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Plant-Based Milk Alternatives from Millets: Nutritional Quality, Processing Challenges and Future Opportunities

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Abstract

The increasing demand for sustainable and plant-based foods has stimulated the development of milk alternatives from cereals, legumes, nuts, and seeds. Millets represent promising raw materials for plant-based beverages because of their nutritional value, gluten-free nature, environmental resilience, and long history of human consumption. Finger millet, pearl millet, foxtail millet, little millet, proso millet, and barnyard millet contain carbohydrates, proteins, dietary fibre, minerals, phenolic compounds, and other bioactive constituents. However, converting millet grains into milk-like beverages presents technological challenges related to starch viscosity, sedimentation, phase separation, undesirable cereal flavours, nutrient bioavailability, and storage stability. Processing strategies such as soaking, germination, enzymatic hydrolysis, wet milling, homogenization, fermentation, and fortification can improve the nutritional, sensory, and physical properties of millet beverages.

Keywords: *Millet milk, plant-based beverages, milk alternatives, millets, nutritional quality, food processing, functional foods.*

1. Introduction

Plant-based milk alternatives have developed from niche products into an expanding segment of the food industry. Consumer interest in plant-based diets, sustainability, lactose-free products, and dietary diversification has encouraged the development of beverages derived from soy, oats, almonds, peas, rice, and other plant sources [1]. Millets provide an interesting alternative raw material for this sector. These small-seeded cereals are cultivated extensively in regions of Asia and Africa and are characterized by their adaptability to relatively dry and marginal environments. Their nutritional composition includes carbohydrates, proteins, dietary fibre, minerals, vitamins, phenolic compounds, and other phytochemicals [2]. Unlike highly refined cereal ingredients, whole millets can provide a broader range of nutrients and bioactive compounds. Millet-based beverages may therefore offer nutritional advantages while supporting the utilization of climate-resilient crops. However, the successful development of millet milk requires careful control of processing conditions to obtain a beverage with acceptable nutritional, sensory, and physical characteristics.

2. Nutritional Quality of Millet-Based Milk Alternatives

The nutritional composition of millet milk varies according to millet species, grain-to-water ratio, extraction efficiency, filtration, processing, and fortification. Carbohydrates generally represent the principal macronutrient fraction, while protein, fat, and dietary fibre vary among millet species. Finger millet is particularly valued for calcium, while pearl millet provides appreciable protein, iron, zinc, and other minerals. Small millets such as foxtail, little, and barnyard millet provide dietary fibre and a variety of phytochemicals [2,3]. Phenolic acids, flavonoids, tannins, and other phytochemicals contribute to the antioxidant potential of millets. Some of these compounds are present in bound forms and may become more accessible following appropriate processing.

Table 1. Nutritional and functional characteristics of selected millets

Millet	Nutritional characteristics	Potential beverage advantage
Finger millet	Calcium, fibre, polyphenols	Mineral-rich beverage
Pearl millet	Protein, iron, zinc, fibre	Nutrient-dense formulation
Foxtail millet	Protein, fibre, minerals	Balanced cereal beverage
Little millet	Fibre, minerals, phytochemicals	Functional beverage
Barnyard millet	Fibre, minerals, complex carbohydrates	Health-oriented formulation
Proso millet	Protein, carbohydrates, minerals	Alternative beverage base

It is important to recognize that unfortified millet beverages may not naturally provide nutritional equivalence to dairy milk. Calcium, vitamin B12, vitamin D, and protein quality may require targeted fortification, particularly when the beverage is intended to replace dairy nutritionally.

3. Processing of Millet Milk

3.1 Soaking and Pretreatment

Cleaning and soaking are common preliminary steps. Hydration softens the grain and facilitates wet milling. Soaking may also influence antinutritional factors and improve extraction efficiency. Germination represents an additional pretreatment that can activate endogenous enzymes and alter starch, protein, and phenolic constituents. It may improve digestibility and reduce selected antinutritional compounds [4].

3.2 Wet Milling and Extraction

Hydrated millet grains are typically wet-milled with water to produce a slurry. The slurry can be filtered or centrifuged to remove coarse insoluble particles. The ratio of grain to water strongly affects the beverage's nutritional concentration, viscosity, and mouthfeel. Excessive filtration can produce a smoother beverage but may remove fibre and other nutrients. Conversely, retaining a larger proportion of grain solids can improve nutritional density but increase sedimentation and viscosity.

3.3 Enzymatic Processing

Millets contain considerable starch, which can cause excessive viscosity in beverages. Enzymatic hydrolysis using appropriate amylases can partially break down starch and produce a beverage with improved flow properties [5]. Enzymatic treatment may also influence sweetness, solids content, and sensory characteristics. The treatment must therefore be carefully controlled to avoid excessive hydrolysis and undesirable flavour development.

3.4 Homogenization and Stabilization

Particle size is a major determinant of physical stability. Homogenization can reduce particle size and improve the uniform distribution of suspended components. Stabilizers may also be used to minimize sedimentation and phase separation. However, excessive use of stabilizers can produce undesirable thickness or alter the natural character of the beverage. Therefore, physical stability should be achieved through an appropriate combination of raw material selection, particle-size control, homogenization, and formulation.

Table 2. Major processing challenges and possible approaches

Processing challenge	Consequence	Possible approach
High starch content	Excessive viscosity	Enzymatic hydrolysis
Insoluble particles	Sedimentation	Fine milling and homogenization
Cereal flavour	Reduced consumer acceptance	Germination, fermentation, flavour optimization
Low micronutrient density	Limited nutritional equivalence	Fortification
Phase separation	Poor appearance and texture	Homogenization and suitable stabilizers
Antinutritional factors	Reduced nutrient bioavailability	Soaking, germination, fermentation
Short shelf stability	Microbial and physicochemical deterioration	Appropriate heat treatment and packaging

4. Fermentation and Functional Enhancement

Fermentation offers an additional strategy for improving millet-based beverages. Lactic acid bacteria can metabolize carbohydrates and produce organic acids, resulting in changes in pH, flavour, texture, and microbial stability. Fermentation can also modify phenolic compounds and selected antinutritional factors [6]. Fermented millet beverages may therefore combine the nutritional characteristics of millets with the functional properties associated with fermented foods. The development of yoghurt-like millet beverages is particularly promising for consumers seeking dairy-free alternatives. However, probiotic functionality should not be assumed simply because fermentation occurs. Specific microbial strains, viable counts, survival during storage, and demonstrated health effects are required before probiotic claims can be scientifically supported.

5. Health and Functional Potential

The potential health benefits of millet-based beverages are associated with their dietary fibre, minerals, proteins, phenolic compounds, and other phytochemicals. Dietary fibre can contribute to gastrointestinal health and may influence glucose and lipid metabolism. Millet phenolics exhibit antioxidant activity and may interact with biological pathways associated with oxidative stress [3].

Millets have also attracted interest in relation to glycaemic management. The presence of fibre and slowly digestible carbohydrate fractions may influence the rate of glucose release. Nevertheless, the effect of a beverage depends strongly on processing, particle size, starch hydrolysis, formulation, and serving size. The use of germinated or fermented millet may further modify bioactive compound availability. Future studies should examine the bioaccessibility and metabolism of these compounds following digestion rather than relying exclusively on chemical antioxidant assays.

6. Consumer Acceptance and Commercial Challenges

The sensory properties of millet milk remain an important barrier to commercialization. Cereal beverages can exhibit characteristic grainy, earthy, bitter, or astringent notes. These characteristics may be influenced by millet species, phenolic content, processing conditions, and storage. Sedimentation and phase separation can also negatively affect consumer perception. Unlike dairy milk, plant-based beverages contain complex mixtures of starch, fibre, proteins, lipids, and phytochemicals that may interact during storage. Economic considerations are equally important. Efficient extraction systems, ingredient standardization, fortification, packaging, and cold-chain requirements can influence the final product cost.

Commercial success will therefore require technologies that are scalable, economical, sustainable, and capable of producing consistent quality.

7. Future Opportunities

Future development of millet milk should focus on improving nutritional quality while minimizing intensive processing. Germination, fermentation, enzymatic hydrolysis, and controlled milling offer promising opportunities for tailoring beverage characteristics. Fortification with calcium, vitamin D, vitamin B12, and high-quality plant proteins could improve the nutritional suitability of millet beverages as dairy alternatives. The incorporation of fruits, nuts, seeds, spices, probiotics, and prebiotic fibres may also expand the range of functional products. Advanced processing technologies, including high-pressure processing, membrane filtration, microencapsulation, and improved homogenization, could further enhance stability and shelf life. Research should also evaluate life-cycle impacts to ensure that millet-based beverages provide genuine sustainability advantages.

8. Conclusion

Millet-based milk alternatives represent a promising intersection of plant-based nutrition, functional food development, and climate-resilient agriculture. Millets provide dietary fibre, proteins, minerals, phenolic compounds, and other bioactive constituents that can contribute to nutritionally diverse beverages. Nevertheless, challenges involving starch-induced viscosity, sedimentation, flavour, nutrient density, and storage stability must be addressed. Soaking, germination, enzymatic treatment, wet milling, homogenization, fermentation, and fortification can substantially improve product characteristics when appropriately optimized. Future research should prioritize nutritional equivalence, bioavailability, sensory acceptance, processing sustainability, and clinical validation. With continued technological development, millet milk could become a valuable component of the expanding plant-based beverage market.

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