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Millet Milk and Its Value-Added Products: Nutritional Composition, Processing Technologies and Functional Potential

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Abstract
Millet milk is an emerging plant-based beverage prepared from nutrient-rich millets and is gaining attention as an alternative to conventional dairy and other plant-based beverages. Millets such as finger millet, pearl millet, foxtail millet, little millet, and proso millet provide carbohydrates, dietary fibre, minerals, proteins, polyphenols, and other bioactive compounds. Their nutritional composition, gluten-free nature, climate resilience, and suitability for diverse food applications make them promising raw materials for functional beverage development. Millet milk can be produced through soaking, germination, wet milling, enzymatic treatment, filtration, homogenization, and thermal processing. Processing conditions strongly influence nutrient availability, viscosity, stability, flavour, and consumer acceptance. Millet milk can further be converted into value-added products including fermented beverages, yoghurt-like products, smoothies, bakery products, desserts, and fortified formulations. This review summarizes the nutritional characteristics, processing technologies, product development opportunities, and functional potential of millet milk, while highlighting major challenges and future research directions.

Keywords: *Millet milk, millets, plant-based beverages, functional foods, fermentation, nutritional composition, value-added products.*

1. Introduction
Millets are ancient cereal crops that have traditionally contributed to human diets in Asia and Africa. In recent years, their importance has increased because of growing interest in climate-resilient crops, dietary diversification, gluten-free foods, and plant-based nutrition. Unlike several major cereals, millets can often be cultivated under relatively low-input conditions and are adapted to environments characterized by limited water availability [1]. Millets contain carbohydrates, proteins, dietary fibre, minerals, vitamins, phenolic compounds, and other phytochemicals. Finger millet is particularly recognized for its calcium content, while pearl millet provides substantial amounts of protein, iron, zinc, and other minerals. Several small millets also contain phenolic compounds and dietary fibre that contribute to their functional potential [2].

The development of millet milk provides an opportunity to transform these cereals into a convenient liquid food. Similar to other plant-based beverages, millet milk may serve as a dairy alternative for consumers seeking plant-based products. It can also function as a carrier for additional nutrients, probiotics, fruit ingredients, or other functional components.

2. Nutritional Composition of Millet Milk
The nutritional profile of millet milk depends strongly on the millet species, grain-to-water ratio, processing conditions, filtration, and subsequent fortification. Carbohydrates generally constitute the major macronutrient fraction, while protein and lipid contents vary according to the raw material and formulation. Processing may alter fibre distribution and the availability of minerals and phytochemicals. Millets contain phenolic acids, flavonoids, tannins, and other compounds that contribute to antioxidant capacity. Processing such as germination and fermentation can modify these compounds and potentially improve their bio-accessibility [3].

Table 1. Selected millet types and their potential contribution to millet-based beverages

Millet	Important nutritional characteristics	Potential beverage advantage
Finger millet	Calcium, fibre, polyphenols	Mineral-rich functional beverage
Pearl millet	Protein, iron, zinc, fibre	Nutrient-dense beverage
Foxtail millet	Protein, fibre, minerals	Smoothies and breakfast beverages
Little millet	Fibre, minerals, phytochemicals	Functional beverage formulations
Proso millet	Protein, carbohydrates, minerals	Plant-based beverage base
Barnyard millet	Fibre, minerals, slowly digestible carbohydrates	Health-oriented formulations

Millet milk may therefore contribute to dietary fibre and micronutrient intake, although its nutritional value should not automatically be considered equivalent to that of cow's milk. Calcium, vitamin B12, vitamin D, and protein quality may require targeted fortification depending on the intended nutritional profile.

3. Processing Technologies

3.1 Grain Preparation and Soaking

The first stage generally involves cleaning and washing the grains, followed by soaking. Soaking softens the grain structure and facilitates subsequent wet milling. It can also reduce selected antinutritional factors and improve the extraction of soluble components.

3.2 Germination

Germination is increasingly investigated as a pretreatment for millet-based beverages. During germination, endogenous enzymes become active and modify starch, proteins, and other components. Germination can potentially improve digestibility, reduce certain antinutritional compounds, and alter the concentration or availability of phenolic constituents [4]. However, germination must be carefully controlled because excessive sprouting can affect flavour, microbial stability, and processing characteristics.

3.3 Wet Milling and Filtration

After hydration, millet grains can be wet-milled with water to produce a slurry. Filtration or centrifugation removes coarse particles and produces a smoother beverage. The degree of filtration affects the final fibre content, viscosity, mouthfeel, and sedimentation behaviour. The incorporation of finely processed whole-grain fractions may increase nutritional value but can also increase sedimentation and reduce physical stability. Consequently, particle-size control is important for beverage quality.

3.4 Enzymatic Treatment and Homogenization

Enzymes such as amylases can modify starch and reduce excessive viscosity. Enzymatic hydrolysis can also influence sweetness and beverage consistency. Homogenization reduces particle size and helps maintain a more uniform dispersion of components. Hydrocolloids or other stabilizing systems may be used to reduce sedimentation, although their concentration must be optimized to avoid undesirable texture.

3.5 Thermal Processing and Fermentation

Pasteurization or other suitable thermal treatments are necessary to improve microbiological safety and shelf stability. Excessive heating, however, may affect flavour and heat-sensitive compounds. Fermentation with selected lactic acid bacteria provides another promising approach. Fermentation may improve digestibility, modify flavour, reduce certain antinutritional compounds, and generate potentially beneficial metabolites [5]. Fermented millet beverages may therefore provide an attractive combination of cereal nutrition and probiotic functionality.

4. Value-Added Products

Millet milk can serve as a base for several value-added products. It may be formulated with fruits, cocoa, spices, nuts, or other plant ingredients to improve flavour and nutritional diversity. Fortification with calcium, vitamin D, vitamin B12, or plant proteins can also be considered depending on the target consumer group. Fermented millet milk can be developed into yoghurt-like products with suitable starter cultures. Such products may provide a dairy-free alternative with improved sensory characteristics and potential probiotic benefits. Millet milk can also be incorporated into bakery formulations, puddings, desserts, smoothies, breakfast cereals, and frozen products. Millet-based beverages may be particularly useful in products targeting consumers interested in gluten-free and plant-based diets.

Table 2. Potential value-added products from millet milk

Product	Main processing approach	Potential functional feature
Millet beverage	Milling, filtration, homogenization, pasteurization	Plant-based nutritional drink
Fermented millet drink	Lactic fermentation	Probiotic potential
Millet yoghurt alternative	Fermentation and stabilization	Dairy-free fermented product
Fruit-fortified millet drink	Blending and stabilization	Enhanced micronutrients and phytochemicals
Millet smoothie	Blending with fruits/seeds	Fibre and bioactive enrichment
Millet-based dessert	Cooking and formulation	Alternative cereal-based dessert
Bakery products	Incorporation into dough/batter	Nutritional diversification

5. Functional Potential

The functional properties of millet milk are largely related to the nutrients and phytochemicals derived from the whole grain. Dietary fibre may support gastrointestinal health and contribute to favourable glucose and lipid metabolism. Phenolic compounds possess antioxidant activity and may interact with pathways associated with oxidative stress and inflammation [6]. Millet-based foods have also attracted interest in relation to glycaemic management.

The presence of dietary fibre, resistant starch, slowly digestible carbohydrates, and phenolic compounds may contribute to a lower postprandial glycaemic response compared with some highly refined cereal products. However, the actual effect depends on millet type, processing conditions, formulation, and serving size. Fermentation may further modify the functional characteristics of millet beverages. Microbial metabolism can transform phenolic compounds and carbohydrates while producing organic acids and other metabolites. Consequently, fermented millet products represent an important area for future functional food research.

6. Challenges and Future Perspectives

Despite its potential, millet milk faces several technological and commercial challenges. Raw millet can produce undesirable cereal flavours, bitterness, or astringency, partly because of phenolic compounds and other constituents. Sedimentation and phase separation may also occur during storage. Another challenge is nutritional standardization. Unlike dairy milk, naturally produced millet milk may contain relatively low levels of certain micronutrients, particularly calcium and vitamin B12. Appropriate fortification may therefore be necessary for products intended as nutritional substitutes. Future research should focus on optimizing germination, enzymatic treatment, homogenization, fermentation, and stabilization techniques. Sensory studies involving diverse consumer groups are also required to identify acceptable flavour and texture profiles. The combination of millet milk with probiotics, prebiotics, fruit extracts, plant proteins, or bioactive compounds may create new generations of multifunctional beverages. Sustainable processing and utilization of millet residues could further enhance the environmental and economic value of the production system.

7. Conclusion

Millet milk represents a promising plant-based beverage with potential nutritional, technological, and functional applications. Its development provides an opportunity to utilize nutrient-rich and climate-resilient millets in convenient modern foods. Soaking, germination, wet milling, enzymatic treatment, homogenization, thermal processing, and fermentation can be combined to improve beverage quality and functionality. Millet milk can also serve as a foundation for fermented drinks, yoghurt alternatives, smoothies, desserts, and fortified products. Nevertheless, improvements in flavour, physical stability, nutritional standardization, shelf life, and consumer acceptance remain necessary. Future research integrating food processing, fermentation, nutrition, and sustainable production could establish millet milk as an important component of the expanding functional and plant-based food sector.

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