch, fibre, minerals, phenolics	Nutrient diversity; gluten-free potential	Grittiness, dark colour, phytate, strong cereal notes
Pearl millet	Starch, protein, lipids, minerals	Good nutrient density; traditional fermentation history	Phytate; characteristic flavour; instability
Sorghum	Starch, protein, phenolics	Gluten-free; diverse phytochemicals	Astringency in tannin-rich types; sedimentation
Almond/nuts	Protein, unsaturated lipids	Creaminess; complementary	Low fermentable sugar; oxidation; allergens

		macronutrients	
Pumpkin/other seeds	Protein, unsaturated lipids, minerals	Nutritional enrichment; blend potential	Bitterness/off notes; oxidation; phase separation

3. Processing and Pretreatment Strategies

Processing before fermentation determines whether nutrients and carbohydrates are accessible to microorganisms and whether the beverage has acceptable physical stability. A typical sequence includes cleaning, soaking, optional germination, wet or dry milling, extraction with water, filtration or separation, thermal treatment, homogenization and cooling before inoculation. The exact sequence should be adapted to the substrate.

Soaking hydrates tissues, softens grains or seeds and can remove soluble compounds, but prolonged soaking at uncontrolled temperature can also support unwanted microbial growth. Germination activates endogenous amylases, proteases and phytases and can therefore increase fermentable sugars and reduce phytate. Its effect depends on germination time, temperature and grain physiology. Because germination is biologically active, hygienic control is essential.

Thermal treatment serves several purposes: microbial reduction, enzyme inactivation, starch gelatinization and protein denaturation. These changes can improve fermentation consistency but can also increase viscosity, promote aggregation or alter flavour. In cereal systems, enzymatic hydrolysis of gelatinized starch is often used to reduce viscosity and generate fermentable sugars. The degree of hydrolysis must be controlled because excessive conversion can produce an overly sweet or thin product.

Homogenization is particularly important for nut- and seed-based beverages, in which oil droplets and insoluble particles can separate rapidly. High-pressure or high-shear homogenization reduces particle size and improves dispersion, although the optimal treatment depends on protein functionality, fat content and stabilizer use. Heat and homogenization should therefore be considered together rather than as independent unit operations (Erem and Kilic-Akyilmaz 2024).

4. Starter Cultures and Fermentation Mechanisms

LAB are the dominant organisms used for controlled fermentation of plant-based dairy analogues. Commonly studied taxa include *Lactiplantibacillus plantarum*, *Lactocaseibacillus casei* and *L. rhamnosus*, *Limosilactobacillus fermentum*, *Lactococcus lactis*, *Streptococcus thermophilus*, *Leuconostoc* and *Pediococcus* species. The reclassification of the former genus *Lactobacillus* should be followed in current manuscripts (Zheng et al. 2020). *Bifidobacteria* and selected yeasts may also be used, alone or in mixed cultures, where their growth requirements can be met.

Starter selection should extend beyond rapid acidification. Important traits include the ability to utilize carbohydrates present in the target matrix, tolerate phenolic compounds, produce desirable volatile compounds, hydrolyse antinutritional factors, generate EPS, maintain viability during refrigerated storage and avoid undesirable metabolites. A strain that performs well in milk may perform poorly in an oat, millet or nut beverage because the available sugars, amino acids and buffering capacity differ markedly.

Acidification is a key process-control parameter. The rate of pH decrease depends on starter activity and substrate buffering capacity. Protein- and mineral-rich systems may resist pH change, while low-buffering beverages may acidify rapidly. Fermentation should therefore be controlled by a validated endpoint—commonly a target pH and titratable acidity—rather than fermentation time alone. Over-fermentation can cause excessive sourness, protein aggregation and post-acidification during storage; insufficient fermentation can compromise flavour and microbiological stability.

Mixed cultures can provide metabolic complementarity. One organism may hydrolyse complex carbohydrates or release amino acids that support another organism, while co-cultures may broaden aroma formation. However, mixed cultures can also create competition and unpredictable post-acidification. Their use therefore requires characterization

of population dynamics rather than assuming that more species will produce a better product (Horlacher et al. 2023; Erem and Kilic-Akyilmaz 2024).

4.1 Exopolysaccharides and texture development

EPS-producing LAB are particularly valuable in plant-based systems because these matrices lack the casein network responsible for dairy-yogurt structure. Microbial EPS can increase viscosity, improve water-holding capacity and reduce syneresis by interacting with proteins and polysaccharides. The magnitude of the effect depends on EPS molecular structure, concentration, culture conditions and matrix composition. EPS-producing strains may therefore support clean-label texture improvement, but their functionality must be demonstrated in the intended substrate (Montemurro et al. 2021).

5. Nutritional and Antinutritional Changes During Fermentation

5.1 Protein and amino-acid availability

Microbial proteases and peptidases can hydrolyse plant proteins into smaller peptides and free amino acids. This may improve protein solubility and in-vitro digestibility and can provide nitrogen sources for the fermenting microorganisms. Acidification itself can also modify protein conformation and aggregation. Nevertheless, increased in-vitro digestibility should not be presented as evidence of improved human protein nutrition without appropriate digestion, bioavailability or clinical data (Erem and Kilic-Akyilmaz 2024).

5.2 Carbohydrates and dietary fibre

Fermentation consumes simple sugars and can modify starch-derived carbohydrates generated during pretreatment. In oat and barley systems, β -glucan contributes to viscosity and nutritional value, but processing conditions can alter its molecular weight and functional properties. In cereal matrices, the combination of germination, enzymatic hydrolysis and fermentation can therefore change both fermentability and texture. The final carbohydrate profile should be measured rather than inferred from the raw ingredient.

5.3 Phytate and other antinutritional factors

Phytate is important in cereals, millets, nuts and seeds because it can bind minerals and reduce their bioaccessibility. Germination activates endogenous phytases, while microbial phytase activity and the acidic conditions of fermentation can promote further phytate degradation. Tannins, oxalates, protease inhibitors and other compounds may also be transformed, but the magnitude of change is strain- and matrix-specific. Claims of “antinutrient removal” should therefore be supported by direct measurement and should identify the compound and analytical method (Horlacher et al. 2023; Erem and Kilic-Akyilmaz 2024).

5.4 Vitamins and minerals

Fermentation may increase selected B-group vitamins when suitable biosynthetic strains are used, but it does not automatically correct the micronutrient limitations of plant beverages. Calcium, vitamin B12, vitamin D, iodine, zinc and other nutrients vary greatly among commercial plant beverages. Fortification may be required when a product is intended to replace dairy nutritionally. The nutrient content of the finished product should therefore be quantified and considered together with bioaccessibility (Ramsing et al. 2023; Kulaksız Gunaydı and Cakmak Kafadar 2026).

6. Bioactive Compounds and Functional Potential

Fermentation can transform phenolic compounds through β -glucosidase, esterases and other microbial enzymes. Bound phenolics may be released from plant structures, while other phenolics may be degraded or converted into metabolites with different chemical activity. Consequently, total phenolic content and antioxidant assay values can increase or decrease depending on the substrate, culture and method.

DPPH, ABTS, FRAP and related assays are useful for comparing chemical antioxidant capacity under defined laboratory conditions, but they do not establish a human health benefit. Similarly, the release of peptides with antioxidant or angiotensin-converting-enzyme inhibitory activity in vitro should be described as potential bioactivity

unless supported by digestion, absorption or clinical evidence. This distinction is essential for avoiding exaggerated functional claims.

The same principle applies to the term probiotic. According to the widely accepted consensus definition, probiotics are live microorganisms that confer a health benefit on the host when administered in adequate amounts (Hill et al. 2014). Viable LAB counts in a beverage demonstrate microbial survival, not probiotic efficacy. Strain identity, dose and evidence of benefit are required before a probiotic claim is scientifically justified.

7. Physicochemical, Structural and Rheological Quality

Physical instability is one of the most persistent challenges in plant-based fermented beverages. Sedimentation results from insoluble particles and density differences; creaming occurs in lipid-rich emulsions; syneresis reflects poor water retention; and acidification can cause protein precipitation. The final structure is governed by solids concentration, particle size, protein functionality, starch state, soluble fibre, fat droplets, pH and microbial EPS.

Rheological measurements are therefore more informative when interpreted together with composition and microstructure. Apparent viscosity alone cannot explain whether a beverage is stable, pourable or sensorially creamy. Flow behaviour, yield stress, viscoelastic properties, water-holding capacity and phase separation can provide a more complete description. For beverage-type products, excessive gel strength can be as undesirable as insufficient viscosity.

Hydrocolloids such as pectin, guar gum or starch-based stabilizers can improve suspension stability, but excessive use may create a gummy mouthfeel or conflict with clean-label positioning. EPS-producing cultures, optimized protein concentration and improved homogenization are alternative or complementary approaches. The best strategy is matrix-specific and should be validated during storage rather than immediately after production.

8. Flavour and Sensory Quality

Sensory acceptance is often the decisive barrier between technically successful fermentation and a commercially viable beverage. Plant matrices can contain beany, grassy, earthy, bitter, astringent, nutty or seed-like notes. Aldehydes such as hexanal contribute green or oxidized aromas in several plant ingredients. LAB can transform volatile precursors and generate organic acids, alcohols, ketones and other compounds, thereby changing the aroma profile (Erem and Kilic-Akyilmaz 2024).

Fermentation is not inherently flavour-improving. Excessive acidification can produce harsh sourness, while some cultures may generate undesirable aldehydes or other metabolites. Culture screening should therefore include sensory assessment and volatile profiling in addition to viable counts and pH. Sweetness, acidity, aroma intensity, mouth-coating, grittiness and aftertaste should be optimized as an integrated sensory system.

Trained descriptive panels and consumer acceptance tests answer different questions. Trained panels characterize sensory attributes, whereas consumer panels establish liking and preference. Studies should report serving temperature, sample coding and order, palate cleansing, panel size and relevant participant characteristics. Instrumental viscosity or volatile data should complement, not replace, sensory evaluation.

9. Microbial Safety and Storage Stability

Fermentation contributes to preservation through acidification and microbial competition, but it is not a substitute for hygienic manufacturing. Soaking and germination create moist environments in which undesirable microorganisms can grow. Raw grains, nuts and seeds can carry spores, moulds and environmental contaminants. Controlled processing therefore requires suitable raw-material specifications, potable water, hygienic equipment, validated heat treatment where appropriate, controlled inoculation, rapid cooling and refrigerated storage.

Storage stability is influenced by continuing microbial metabolism, post-acidification, oxidation, phase separation and changes in aroma and texture. Refrigeration slows these processes but does not stop them. Viable LAB may decline because of acid stress, oxygen exposure and nutrient depletion, whereas yeasts and moulds can become limiting

spoilage organisms. A storage study should therefore evaluate physicochemical, microbiological and sensory parameters at multiple time points using independent production batches.

For lipid-rich nut and seed beverages, oxidative stability deserves particular attention. Grinding and homogenization increase surface area and oxygen exposure, and unsaturated fatty acids are susceptible to oxidation. Packaging with appropriate oxygen and light barriers can help, but peroxide value, secondary oxidation products or validated sensory indicators should be considered when establishing product stability.

Shelf-life claims should be distinguished from storage-stability observations. Demonstrating acceptable pH or LAB survival for a defined period is insufficient by itself to establish shelf life. A defensible shelf-life claim requires product-specific validation incorporating microbiological safety, spoilage, sensory acceptability, chemical stability and packaging under the intended distribution conditions.

Table 2. Recommended analytical framework for fermented plant-based beverage studies

Domain	Measurements	Interpretive value
Fermentation kinetics	pH, titratable acidity, time, sugar utilization	Starter performance and endpoint control
Microbiology	Viable LAB; yeast/mould; hygiene indicators; strain identity where relevant	Culture survival and microbiological quality
Composition	Protein, fat, carbohydrate, fibre, ash, minerals, vitamins where relevant	Nutritional characterization
Antinutrients	Phytate; tannins/oxalate/protease inhibitors when matrix-relevant	Evidence for fermentation-associated reduction
Physical quality	Particle size, viscosity/rheology, water-holding, syneresis, sedimentation	Texture and colloidal stability
Oxidation	Peroxide/secondary oxidation markers in lipid-rich systems	Chemical storage stability
Sensory	Descriptive attributes and/or consumer acceptance	Real-world product acceptability
Storage	Repeated physicochemical, microbial and sensory testing	Storage-stability evidence
Functional evidence	Phenolics, antioxidant assays, digestion/bioaccessibility as justified	Potential functionality without overclaiming

10. Composite Cereal–Nut and Millet–Seed Formulations

Composite formulations can exploit nutritional and technological complementarity. A carbohydrate-rich cereal may support fermentation while a nut or seed contributes protein and unsaturated lipids. Conversely, the added lipid and protein can improve body and nutritional density but may slow acidification or destabilize the emulsion. Composite design should therefore be treated as a formulation problem rather than simply combining two “healthy” ingredients.

Examples with strong conceptual potential include rice–almond, finger millet–almond, pearl millet–pumpkin seed and sorghum–pumpkin seed systems. Such combinations can balance starch with protein and lipid, but they also introduce interactions among starch gelatinization, protein aggregation, oil droplets, fibre and phenolic compounds.

Optimization should include mixture ratio, total solids, heat treatment, homogenization, starter concentration, fermentation endpoint and storage stability.

Recent work on blended plant matrices supports the broader principle that co-formulation can produce structural and fermentation behaviour different from either ingredient alone. This reinforces the need to evaluate composite systems experimentally rather than predicting performance from the individual raw materials.

11. Comparison with Fermented Dairy Products

Plant-based fermented beverages and dairy products can occupy similar consumption occasions, but they should not be assumed to have the same nutritional profile. Cow's milk provides high-quality protein and characteristic levels of calcium and other micronutrients, whereas plant beverages show broad variation depending on raw material, dilution and fortification. Almond- and rice-based beverages can be relatively low in protein, while other plant matrices may provide more substantial protein but differ in amino-acid profile and digestibility (Chalupa-Krebzdak et al. 2018; Ramsing et al. 2023).

Plant matrices also provide components not characteristic of dairy, including dietary fibre, β -glucans, phenolic compounds and phytosterols. Their value should therefore not be judged solely by their ability to imitate milk. A scientifically sound product-development objective is to create nutritionally appropriate, safe and acceptable fermented plant foods while clearly communicating where fortification or dietary complementation is necessary.

Environmental comparisons also require careful interpretation. Reviews generally report lower greenhouse-gas impacts for many plant-based milks than cow's milk, but impacts vary by crop, water demand, location, processing, packaging and transport. Sustainability should therefore be evaluated using life-cycle approaches rather than assumed from the word "plant-based" alone (Ramsing et al. 2023).

12. Commercialization and Scale-Up Challenges

Laboratory formulations often perform differently at industrial scale. Raw-material composition varies by cultivar, harvest, storage and degree of milling; larger equipment changes heat-transfer and shear conditions; and fermentation tanks can develop gradients in temperature and solids distribution. Robust commercial processes therefore require raw-material specifications, standardized solids, controlled inoculation, validated mixing and temperature control, and defined fermentation endpoints.

Cold-chain requirements, packaging cost, clean-label expectations and consumer price sensitivity further influence commercialization. Fortification can improve nutritional adequacy but may affect flavour and mineral stability. Stabilizers improve texture but may be undesirable to consumers seeking short ingredient lists. Product design therefore involves trade-offs among nutrition, processing robustness, sensory quality, label simplicity and cost.

Regulatory terminology must also be considered. Probiotic claims require strain-specific evidence and compliance with jurisdiction-specific rules. Allergen declarations are essential for relevant nuts and seeds. Claims relating to protein, fibre, vitamins, minerals, antioxidant effects or health benefits should be supported by compositional or clinical evidence as required by the target market.

13. Research Gaps

Despite rapid growth of the field, direct comparisons across plant matrices remain limited. Many studies use different starter cultures, solids concentrations, fermentation temperatures and analytical methods, making it difficult to determine whether observed differences arise from the raw material or the process. Studies that ferment multiple matrices under standardized conditions would provide stronger comparative evidence.

Seed-based beverages are underrepresented relative to oat, soy and almond systems. Pumpkin, sunflower, sesame, hemp and flax deserve systematic evaluation for fermentation kinetics, protein functionality, lipid oxidation, sensory acceptance and storage stability. Likewise, millet research should move beyond proof-of-concept acidification toward detailed structure–flavour–nutrition relationships.

Another weakness is the frequent emphasis on measurements immediately after fermentation. Longitudinal storage studies are needed to understand post-acidification, microbial survival, oxidation, syneresis and sensory deterioration. Independent production batches should be treated as the experimental unit; repeated analytical measurements on one batch do not substitute for biological or process replication.

Functional claims also require stronger evidence. Chemical antioxidant assays and viable LAB counts are useful analytical endpoints but should not be interpreted as demonstrated human health benefits. Future studies should incorporate standardized in-vitro digestion, bioaccessibility, strain characterization and, where justified, human intervention studies.

Finally, sensory research needs broader consumer validation. Many experimental studies use small, trained panels, which are appropriate for descriptive work but cannot establish population-level preference. Consumer studies should consider familiarity with plant-based products, dietary pattern, age and cultural context.

14. Future Perspectives

The next phase of development is likely to focus on precision starter selection. Instead of choosing cultures solely because they are established dairy starters, strains can be screened for growth on specific plant carbohydrates, phytase or β -glucosidase activity, EPS production, aroma formation, phenolic tolerance and storage survival. Genome-informed screening can support this process, but phenotypic validation in the actual food matrix remains essential.

Metabolomics can identify organic acids, phenolic metabolites and volatile compounds generated during fermentation; proteomics can track protein hydrolysis; metagenomics can characterize complex microbial consortia; and microscopy and rheology can connect molecular changes with product structure. Integrating these approaches can clarify why a particular strain–matrix combination succeeds or fails.

Predictive modelling and artificial-intelligence-assisted optimization may help integrate formulation variables such as substrate ratio, solids, temperature, inoculum and fermentation time. These tools should be used to define experimentally testable process windows rather than replace experimental validation. Digital pH, temperature and fermentation monitoring can also improve reproducibility during scale-up.

Composite formulations are a particularly promising research direction. Cereal–nut and millet–seed systems can potentially combine fermentable carbohydrate, protein, unsaturated lipid, fibre and phytochemicals in one product. Future work should establish whether such combinations genuinely improve nutrient density and sensory quality after accounting for dilution, processing losses and storage changes.

Sustainability assessment should increasingly accompany product development. Water and energy use during soaking, heating, homogenization and refrigeration; ingredient transport; packaging; and by-product management can influence environmental performance. Valorization of cereal bran, press cake and seed residues may improve resource efficiency if safety and sensory quality are maintained.

15. Conclusion

Plant-based fermented beverages are heterogeneous food systems whose quality is determined by interactions among raw-material composition, pretreatment, microbial metabolism and storage conditions. Fermentation can improve acidification, flavour, texture, nutrient accessibility and selected antinutritional characteristics, but the magnitude and direction of these changes are matrix- and strain-specific. It should therefore be regarded as a controlled bioprocess rather than a universal solution to the limitations of plant-based foods.

Cereal and millet matrices offer accessible carbohydrate and diverse fibre and phytochemical profiles but often require improvements in protein density, particle control and colloidal stability. Nut- and seed-based beverages can contribute protein and unsaturated lipids but demand careful management of fermentable sugars, oxidation, allergenicity and emulsion stability. Composite formulations offer a rational route to nutritional and technological complementarity, provided that interactions among ingredients are experimentally optimized.

Future progress will depend on matrix-specific starter cultures, stronger process standardization, rigorous storage-stability studies, meaningful sensory evaluation, appropriate fortification and careful distinction between analytical

indicators and demonstrated health effects. With these principles, fermented plant beverages can develop as scientifically designed foods with their own nutritional and sensory identity rather than as simple imitations of dairy products.

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