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# Plant based Milk (Millet Milk) as a Vegan Alternative to Bovine Milk: A Comprehensive Review

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## ABSTRACT

Plant-based milk refers to a plant-derived liquid that mimics the texture and appearance of bovine milk. Plant-based milk alternatives (PMAs) have emerged as viable substitutes for cow's milk, driven by rising consumer demand for allergen-free, nutritionally enriched and environmentally sustainable products. This review provides an in-depth examination of millet milk, focusing on its nutritional profile, processing technologies, functional properties, health implications and ecological sustainability. Millets, often referred to as "nutri-cereals," are inherently gluten-free and abundant in essential nutrients, antioxidants and bioactive compounds, making them particularly suitable for individuals with lactose intolerance, as well as vegan and health-conscious populations. Both traditional (soaking, germination, fermentation) and advanced methods (ultrasonication, enzyme-assisted extraction, high-pressure processing) are emphasized for their roles in improving the nutritional quality, sensory acceptability and storage stability of millet-based milk. Furthermore, millet milk demonstrates significant potential in functional food innovation, including probiotic beverages, dairy analogues and health-oriented snacks. Beyond notable health benefits such as anti-inflammatory, anti-diabetic and gut-regulatory effects, millet cultivation supports sustainable agricultural practices due to its minimal input requirements and low environmental impact. Nevertheless, concerns regarding product uniformity, consumer acceptance and regulatory policies remain. Ongoing advancements and growing awareness indicate that millet milk could substantially contribute to the future of plant-based dairy, while promoting food security and environmental resilience.

**Key words:** Bioactive compounds, Functional food, Millet milk, Plant-based milk, Processing innovations, Sustainable nutrition, Vegan dairy alternative.

Millets, or "Nutri cereals," are small-seeded cereal crops long used in Asia and Africa. They are valued for nutritional content, adaptability and health benefits. Traditionally cultivated millets like finger, pearl and foxtail are gluten-free, rich in fibre, amino acids, antioxidants and minerals such as calcium, iron and magnesium. These traits make them suitable for health-conscious consumers and sustainable for food systems. Their use in millet-based milk offers opportunities for diversifying the plant milk industry, supporting agriculture and improving food and nutritional security (Hrideek and Nampoothiri, 2017).

In recent years, a significant global transition has been observed in consumer preferences towards plant-derived milk alternatives. Health, environmental and ethical considerations are responsible for the rise of plant-based milk substitutes. This transition is additionally supported by the widespread occurrence of lactose intolerance and milk allergies, which impact a substantial segment of the worldwide population. Traditional dairy milk, being nutritionally rich, poses challenges for individuals with lactose intolerance, milk protein allergies and those following vegan or vegetarian lifestyles (Yaman, 2024). As consumers become more health-conscious and aware of the environmental impact of traditional dairy farming, the demand for plant-based milk alternatives (PMA) has surged. Plant-derived milk substitutes present a sustainable and ethically preferable alternative, diminishing dependence on animal farming and its correlated ecological impact. As a result, there has been a significant increase in the demand for non-dairy milk alternatives such as soy, almond, oat, coconut and rice milk, experiencing a rise in popularity across both developed and developing nations. Within this category of alternatives, millet milk is gaining recognition as a viable option owing to its nutritional advantages and potential for value addition. According to

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market analyses, the global plant-based milk industry is projected to continue its upward trend, driven by innovation, increasing awareness and a growing flexitarian population (Industry Report, 2023).

Millet milk is increasingly receiving considerable scholarly attention as a promising substitute for conventional dairy milk, attributed to its enhanced nutritional composition in comparison to other plant-derived milk alternatives. Millets are rich in nutrients but contain antinutritional factors that require pretreatment before milk extraction. Once processed, millet milk can be used to develop various value-added products (Pandey and Singh, 2024). The nutritional advantages associated with millet milk, in conjunction with its potential for additional value creation, position it as a promising option within the plant-based milk sector. While plant-based milk substitutes present numerous advantages, they concurrently encounter challenges, particularly concerning nutritional inadequacies when compared with animal-derived milk, especially regarding protein content and vital vitamins and minerals. Notwithstanding fortification initiatives, plant-based milks frequently do not achieve the same nutritional equivalence as dairy milk, which may influence consumer preferences and the broader market acceptance. Moreover, the sensory characteristics of plant-based milks, encompassing attributes such as flavour and texture, are pivotal for consumer acceptance and ongoing research endeavours aim to improve these qualities through advanced processing techniques. Furthermore, the sensory characteristics of plant-derived milks, including flavour and mouthfeel, are essential for consumer acceptance and continuous investigations seek to enhance these dimensions through sophisticated processing methodologies (Sethi *et al*., 2016).

## Nutritional composition of milelt milk

Millet milk, derived from various millet grains, is gaining attention as a nutritious alternative to dairy milk. This scholarly interest is driven by the distinctive nutritional composition and prospective health advantages, especially for individuals with dietary limitations such as lactose intolerance or gluten sensitivity. Millets possess a high concentration of proteins, vitamins, essential amino acids and dietary fibres, rendering them a crucial element of a nutritionally balanced diet.

Millets as nutritionally rich grains, offering 60%-70% carbohydrates, 3.5%-5.2% fats and 7.52%-12.1% proteins, along with essential amino acids such as cysteine, isoleucine and lysine which improves the protein quality of millets (Raju *et al*., 2024). Key minerals in millets are calcium, phosphorus and magnesium making them valuable for improving nutritional security. Bioactive compounds found in millets, such as polyphenols, flavonoids and soluble fibre, support disease prevention and contribute to millets' role as a sustainable solution to global food and health challenges. Millets have less fat content, ranging from 3.5% to 5.2%, as compared to whole dairy milk. This makes millet milk a lower-fat alternative, suitable for those seeking to reduce fat intake (Mazumder *et al*., 2024). Millets possess essential vitamins such as niacin, thiamine, riboflavin, folate and vitamin E (including both tocopherols and tocotrienols) and minerals like iron, zinc, magnesium, calcium and phosphorus. These nutrients are essential for various bodily functions and are present in higher concentrations in millets compared to dairy milk (Ahirwar and Singh, 2023).

Millets serve as a superior source of dietary fibre, a component that is absent in dairy milk. This dietary fibre significantly contributes to the facilitation of the digestive process and supports the maintenance of a healthy gastrointestinal microbiome (Tripathi *et al*., 2023). Millets contain a variety of amino acids, such as methionine, tryptophan and valine, which are not synthesized by the human organism and must consequently be acquired through dietary sources (Mazumder *et al*., 2024). Millets are rich in bioactive compounds, including polyphenolic compounds, antioxidants and flavonoids, which significantly enhance their health-promoting characteristics. Additionally, millets are acknowledged as a gluten-free alternative, making them a suitable option for individuals suffering from celiac disease or demonstrating gluten sensitivity; their incorporation into the diet can assist in remedying nutritional deficiencies while simultaneously promoting overall health (Mishra *et al*., 2022).

## Properties of plant based milk alternatives

Millet milk, as a plant-based alternative, offers distinctive functional and sensory attributes when compared to other plant-based milks. The texture, flavour profile and pigmentation are influenced by the intrinsic properties of millet as well as the methodologies employed in its processing. Although millet milk has potential health benefits and nutritional advantages, its sensory qualities and consumer acceptance are areas of active research and development.

### Sensory properties of millet milk

#### Texture

Millet milk's texture is influenced by its starch and protein content. The use of sprouted millets can improve solubility and extractability, enhancing the texture of the milk. The pseudo-plastic nature of millet-based beverages indicates a smooth texture, which is desirable in milk alternatives (Agrahar-Murugkar *et al*., 2020). The incorporation of sprouted millets not only enhances the texture but also contributes to the overall nutritional profile of millet milk, making it a competitive dairy alternative (Pandey and Singh, 2024).

#### Taste

Millet milk has a distinct plant flavour, which can be a barrier to consumer acceptance. However, flavouring with natural ingredients like jaggery or cardamom can improve its taste and overall acceptability (Geetha and Preethi, 2020). To enhance consumer acceptance, it is crucial to explore innovative flavouring techniques and potential ingredient pairings that can mask the inherent plant flavour of millet milk.

### Colour

The colour of millet milk can fluctuate based on the specific variety of millet employed and the methodologies utilized in its processing. For example, the incorporation of buttermilk yields a lighter colour, whereas the addition of jaggery confers a caramelized hue (Agrahar-Murugkar *et al*., 2020). To further enhance the appeal of millet milk, integrating flavourings such as fruit purees or spices could significantly improve consumer acceptance and marketability (Cichoñska and Ziarno, 2020).

### Flavour/Aroma

The aroma and flavor of plant-based milk alternatives are critical factors influencing consumer acceptance and market success. These alternatives, derived from various plant sources such as nuts, seeds and grains, often face challenges in replicating the sensory attributes of traditional dairy milk. The development of desirable flavors and aromas in plant-based milks involves addressing issues related to off-flavors and enhancing the overall sensory profile through innovative processing techniques and ingredient fortification.

The incorporation of natural stabilising agents, including pectin and agar-agar, has the potential to mitigate delamination and enhance the stability of millet milk (Cichoñska and Ziarno, 2020). Furthermore, exploring consumer preferences through sensory evaluation can guide the development of millet milk products that meet the market demands and enhance overall acceptability.

Incorporating functional ingredients such as soluble fibre can significantly enhance the nutritional composition and sensory characteristics of millet milk, thus rendering it more appealing to health-conscious consumers (Shanmugam *et al*., 2017). Moreover, understanding consumer preferences for Flavors and textures is essential for developing successful millet milk products that can compete in the growing plant-based beverage market (Cichoñska and Ziarno, 2020).

## Processing methods of millet milk

Millet milk, an alternative plant-based option to traditional dairy milk, has attracted considerable interest due to its nutrient-dense characteristics and its capacity to cater to diverse dietary preferences or needs, such as veganism and lactose intolerance.

## Traditional processing methods

### Soaking and germination

Soaking and germination are widely used to enhance the nutritional profile of millet milk. These biochemical processes improve the nutritional bioavailability through the degradation of antinutritional components, including phytic acid and tannins (Fig 1). Empirical research has demonstrated that germination significantly elevates the phenolic concentration and antioxidant efficacy of millet milk by 92% and 33%, respectively (Saxena *et al*., 2023). Moreover, the germination process enhances the palatability of millet milk by reducing the viscosity (Geetha and Preethi, 2020).

### Fermentation

Fermentation constitutes a traditional technique employed in the processing of millet milk. This technique encompasses the utilization of microbial cultures to break down complex compounds, thereby improving the

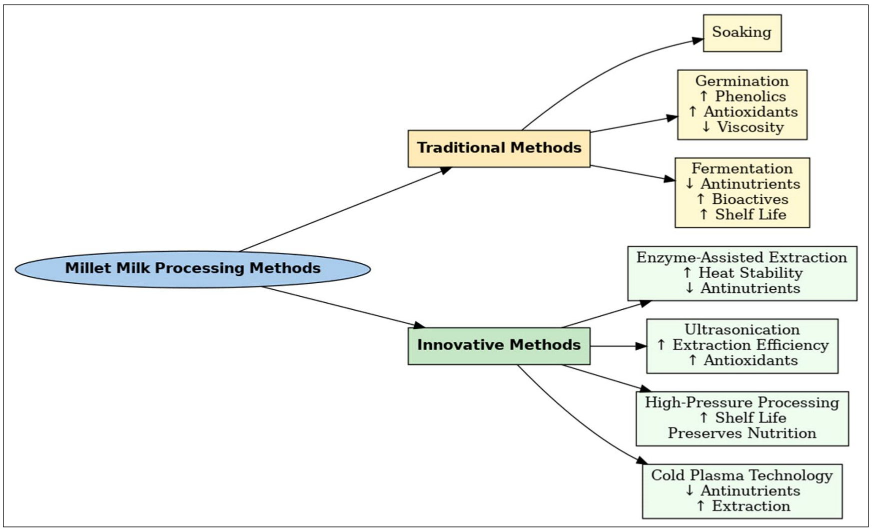


**Fig 1:** Traditional and modern methods of millet milk processing and their effects on nutritional and functional properties.

digestibility and prolonging the shelf life of the milk (Table 1). Empirical studies have demonstrated that fermented millet milk exhibits higher protein content and reduced levels of antinutrients in comparison to raw millet milk. Furthermore, the process of fermentation not only augments the nutritional profile but also elevates the sensory characteristics, rendering millet milk a more desirable choice for consumers. Incorporating fermentation techniques, particularly with beneficial microorganisms, can enhance the antioxidant capacity and nutritional value of millet milk, aligning with consumer preferences for health-oriented products (Samtiya *et al.*, 2024).

### Extraction techniques

Millet milk is conventionally obtained via mechanical methodologies, encompassing grinding and filtration processes. The ratio of millet to water and the extraction time significantly influences the yield and quality of the milk. The meticulous optimization of these variables is imperative to attain a stable and nutrient-rich product (Sudha *et al.*, 2016). The optimization of extraction methodologies, in conjunction with fermentation processes, has the potential to produce a millet milk that is not only more nutritious but also more palatable, thus addressing the growing demand for plant-based alternatives (Fig 1). Furthermore, the synergistic effect of fermentation and optimized extraction methodologies can significantly enhance the overall quality of millet milk, rendering it a feasible and nutritious substitute for conventional dairy products.

## Innovative processing methods

### Enzyme-assisted extraction

Enzyme-assisted extraction has been recognized as an innovative methodology for improving both the yield and quality of millet milk. Enzymes such as pure α-amylase or diastase are used to hydrolyse starches, thereby reducing the viscosity of the milk and enhancing its stability (Fig 1). Empirical data indicate that this methodology significantly enhances the thermal stability and sedimentation rate of millet milk, thereby rendering it suitable for large-scale industrial production (Shunmugapriya *et al.*, 2020). This progress in enzyme-assisted extraction not only increases the yield but also elevates the overall sensory and nutritional profile of millet milk, making it a competitive alternative within the plant-based market.

### Ultrasonication

Ultrasonication, recognized as a non-thermal processing methodology, has demonstrated significant potential to augment the extraction efficacy of millet milk (Fig 1). This methodology utilizes high-frequency acoustic waves to compromise the structural integrity of the grain, thus promoting the liberation of an increased quantity of nutrients into the resultant milk. Ultrasonication has been shown to enhance the antioxidant activity and reduce antinutrient levels in millet milk (Choudhary *et al.*, 2023). Moreover, the integration of enzyme-assisted extraction with ultrasonication has the potential to produce synergistic effects, further refining both the sensory and nutritional attributes of millet milk, thus broadening its appeal to diverse consumers.

### High-pressure processing (HPP)

High-pressure processing represents a novel methodology employed to enhance the quality of millet milk (Table 1). This technique effectively inactivates microorganisms and enzymes without causing significant alterations to the nutritional composition of the milk (Fig 1). This method is particularly effective in extending the shelf life of millet milk while preserving its functional properties (Kaur and Kaur, 2024). Furthermore, the combination of high-pressure processing with additional innovative methodologies may further elevate the overall quality and marketability of millet milk, catering to consumer demands for safe and nutritious plant-based beverages. The investigation of advanced processing techniques, including enzyme-assisted extraction and high-pressure processing, is essential for maximizing the quality and attractiveness of millet milk within the competitive landscape of plant-based beverage market.

## Effects processing on nutritional properties

### Reduction of antinutritional factors

The application of processing techniques, including germination, fermentation and enzymatic treatment, demonstrates efficacy in the mitigation of antinutritional components such as phytic acid, tannins and trypsin

**Table 1:** Comparison of processing methods.

| Processing method | Key effects | Citation |
|---|---|---|
| Germination | Increases phenolic content and antioxidant activity; reduces viscosity | (Saxena *et al.*, 2023; Geetha and Preethi, 2020) |
| Fermentation | Reduces antinutritional factors; enhances bioactive compounds and shelf life | (Samtiya *et al.*, 2024; Bheemaiah Balyatanda *et al.*, 2024) |
| Enzyme-sssisted extraction | Improves heat stability and reduces antinutrient levels | (Shunmugapriya *et al.*, 2020) |
| Ultrasonication | Enhances extraction efficiency and antioxidant activity | (Choudhary *et al.*, 2025) |
| High-pressure processing | Extends shelf life and preserves nutritional properties | (Kaur and Kaur, 2024) |
| Cold plasma technology | Reduces antinutrient levels and improves extraction efficiency | (Ramakrishnan *et al.*, 2023) |

inhibitors. Empirical studies have demonstrated that fermentation can effectively decrease levels of phytic acid by around 84% and cut down tannin content by 57% in pearl millet (Choudhary *et al*., 2023). Similarly, enzymatic treatment reduces phytic acid and tannin levels in millet milk, enhancing its nutritional quality (Shunmugapriya *et al*., 2020).

### Enhancement of bioactive compounds

Processing methodologies, including germination and fermentation, enhance the synthesis of bioactive constituents, encompassing phenolics and flavonoids. Empirical evidence indicates that germinated millet milk exhibits a greater concentration of phenolic compounds and superior antioxidant properties relative to its raw millet milk equivalent. These bioactive molecules are essential in providing the health-promoting attributes associated with millet milk. The antioxidant efficacy is further enhanced through processing techniques such as germination and sonication, which elevate phenolic content by 92% and antioxidant activity by 33.42% (Saxena *et al*., 2023).

### Improvement in protein and starch digestibility

Enzymatic treatment and fermentation improve the digestibility of proteins and starches in millet milk. Enzymatic agents, including α-amylase, function as catalysts in the hydrolysis of starch into monosaccharide units, while proteolytic enzymes promote the digestion of proteins. These processes make millet milk more suitable for consumers with dietary restrictions. The application of enzyme treatment can significantly increase the protein digestibility of millet milk, thereby rendering it a more attractive alternative for consumers pursuing plant-based nutritional options. Protein and starch digestibility is crucial for ensuring that millet milk meets the nutritional needs of consumers, particularly those with specific dietary requirements (Bheemaiah *et al*., 2024).

## Effects of processing on functional properties

### Viscosity and stability

The rheological properties and stability of millet milk are significantly affected by various processing techniques, including germination, enzymatic modification and ultrasonication. Germination leads to a decrease in the viscosity of millet milk, thereby enhancing its organoleptic appeal. The application of enzymatic treatment enhances the thermal stability of milk, thereby inhibiting sedimentation throughout the storage period (Shunmugapriya *et al*., 2020). Viscosity is a critical factor that influences consumer perception and acceptance of plant-based beverages. Therefore, optimizing these properties through innovative processing methods is essential to enhance the overall marketability of millet milk.

### Shelf life

Innovative processing methods such as HPP and cold plasma technology extend the shelf life of millet milk by inactivating microbes and enzymes. These methodologies preserve the nutritional and functional attributes of the milk whilst guaranteeing its safety for human consumption (Kaur and Kaur, 2024). The shelf life of millet milk can be markedly improved through the application of these sophisticated processing strategies, thereby ensuring its status as a viable alternative to conventional dairy products while fulfilling consumer expectations for quality and safety (Ramakrishnan *et al*., 2023).

### Sensory characteristics

The processing techniques of fermentation and flavour enhancement significantly augment the sensory attributes of millet milk. The acceptability rating of fermented millet milk is notably elevated owing to its superior flavour profile and texture consistency (Sudha *et al*., 2016). Incorporation of flavourings agents, such as sucrose and cardamom, further enhances the palatability of the milk (Geetha and Preethi, 2020). Sensory attributes are integral to consumer acceptance of millet milk, thereby necessitating a concentrated focus on these characteristics throughout the product development process. To further improve consumer acceptance, it is essential to continue exploring innovative flavouring techniques and combinations that can effectively mask the inherent plant flavours of millet milk.

### Health benefits of millet milk consumption

Millet-based functional foods offer several health benefits, including.

### Glycaemic control

Millets are known for their low glycaemic index, making millet-based beverages and snacks suitable for diabetic patients (Fig 2). A clinical study on pearl millet beverages found that they maintain glycaemic and insulinemic control in healthy adults (Magalhães *et al*., 2024). Effective glycaemic regulation is essential in the management of diabetes and the prevention of associated complications, thereby rendering millet-based functional foods a highly advantageous dietary alternative for individuals striving to achieve stable blood glucose levels (Table 2).

### Antioxidant activity

Millet-based products are rich in antioxidants, which help protect against oxidative stress and chronic diseases (Fig 2). For instance, finger millet-based beverages have been shown to exhibit high DPPH radical scavenging activity (Mishra *et al*., 2022). The activity of antioxidants is essential for mitigating the likelihood of diseases associated with oxidative stress, thereby rendering millet-derived products a significant enhancement to health-oriented dietary regimens (Table 2).

### Prebiotic properties

Some millet-based beverages contain prebiotic oligosaccharides, which support gut health by promoting the growth of beneficial gut microbiota (Arya and Shakya, 2021). Prebiotic oligosaccharides serve an integral function in promoting digestive health and overall wellness, positioning millet-based functional foods as an outstanding option for individuals seeking to improve gut microbiota diversity and functionality (Fig 2).

### Nutritive

Millet-based foods are abundant in dietary fibres, proteins and minerals, including calcium, iron and zinc (Table 2). These products are particularly beneficial for lactose-intolerant and vegan consumers seeking nutrient-dense alternatives to dairy products (Kubade *et al*., 2023). The potential of millet-based functional foods to support health, particularly in managing chronic diseases and improving overall nutrition, positions them as valuable dietary options in contemporary health-conscious markets.

### Personalized nutrition

Beyond general nutritional benefits, millet milk demonstrates strong potential in personalized nutrition, offering tailored dietary options for specific consumer needs.

### Gluten-free diets

Millet milk is naturally free from gluten, making it a safe and nutritious alternative for individuals with celiac disease or gluten sensitivity. Its nutrient-rich profile positions it as a viable substitute for conventional plant-based milks (Kubade *et al*., 2023).

### Low-glycaemic index diets

Due to its low GI, millet milk supports better blood glucose regulation and is particularly suitable for diabetic individuals or those aiming to stabilize sugar levels. Its high fibre and resistant starch content slow down carbohydrate digestion and absorption (Ali *et al*., 2023).

### Targeted nutritional profiles

Millet milk can be fortified or processed to meet specialized nutritional needs. Protein enrichment through enzymatic hydrolysis makes it suitable for high-protein diets, while fermentation and probiotic fortification enhance its antioxidant and phenolic profile, turning it into a functional food tailored for health-conscious consumers (Yadav *et al*., 2024).

## Application of plant based/millet milk

### Beverages

Millet-derived beverages are gaining substantial popularity owing to their nutritional advantages and prospects as alternatives to dairy products. These beverages can be developed in diverse formulations, encompassing flavoured, probiotic and prebiotic variants.

### Probiotic millet beverages

Probiotic beverages made from millet have been developed using strains such as Lactobacillus rhamnoses and Saccharomyces cerevisiae. These beverages exhibit high antioxidant activity, low fat content and improved nutritional profiles. For instance, barnyard millet-based probiotic beverages have shown increased protein content and reduced glycaemic index (Manasa *et al*., 2022). Probiotic beverages not only augment the nutritional value of millet-based drinks but also foster gastrointestinal health by integrating beneficial microorganisms, thereby aligning

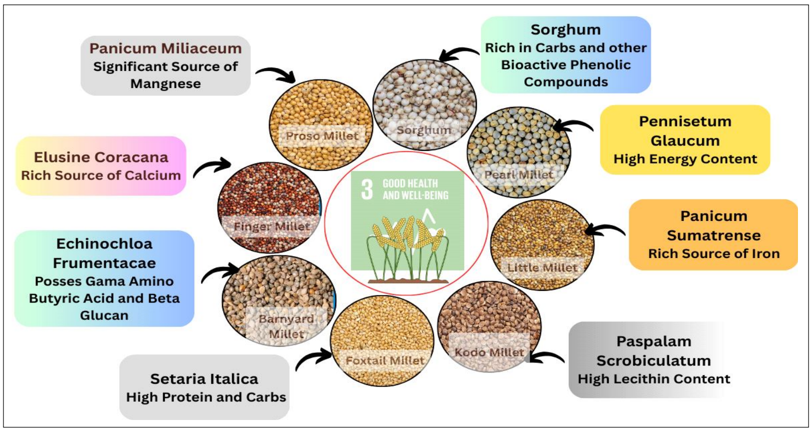


**Fig 2:** Health benefits of millets.

**Table 2:** Comparison of millet milk with other plant-based milks.

| Milk type | Nutritional profile | Processing methods | Citation |
|---|---|---|---|
| Millet milk | High in protein, fibre and antioxidants | Soaking, germination, enzymatic extraction | (Shunmugapriya *et al*., 2020). |
| Almond milk | Low in calories, rich in vitamins | Blending and filtration | (Saxena *et al*., 2023) |
| Soy milk | High in protein, isoflavones | Extrusion and enzymatic treatment | (Pandey and Singh, 2024) |
| Oat milk | High in fibre, low in fat | Enzymatic extraction and pasteurization | (Pandey and Singh, 2024) |

with the growing consumer interest in functional foods and probiotics (Challa *et al*., 2025). This interaction between millet and probiotics offers a promising avenue for the advancement of health-focused beverages that align with modern dietary trends.

**Fermented millet drinks**

Fermentation markedly enhances the functional properties of millet-derived beverages. An investigation into barnyard millet beverages supplemented with Chlorella sp. revealed an increased protein concentration and elevated antioxidant efficacy. The integration of probiotics such as *Lactobacillus rhamnosus* further augmented the functional properties of the product (Joseph *et al*., 2024). Furthermore, the application of fermentation methodologies can substantially improve the nutritional composition and sensory qualities of millet-based beverages, rendering them more attractive to health-oriented consumers (Samtiya *et al*., 2024).

**Flavoured and enriched beverages**

Millet-derived beverages can be flavoured with natural constituents such as fruit purees or herbs to elevate their sensory appeal. For example, a kodo millet-based beverage flavoured with cardamom and sweetened with sugar has been developed, offering a nutritious and flavourful alternative to traditional dairy beverages (Geetha and Preethi, 2020). The development of millet-derived beverages, particularly via fermentation processes, is gaining momentum owing to their superior nutritional profiles and prospective health advantages, which resonate with health-conscious consumers.

**Prebiotic and multigrain beverages**

A high-fibre, low-glycaemic-index beverage made from a combination of barnyard, foxtail and kodo millets has been formulated. This beverage contains prebiotic oligosaccharides and exhibits strong antioxidant activity, making it a functional food product (Arya and Shakya, 2021). Prebiotic oligosaccharides in these beverages not only support gut health but also enhance the overall nutritional value, aligning with consumer trends towards functional foods that promote well-being.

**Snacks**

Millet-based snacks are another category of functional foods that leverage the nutritional benefits of millets. These snacks are frequently designed to be gluten-free and abundant in dietary fibre and antioxidants.

**Extruded millet snacks**

Extrusion cooking is a common method for producing millet-based snacks. Pearl millet flour, when extruded, can be used to create instant beverage powders or ready-to-eat snacks. These products are rich source of dietary fibres and antioxidants (Obilana *et al*., 2018). As consumer preferences shift towards healthier alternatives, millet snacks present an innovative solution that aligns with modern dietary trends and nutritional needs.

**Malted millet snacks**

Malting enhances the digestibility and nutritional quality of millets. Malted finger millet powder has been used to develop snacks with improved sensory attributes and functional properties (Ahmed, 2024). The integration of malted millets into snack formulations can markedly enhance their nutritional composition and sensory characteristics, thereby rendering them more attractive to consumers who are in pursuit of healthier snack alternatives.

**Composite millet snacks**

Blending millets with other grains or legumes can enhance the nutritional profile of snacks. For instance, a composite snack made from finger millet and oats offers a balanced mix of dietary fibres, proteins and antioxidants (Kumar *et al*., 2020). Such composite snacks are capable of addressing varied consumer preferences while optimizing the nutritional advantages provided by millets, thereby contributing to a more healthful snacking alternative.

**Dairy alternative**

Millet milk functions as an exceptionally suitable base for plant-derived alternatives, including products such as yoghurt and cheese. These products are especially appealing to individuals diagnosed with lactose intolerance, as well as those who follow a vegan dietary lifestyle.

Finger millet flour has been incorporated into set yoghurt to enhance its nutritional and functional properties, with a study showing that 7% finger millet flour incorporation improved the yoghurt's dietary fibre, phenolic content and antioxidant activity without affecting its sensory properties (Sachini *et al*., 2024). Finger millet yoghurt thus represents a viable substitute for conventional dairy yoghurts, providing superior nutritional advantages while addressing the needs of health-oriented consumers. Similarly, probiotic yoghurt made from barnyard millet using *Lactobacillus acidophilus* has been developed, exhibiting high microbial counts and improved nutritional profiles, making it a healthy dairy alternative (Amrutha and Sharon, 2023). The integration of millet flour into yoghurt formulations not only enhances nutritional properties but also aligns with consumer preferences for functional foods that promote health and wellness (Sachini *et al*., 2024). Millet-derived yoghurt may further be augmented with organic constituents such as sapodilla or fortified with botanical extracts to improve its sensory attributes and functional characteristics, as demonstrated by sapodilla-flavoured yoghurt enriched with kodo millet milk, which offers a nutritious and flavourful product (Mariam and Kumari, 2024). In addition, a novel yoghurt derived from millet has been developed incorporating superoxide dismutase (SOD), an effective antioxidant enzyme, which exhibits higher antioxidant activity compared to commercial dairy yoghurt products (Fan *et al*., 2022). In commercially available soy and almond "milks" the levels of oxalate was found that 100 mL of soymilk could contribute as much as ~50% of the daily recommended intake (RDI) of oxalate (~50 mg/day) and a 240 mL (1 cup) intake might provide up to ~120% of RDI under some formulations (AbuKhader and Al Lawatia, 2022) (Nande *et al*., 2008). Plant-based milks can replace bovine milk in many contexts, but attention must be given to nutrient equivalence (Chatterjee *et al*., 2025) (Shruthi *et al*., 2025).

While less common, millet milk can also be used to produce cheese alternatives. The process involves coagulation and fermentation, similar to traditional dairy cheese production. However, research in this area is still emerging and commercial products are limited. Cheese production from millet milk holds potential for creating plant-based alternatives that cater to lactose-intolerant individuals and those seeking healthier options. Additional research is imperative to refine the formulation and processing techniques for these cheese alternatives.

**Challenges and opportunities in millet milk**

Millet milk, a plant-based alternative to dairy, has gained significant attention due to its nutritional profile and potential to address dietary preferences and sustainability concerns. However, its production, scaling and market penetration face several challenges. This section explores the challenges and opportunities in millet milk, focusing on production, consistency, scaling, regulatory issues, labelling, market challenges, innovation, fortification, niche markets and local production.

**Production and consistency**

The production of millet milk involves the extraction of liquid from millet grains, which requires specific pretreatment processes aimed at mitigating antinutritional factors such as phytates and tannins. These pretreatments, including soaking, germination and sonication, are essential to enhance the nutritional quality and sensory acceptability of the final product (Pandey and Singh, 2024). Germination significantly increased the phenolic activity and antioxidant activity of millet milk, with increases of 92±1.99% and 33.42±0.55%, respectively, indicating enhanced nutritional properties after this process. The combination of sonication and germination techniques effectively reduced the average antinutrient concentration in millet milk to 23.31± 0.36%, suggesting that this combined approach improves the functional properties of millet milk and could be a promising method for producing nutritious plant-based (Saxena *et al*., 2023).

Ensuring consistency in millet milk production is challenging due to variations in raw material quality, processing methods and environmental factors. For instance, the protein and fat content of millet milk can differ significantly based on the millet type and extraction techniques (Hemasankari *et al*., 2023). Additionally, the natural astringency and bitterness of some millets can affect the flavour profile, making it difficult to achieve a consistent taste. In order to effectively tackle these challenges, it is imperative to standardize processing methodologies and implement quality control protocols that ensure consistency in the resultant product. Standardizing production processes and quality control measures will be crucial for achieving consistency in millet milk, thereby enhancing its marketability and consumer acceptance.

**Scaling and regulatory issues**

Scaling up millet milk production requires advanced processing technologies to maintain nutritional integrity and extend shelf life. Traditional methods, such as germination and fermentation, are effective but labour-intensive and unsuitable for large-scale production (Latha and Rana, 2024). Novel processing techniques, such as ultrasound and high-pressure processing, have shown promise in enhancing the functional properties of millet milk while maintaining its nutritional benefits (Srenuja *et al*., 2023). To effectively address these scaling challenges, it is paramount to allocate resources towards research and development to enhance processing methodologies and augment the economic feasibility of millet milk production.

The regulatory framework for plant-based milk alternatives, including millet milk, varies across regions. In some countries, labelling restrictions and nutritional standards can create barriers to market entry. For example, the use of the term "milk" for plant-based products is regulated in certain jurisdictions, requiring clear labelling to distinguish them from dairy products (Kalpana *et al*., 2024). Compliance with food safety standards, such as HACCP and ISO certifications, is also critical for scaling production and ensuring consumer trust. Efforts aimed at the standardization of processing methodologies and the enhancement of quality control mechanisms will be paramount in overcoming the obstacles encountered in millet milk production, thereby facilitating greater consumer acceptance and an amplified market presence (Latha and Rana, 2024).

**Labelling requirements**

Labelling is a critical aspect of millet milk production, as it must comply with regional regulations and consumer expectations. Labels must clearly indicate the product's plant-based origin, nutritional content and allergen information. Moreover, emphasizing the health advantages, including the absence of gluten and a high dietary fibre content, has the potential to attract consumers who are health-conscious (Chaudhary and Verma, 2024). In order to effectively comply with labelling mandates, it is imperative to ensure that millet milk products are accurately represented and marketed to underscore their nutritional merits, thus nurturing consumer trust and acceptance.

**Market challenges**

The market for millet milk faces competition from other plant-based milk alternatives, such as almond, soy and oat milk. Consumer perception and acceptance about millet milk play a significant role in market penetration. Factors such as taste, texture and price influence purchasing decisions. Educating consumers about the nutritional and environmental benefits of millet milk can help differentiate it from competitors (Pampackal *et al*., 2024) (Vaswani *et al*., 2024). To overcome these challenges, targeted marketing strategies and consumer education initiatives are essential for increasing awareness about the benefits of millet milk and enhancing its market presence.

**Future prospects and research directions for millet milk**

Millet milk, an alternative to conventional dairy milk derived from plants, has gained considerable interest owing to its nutritional composition, ecological sustainability and capacity to meet diverse dietary needs, including gluten-free and low glycaemic index (GI) diets.

The global demand for plant-derived milk alternatives is on the rise, caused by various considerations including lactose malabsorption, ecological sustainability and moral considerations. Millet milk, characterized by its enhanced nutritional composition and ecological viability, is strategically positioned to capitalize on this trend (Pandey and Singh, 2024). The increasing consumer interest towards plant-based dietary regimens, in conjunction with the distinct nutritional advantages conferred by millet milk, underscores its capacity to emerge as a conventional substitute for traditional dairy products.

Consumer awareness of the health benefits of millets is increasing, driven by systematic research and strategic marketing initiatives. This increased awareness is expected to drive the demand for millet-based products, including millet milk (Dekka *et al*., 2023). The future of millet milk appears promising as consumer preferences shift towards healthier, plant-based alternatives, emphasizing its nutritional benefits and potential for addressing dietary needs.

## CONCLUSION

Millet milk represents a scientifically promising, plant-derived alternative to conventional dairy, enriched with bioactive compounds such as phenolics, antioxidants and dietary fibres. Its formulation benefits from both traditional methods like germination, fermentation and enzymatic hydrolysis and emerging technologies, including ultrasonication, high-pressure processing (HPP) and cold plasma treatment. These approaches not only enhance the bioavailability of essential nutrients but also improve microbiological safety, shelf life and sensory characteristics, making millet milk a functionally superior beverage. Beyond its nutritional advantages, millet cultivation supports climate-resilient agriculture due to its low water requirements, drought tolerance and adaptability to marginal soils offering a sustainable route toward global food and nutrition security. As consumer awareness grows around health, sustainability and ethical consumption, millet milk meets the demand for gluten-free, lactose-free and environmentally conscious alternatives. However, realizing its full potential requires addressing technological challenges related to formulation stability, regulatory compliance and sensory optimization. With continued scientific research, thoughtful innovation and strategic market positioning, millet milk is not just a substitute for dairy it's a forward-looking solution in the shift toward sustainable, personalized and health-driven food systems.

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**Conflict of Interest**

The authors declare that there is no conflict of interest regarding the publication of this research paper.

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