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REVIEW ARTICLE

Concise Reviews and Hypotheses in Food Science

A concise review of millet milk development

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Abstract: There is a growing global shift from dairy milk to plant-based milk alternatives (PBMAs) due to environmental, ethical, and health concerns. PBMAs such as oat, soybean, and nut milk are commercially available, whereas millet milk is notable for being allergen-free. Millet is a nutrient-dense and cost-effective option, providing essential amino acids, minerals, and antioxidants. However, factors such as millet type, extraction methods, and processing techniques significantly impact the nutritional quality of the millet milk. A standardized processing pathway is essential to achieve an optimal nutritional profile, yet the lack of such a pathway remains a significant challenge in millet milk production. Therefore, this comprehensive review explores the impact of various preprocessing techniques and extraction methods for millet milk, as well as the application of novel stabilization techniques such as high- and ultrahigh-pressure homogenization, ultrasound, microfluidization, and pulsed electric fields on other PBMAs, proposing their potential for millet milk. Additionally, the existing millet milk processing techniques are compiled to a framework, and the nutritional composition of millet milk is compared to other PBMAs and cow milk. Lastly, the recommendations for future research, focusing on the development and nutritional optimization of millet milk, are presented.

KEYWORDS
extraction, framework, millet milk, preprocessing

1 | INTRODUCTION

Milk is a globally consumed nutritious food item. However, medical concerns such as cow milk protein allergy (CMPA), lactose intolerance (LI), phenylketonuria, and cholesterol-related health issues pose challenges to its acceptability. Additionally, changes in consumer's lifestyle and the rising trend of veganism have led to a decline in milk consumption in developed countries (Aydar et al., 2020; Moore et al., 2024). It is reported that 75% of the global population experiences LI symptoms such as abdominal pain and diarrhea after consuming dairy milk due to insufficient lactase enzymes (Aydar et al., 2020; Silva et al., 2020). CMPA is a condition that triggers an immune response to milk protein and typically appears in early childhood (Flom & Sicherer, 2019). Consequently, plant-based milk alternatives (PBMAs) from soybean, lentils, and nuts are gaining popularity. This shift is driven by consumers' desire for new flavors and tastes, as well as health and wellness concerns like obesity and diabetes, prompting the adoption of PBMAs over dairy (Siddiqui et al., 2023; Silva et al., 2020). Besides, studies also highlighted the need for a concerted effort to develop robust sustainability frameworks and practices within the dairy industry to address its significant environmental impacts (greenhouse gas emission and water use) (Blok et al., 2015; Feil et al., 2020).

PBMAs are nondairy beverages made from the water-soluble extracts of legumes, cereals, pseudocereals, nuts, oilseeds, and vegetables (Gajdoš Kljusurić et al., 2015; Silva et al., 2020). These plant-based fluids are colloidal suspensions and/or emulsions containing disintegrated and dissolved plant material (Aydar et al., 2020; Scholz-Ahrens et al., 2020). Plant-based milks are typically extracted by adding water to the raw material followed by homogenization. However, the particle size distribution and composition of PBMAs vary (Mäkinen et al., 2016). Sethi et al. (2016) stated that the particle size of PBMAs ranges from 5 to 20 μm, resembling cow milk in texture and appearance (Jeske et al., 2017). Several studies on the nutritional and organoleptic evaluation of PBMAs derived from various sources, namely, soybean, oats, lentil (Jeske et al., 2019), coconut, almond, hazelnut, hemp, and peanut, were reviewed by Jeske et al. (2017) and Reyes-Jurado et al. (2023). Though various PBMAs have been extensively studied, millet-based beverages are gaining traction as a promising alternative, owing to their hypoallergenicity, sustainability and adaptability to changing climates (Nair et al., 2020; Saxena et al., 2023).

Millets are rich in protein, dietary fiber, essential fatty acids, and resistant starch. They are an opulent source of micronutrients such as vitamins (B complex—B3, B6, and B9), calcium, zinc, iron, potassium, and magnesium (Saini et al., 2021), making them an excellent dairy substitute, especially when nutrient-dense and less calorie foods are preferred. Millets contain a significant amount of methionine and cysteine (sulfur-containing essential amino acids), which sets them apart from other cereals (Sudha et al., 2016), and nearly half the lysine content found in high-quality proteins like meat. Generally, finger millet, pearl millet, barnyard millet, foxtail millet, sorghum, kodo millet, and little millet have been used for milk extraction. Studies have explored various preprocessing techniques and extraction methods for millet milk, including soaking, blanching (Pan et al., 2019), sprouting (Nair et al., 2020), ultrasound treatment (Saxena et al., 2023), and enzymatic hydrolysis (Shunmugapriya et al., 2020). Additionally, factors such as the nature of raw material, method of disintegration, homogenization or thermal treatments, and the storage conditions significantly influence the final product stability, particle size, and nutritional profile of PBMA (Sethi et al., 2016). Despite the diverse methods explored, the lack of standardized extraction, processing, and stabilization techniques remains a notable challenge in optimizing millet milk production.

Therefore, a comprehensive review has been conducted on various pretreatments, including soaking, sprouting, blanching, ultrasound, and extraction techniques of millet milk such as enzymatic hydrolysis and electrolysis. Additionally, novel stabilization techniques such as high-pressure homogenization (HPH) and ultrahigh-pressure homogenization (UHPH), ultrasound, microfluidization, and pulsed electric fields (PEFs) are investigated for their potential to improve millet milk stability, through a review of their use in other PBMAs. The nutritional profile of millet milk is compared to that of other PBMAs and cow milk. This review aims to be a pioneering effort in the commercial production of millet milk by standardizing production pathways and providing robust scientific evidence on its nutritional value and stability.

2 | PREPROCESSING TECHNIQUES FOR MILLET MILK

Millets contain antinutrients that hinder the absorption and bioavailability of essential nutrients (Mahajan et al., 2024). Thus, preprocessing techniques are used to improve the nutritional profile by reducing antinutrient levels, enhancing protein and starch digestibility, and increasing the bioavailability of vitamins and minerals (Nair et al., 2020; Sunil et al., 2024). This section explores the different preprocessing techniques for millet milk (Figure 1) and their effects on quality attributes (Table 1).

2.1 | Soaking and sprouting

Soaking or steeping effectively leaches out tannins, phytates, and other antinutrients due to the aqueous environment. Additionally, sprouting activates polyphenol oxidase, further leaching out antinutrients and increasing phenolic content and antioxidant activity (Shahidi & Chandrasekara, 2013). Sprouting increases protein and fiber content due to the utilization of stored nitrogen and dry matter for embryo development (Geetha & Preethi, 2020; Nair et al., 2020). Sprouted millet milk exhibits lower fat, ash content, and viscosity due to lipid hydrolysis and nutrient leaching resulting from increased kernel fragility during soaking and sprouting (Nair et al., 2020). Additionally, lower total sugar levels in sprouted millet milk result from amylase activation, which breaks down sugars into simpler forms (Geetha & Preethi, 2020). Nair et al. (2020) soaked millets for 8–12 h and sprouted them for 24 h at 25–30°C before grinding and filtering to produce milk. The sprouted millet milk had a higher protein (9.7% ± 0.033%) and crude fiber (0.97% ± 0.055%) than non-sprouted millet milk (protein content = 9.17 ± 0.062; fiber = 0.9 ± 0.016).

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TABLE 1 Effects of various preprocessing techniques and extraction methods on the quality attributes of millet milk.

Preprocessing	Extraction	Product	Proximate		Inference	References
Soaking (8–12 h) and sprouting (24 h)	Wet grinding using colloid mill	Millet milk and sprouted millet milk	Millet milk Protein—9.17% ± 0.062% Fat—0.08% ± 0.016% Crude fiber—0.9% ± 0.016% Carbohydrate—78.727 ± 0.015 Ash—0.35% ± 0.009% Energy value—383.108 ± 0.003 kcal	Sprouted millet milk Protein—9.69% ± 0.033% Fat—0.6% ± 0.005% Crude fiber—0.97% ± 0.055% Carbohydrate—78.72% ± 0.023% Ash—0.05% ± 0.012% Energy value—380.96 ± 0.028 kcal	Sprouting reduces total solids by decreasing moisture content and mobilizes stored nitrogen	Nair et al. (2020)
Soaking (12 h) and sprouting (48 h)	Wet grinding using mixer-grinder at 1:2 ratio of millet to water	Millet sprout milk beverage (Finger millet: pearl millet: sorghum: skim milk = 30%:23.9%:21.1%:25%	Protein—0.5% Fat—1.3% Sedimentation value—0.85 mL/10 mL Wheying-off—0.014%–0.02%		Sorghum milk increased sedimentation and wheying off, whereas finger millet milk increased sedimentation and reduced wheying off	Sudha et al. (2016)
$NaHCO_3$ soaking (0.5 g/100 mL for 16 h) and blanching (95°C for 15 min)	Wet grinding at 9000 rpm for 20 min	Millet skim milk beverage	Protein—3.15 ± 0.15 g/100 g Ash—6.65 ± 0.06 g/100 g pH—6.69 ± 0.003 Total solids—10.08 ± 0.36 g/100 g Viscosity—10.91 ± 1.01 cP		Protein content increases with an increase in blanching time. Soaking millet in $NaHCO_3$ water	Pan et al. (2019)
Soaking (12 h) and sprouting (36–48 h)	Wet grinding	Kodo millet-based functional beverage	Raw beverage Protein—1.71% ± 0.144% Fat—1.22% ± 0.078% Carbohydrate—6.01% ± 0.15% Total sugar—3.82 ± 0.16 g% Acidity—0.74 ± 0.07 TSS—15 ± 0.10°Brix	Sprouted beverage Protein—1.75% ± 0.149% Fat—1.21% ± 0.074% Carbohydrate—5.73% ± 0.13% Total sugar—3.26 ± 0.17 g% Acidity—0.86 ± 0.09 TSS—15 ± 0.10°Brix	Sprouting activated enzymatic proteins. Amylase simplified sugars during malting	Geetha and Preethi (2020)

(Continues)

TABLE 1 (Continued)

Preprocessing	Extraction	Product	Proximate	Inference	References
Soaking (13–20 h) and sprouting (24 h)	Enzymatic hydrolysis (α-amylase)	Millet milks (finger millet, little millet, Barnyard millet, Kodo millet)	Protein—1.23 ± 0.03 g/100 mL[a] Total sugars—3.7 ± 0.08 g/100 mL[a] Acidity—0.69 ± 0.05[a] pH—6.45 ± 0.13[a] TSS—2.25 ± 0.14°Brix[a] Sedimentation rate—1.04 ± 0.04 g/40 mL[a] Viscosity—2.58 ± 0.03[a]	Enzyme hydrolysis increased sugar content, in vitro protein and starch digestibility	Shunmugapriya et al. (2020)
Soaking (12 h)	Wet grinding using mixer-grinder for 12 min	Proso millet milk	Protein—1.65 ± 0.05 g/100 g Fat—0.42 ± 0.02 g/100 g Dietary fiber—0.86 ± 0.05 g/100 g Carbohydrate—2.52 ± 0.13 g/100 g Ash—0.10 ± 0.02 g/100 g Energy value—20.66 ± 0.57 g/100 g	–	Subasshini and Thilagavathi (2021)
Ultrasound pretreatment (180 W for 20 min) and sprouting (24 h)	Wet grinding using mixer-grinder at 1:2 ratio of millet to water	Millet based milk (Sorghum, Pearl millet, Barnyard millet, Finger millet, and Kodo millet)	Protein—5.23 ± 0.11 to 7.31% ± 0.24% Sugar—2.73% ± 0.03% to 14.8% ± 0.78% pH—6.4 ± 0.03 to 6.0 ± 0.01	Combined sonication-germination decreased sedimentation index and wheying off, enhancing milk's consistency	Saxena et al. (2023)
Ultrasound hydration (1:3 millet: water, 66% amplitude, 26 min)	Wet grinding using mixer grinder	Probiotic finger millet milk	pH—6.517 ± 0.009	Ultrasound hydration decreased the pH of the sample compared to conventional hydration (at 4–10°C and 25–30°C)	Yadav et al. (2024)

[a]The average values for all the millet milk samples in the study are presented in the table.

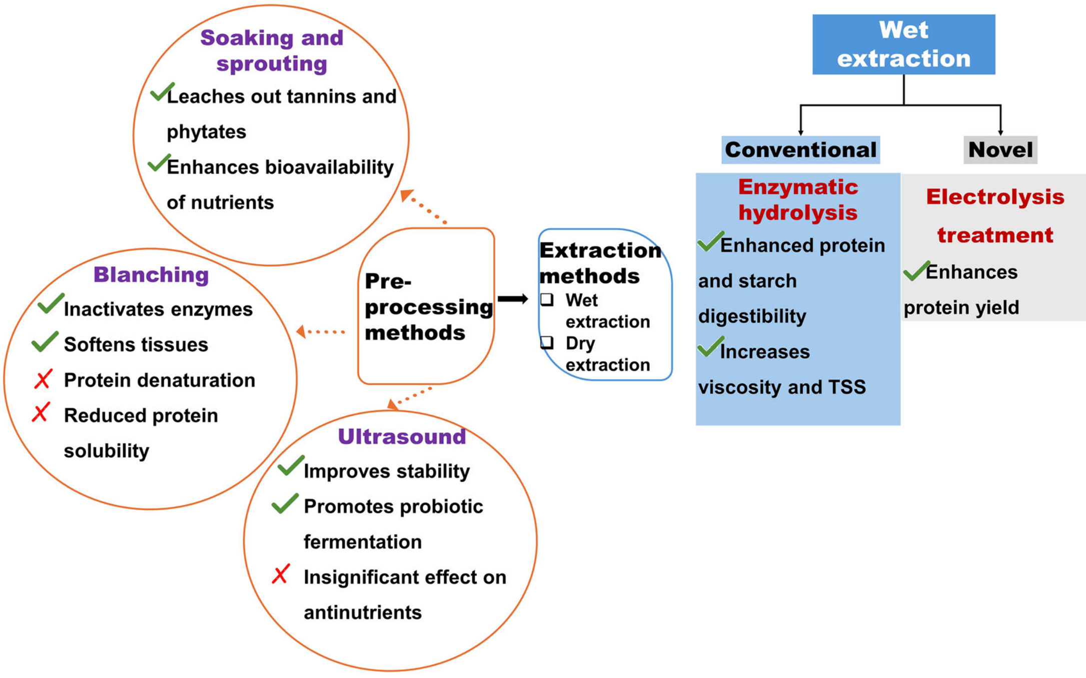

FIGURE 1 Preprocessing and extraction methods for millet milk.

Subasshini and Thilagavathi (2021) identified the optimal conditions for proso millet milk extraction as soaking the millet for 12 h at a millet-to-water ratio of 1:3, followed by grinding for 30 min. The results are presented in Table 1.

2.2 | Blanching

Blanching in hot water (75–100°C for 2–15 min) is common method used to inactivate enzymes such as lipoxygenase and trypsin inhibitors, reduce microbial load, and soften raw materials, thereby facilitating milk extraction from plant sources (Aydar et al., 2020). PBMAs made from blanched soybean, peanuts, and almonds indicated that blanching effectively reduced beany and rancid flavors (Aydar et al., 2020; Kundu et al., 2018; Sethi et al., 2016). This effect is attributed to the denaturation of the enzyme's protein structure, which inhibits its ability to catalyze lipid oxidation, preventing off-flavors and rancidity (Chong et al., 2019). Additionally, blanching millets at 85°C for 15–30 min increases viscosity and decreases protein content and total solids in the milk (Pan et al., 2019). This occurs due to the denaturation of heat-sensitive proteins and a decrease in protein solubility, resulting in higher viscosity (Kawada et al., 2002). Therefore, alternative methods such as pressure blanching and steaming should be considered to minimize heat exposure, thereby preventing protein denaturation and loss of total solids.

2.3 | Ultrasound

The ultrasound method utilizes sound waves (20–200 kHz, >1 W/cm^2) to create rapid compression and decompression in solids, generating high pressures and temperatures. This creates microscopic channels that improve heat and mass transfer, breaking down the biological matrix (Dey et al., 2023; Yadav et al., 2021). Subsequently, studies have examined the effects of ultrasound and its combination with other techniques on the nutritional and functional properties of millet milk. Saxena et al. (2023) investigated the effect of ultrasound, germination, and their combination on the nutritional properties of millet milk derived from various sources, including finger millet, pearl millet, barnyard millet, sorghum, and kodo millet. The results revealed that combined ultrasound and germination decreased the average antinutrient concentration to 23%. The ferric reducing antioxidant power assay (FRAP) activity and average total phenolic activity of germinated samples increased by 33% and 92%, respectively, compared to soaked samples (20.08 mg GAE/mL). In contrast, ultrasound treatment alone was insignificant in reducing antinutrient content (Saxena et al., 2023). Yadav et al. (2024) explored the fermentation of ultrasound-hydrated finger millet milk using the probiotic *Lactiplantibacillus plantarum* (MCC 2974). Finger millet grains were subjected to ultrasound hydration at 20 kHz frequency, 66% amplitude for 26 min, using a millet-to-water ratio of 1:3, resulting in a yield of 91.7% ± 0.06%. The extracted milk was stabilized with xanthan gum, pasteurized, and then fermented. It was reported that ultrasound treatment enhanced the availability of resistant starch by generating high-pressure gradients and local velocities, which produced shear forces that damaged granules and broke long chains into shorter segments (Babu et al., 2019). This process demonstrates prebiotic activity, promoting the growth of *L. plantarum* sp. Therefore, ultrasound is a promising technique to facilitate millet milk extraction that supports probiotic fermentation but is insignificant in reducing antinutrients.

3 | EXTRACTION METHODS FOR MILLET MILK

The milk extraction methods can be classified into dry extraction and wet extraction. Further, wet extraction methods include emerging techniques such as enzymatic hydrolysis and electrolysis treatment. This section investigates each of these techniques highlighting its distinct advantages and limitations. Table 1 summarizes various extraction methods employed for millet milk along with its quality attributes.

3.1 | Dry extraction

In this method, the millets are ground to a fine powder and mixed with water to create a slurry before homogenization. Dry extraction is generally not preferred for developing PBMAs because the solids tend to settle, leading to suspension instability. However, a patented process for almond milk has been developed using roasted almond powder (Berger et al., 1997). Briefly, the aqueous suspension of roasted almond flour (8% ± 1% by weight) mixed with 0.1% stabilizer was heated at 90°C followed by grinding in a colloid mill and centrifugal clarification to remove larger particles. The obtained product was further sterilized and homogenized at 18 MPa. It was reported that the texture and color of the almond milk resembled semi-skimmed cow milk. Further, the patent suggests that this extraction method primarily applies to nuts rich in nitrogenous compounds, limiting its application to millets.

3.2 | Wet extraction

This method is commonly used for extracting PBMAs. It involves grinding raw materials with water to create a suspension, typically using blenders or a colloid mill for the wet grinding process. A colloid mill uses the rotor-stator principle to generate shear forces that break down particles. The process starts with coarse grinding, followed by fine grinding after multiple passes (Maindarkar et al., 2014). This reduces particle size and improves suspension stability (Dhankar & Kundu, 2021). Optimal processing parameters minimize heat exposure during milling, preserving the nutritional quality and physical stability of PBMAs (Lopes et al., 2020). Research indicates that the solid-to-water ratio required for wet grinding depends on the type of raw material, for instance, soybean (1:9), oats (1:2.7), kodo millet (1:7), and proso millet (1:7) (De et al., 2022; Deswal et al., 2014; Geetha & Preethi, 2020; Subasshini & Thilagavathi, 2021).

3.2.1 | Enzymatic hydrolysis

Enzymatic hydrolysis (worting) uses native enzymes or externally added fungal/bacterial alpha-amylase to break down starch into simpler sugars (maltodextrins), preventing gelatinization at higher temperatures. This process increases total solids while reducing the viscosity of the extract. The primary methods of wort preparation are infusion, decoction, and double decoction (Rao et al., 1976). Among these, the infusion method is commonly employed for millets. Briefly, a millet slurry (1:6 millet-to-water ratio) is prepared and adjusted to the optimal pH for alpha-amylase activity. The enzyme is then added and allowed to digest at the ideal temperature and duration. Finally, the mixture is heated to the enzyme-specific inactivation temperature to cease its activity (Geethambika et al., 2023; Kumar et al., 2016; Shunmugapriya et al., 2020). Geethambika et al. (2023) used alpha-amylase enzyme to hydrolyze barnyard millet and foxtail millet starches. The wort prepared was incorporated into milk and spray-dried to produce milk-millet powders. Similarly, Shunmugapriya et al. (2020) employed the enzymatic (alpha-amylase) extraction technique to standardize millet milk derived from barnyard, little, kodo, and finger millet. The in vitro protein and starch digestibility of enzymatically hydrolyzed millet milks ranged from 69.28% ± 0.28% to 85.57% ± 1.39% and 63.36 ± 0.12 to 69.75 ± 0.56 mg maltose/mL.

3.2.2 | Electrolysis treatment

This process applies electrical voltage through metal electrodes into the sample, generating ionic species and shock waves (Strieder et al., 2023). It also creates cavitation bubbles that collapse and release energy to disrupt cell walls, enhancing the release of proteins and other nutrients. This method is typically used to extract proteins from raw materials such as olive kernel (Roselló-Soto et al., 2015) and microalgae (Sankaran et al., 2018).

Strieder et al. (2023) explored the development of PBMA from barley, examining the effects of mechanical extraction combined with electrolysis treatments (0, 5, and 15 V) on protein content. The aqueous extract processed at 15 V yielded the highest protein (26 g protein/100 g dried barley) and total soluble solids (39 g dried extract/100 g dried barley), compared to 0 V (24 g protein/100 g dried barley; 36 g dried extract/100 g dried barley) and 5 V (25 g protein/100 g dried barley; 37 g dried extract/100 g dried barley). This is attributed to enhanced cell disruption, facilitating increased protein release at higher voltages (Sankaran et al., 2018). Notably, the voltage did not affect the pH or visual appearance of the extract, but phase separation occurred after 1 h of storage at ambient temperature (24 ± 1°C). Thus, to improve the stability, the extract was homogenized at 21,500 rpm for 10 min at 30 and 60°C. This study demonstrates the potential of electrolysis treatment to enhance protein yield in PBMAs, indicating that optimal voltage conditions can maximize yield while maintaining quality.

4 | PROCESSING AND PRESERVATION

Assessing the thermal stability of millet milk and the effect of temperatures on protein and fat is crucial for selecting the appropriate processing technology. Fats contribute to food flavor generation in two ways. First, they degrade into volatile compounds during processing and storage. Second, lipid interactions with other food constituents facilitate these flavor-producing reactions (Shahidi & Hossain, 2022). As flavor compounds are fat-soluble, the interactions between fats and proteins provide an ideal environment for these flavor-generating processes (Lopez, 2005; Nair et al., 2020). Additionally, the fat content significantly influences food texture, whereas protein–fat interactions are crucial for emulsion activity, making them key components in the processing of emulsion-based products such as milk and milk product alternatives (Nair et al., 2020). Further, processing also enhances the shelf life and maintains the overall quality of the products.

Sandhya and Anandakumar (2021) examined the effects of retort processing at 75, 85, and 95°C for 15 min on a blend of foxtail millet milk and coconut milk. The L^* values exhibited minimal changes due to small temperature differences (10°C), whereas a^* values increased and b^* values decreased, owing to the Maillard reaction and starch gelatinization. Acidity increases with storage time, particularly at higher temperatures. High temperatures and long processing times also caused greater nutrient degradation, clumping, and coagulation. However, processing at 85°C for 15 min maintained commercial sterility and nutrient retention, highlighting the need for precise temperature control to ensure product safety and quality. Therefore, optimizing processing techniques to maximize nutritional benefits and extend the shelf life of millet milk is obvious in promoting millet-based products as sustainable and nutritious dairy alternatives in the food industry.

5 | STABILIZATION TECHNIQUES

PBMAs often encounter stability challenges, such as phase separation and sedimentation, due to their complex composition involving disintegrated raw material, proteins with low water solubility, fat, small molecular weight components, and polysaccharides (Dhankhar & Kundu, 2021). Over time, these components may also develop undesirable flavor and texture due to thermal and mechanical fluctations, oxidation/hydrolysis and microbial growth (McClements., 2020). Additionally, the stability of these colloidal suspensions is influenced by the size of the dispersed phase particles (Bernat et al., 2015). Therefore, it is crucial to use effective technologies and appropriate ingredients to ensure the stability and phase stabilization of these beverages. As millet milk is still in its infancy, only a few studies on its stabilization have been reported, as shown in Table 2. The stability of millet milk is enhanced through (i) homogenization, (ii) the use of stabilizers and emulsifiers, or a combination of these techniques (Table 2). Further, the enzymatic hydrolysis process of millet milk extraction maintains the consistency of the milk at high temperatures, ensuring thermal stability (Shunmugapriya et al., 2020).

5.1 | Novel stabilization techniques

This section examines innovative stabilization techniques, such as HPH and UHPH, ultrasound, microfluidization, and PEF, detailing their mechanisms of operation and effects on product properties. Although these techniques have not yet been extensively studied in millet milk, they have been widely applied to other PBMAs. Given the unique composition of millet milk—particularly its starch, protein, and fiber interactions—its stabilization challenges may differ from nut-based or high-fat PBMAs (e.g., hazelnut, tiger nut, coconut, and almond milk). The following sections therefore do not directly compare millet milk to these PBMAs but rather draw insights to identify optimal processing parameters that can be adapted for millet milk.

5.1.1 | High-pressure homogenization

HPH and UHPH are effective techniques for stabilizing PBMA without affecting their nutritional profile. HPH operates at 50–300 MPa, whereas UHPH functions at

TABLE 2 Stabilization techniques on different millet-based beverages.

Sl. No.	Stabilization technique used	Parameters	Product	References
1)	Enzymatic hydrolysis	α-Amylase at 0.5% concentration	Millet milk (barnyard millet, little millet, kodo millet, and finger millet)	Shunmugapriya et al. (2020)
2)	Homogenization	Ultra Turrax homogenization at 14,000 rpm for 15 min	A blend of foxtail millet milk and coconut milk	Sandhya and Anandakumar (2021)
		NA	Kodo millet functional beverage	Geetha and Preethi (2020)
3)	Hydrocolloids ➢ Xanthan gum	0.05% (w/v) stirred for 2 h at 30°C	Fermented finger millet milk	Yadav et al. (2024)
4)	Combined treatment ➢ Addition of stabilizer followed by homogenization	Xanthan gum at 0.05% (w/v) and carboxymethylcellulose at 0.01% (w/v) Two-stage homogenization (200/50 bar) at 60°C	Millet-skim milk beverage	Pan et al. (2019)

Abbreviation: NA, Information not available.

400 MPa or higher (Mesa et al., 2020). The process involves shear, cavitation, and turbulence as the fluid passes through narrow gaps, with a temperature increase of 2–3°C for every 10 MPa (Augusto et al., 2018). These effects reduce the particle size of macromolecules, fat droplets, and fat–protein aggregates, creating a uniform product without compromising nutritional quality. The efficiency of homogenization depends on the applied pressure and the number of passes (Bevilacqua et al., 2019). Codina-Torrella et al. (2017) subjected tiger nut milk to pressures of 200 and 300 MPa, resulting in a particle size range of 0.05–0.9 µm, compared to the broader range of 0.06–3.7 µm observed with conventional homogenization. The reduced particle size enhances colloidal stability and minimizes creaming due to the greater surface area and improved particle interaction (Torella et al., 2017). A secondary peak of 2–150 µm particles was also observed in the particle size distribution curve, with 300 MPa treatments showing a higher proportion of these particles due to partial aggregation of inadequately stabilized small globules (Dong et al., 2011). Similarly, Gul et al. (2017) evaluated the impact of HPH on cold-pressed hazelnut milk, finding that pressures from 0 to 150 MPa significantly increased protein solubility, maximal at 100 MPa with a value of 3.17 g/100 mL, then insignificantly decreased to 3.12 g/100 mL at 150 MPa. This increase is due to protein unfolding, which exposes acidic and basic subunits for better interactions. However, excessive pressure exposes hydrophobic sites that can cause aggregation resulting in decreased solubility (Dong et al., 2011). HPH reduced the particle size of the hazelnut milk, transforming a bimodal to a monodisperse particle distribution, indicating uniform dispersion (Bernat et al., 2015; Gul et al., 2017). Further, the effectiveness of homogenization is largely influenced by valve design, pressure, and the number of passes for specific food matrices (Mesa et al., 2020).

5.1.2 | Ultrasound

As previously stated, this technique works on acoustic cavitation, where microbubbles of gas/vapors are generated that collapse at a critical frequency, producing shear stress within the material (Silva et al., 2015). This shear stress results in increased thermal energy, turbulence, and dynamic agitation, all of which contribute to the reduction of colloidal particle size (Li et al., 2021). The improved stability is linked to cavitation-induced fragmentation of colloidal polysaccharide molecules into smaller particles (Cheng et al., 2007). This reduction in the size of plant cellular material helps keep them in suspension, thereby enhancing overall stability. Iswarin and Permadi (2012) assessed the impact of ultrasound on the droplet diameter of coconut milk. The ultrasound treatment was applied at various power levels (2.5–7.0 W) and exposure times (5–25 min). The initial droplet diameter of 5.44 ± 0.15 µm decreased to 3.64 ± 0.15 µm at 7.0 W and 25 min, indicating that particle size decreased with increasing ultrasound power and duration. Similarly, Maghsoudlou et al. (2016) investigated the effect of ultrasonication on the physical stability of almond milk, applying a power level of 300 W for 2.5 and 5 min. The study revealed a decrease in the sedimentation tendency and viscosity of the almond milk treated for 5 min. Additionally, ultrasound treatment effectively retains bioactive compounds by creating localized pressures and temperatures that prevent a significant rise in the overall material temperature (Li et al., 2021). Thus, ultrasound processing at optimal conditions is effective for thermolabile materials.

5.1.3 | Microfluidization

The microfluidization process operates under high pressures (up to 206.9 MPa) within specially designed microchannels (Microfluidics, n.d.). This high-energy technique generates intense shear forces, hydrodynamic cavitation, and rapid pressure drops, producing nanoparticles and homogeneous products (Guo et al., 2020). These effects can disrupt hydrogen bonds in starch molecules, break down long-chain amylose and amylopectin, and dissolve short-chain amylose, enhancing the hydration capacity of starch (Chen et al., 2021). Additionally, it increases protein solubility by disrupting compact structures and transforming insoluble agglomerates into soluble ones (Hu et al., 2021). Microfluidization also improves the emulsion activity and emulsion stability of proteins, likely due to enhanced protein solubility and surface hydrophobicity (Hu et al., 2021; Kumar et al., 2022). These changes illustrate the potential of this technique to enhance the overall functionality of carbohydrates and proteins toward improving stability and preventing phase separation, which is a key concern for PBMAs. Kavinila et al. (2023) reviewed the effectiveness of this technique in reducing milk droplet size compared to conventional homogenization, as well as its applications in dairy products like yogurt, cheese, and ice cream. However, the high cost of equipment and operation remains a significant challenge.

5.1.4 | Pulsed electric field

In this method, food products are placed between two electrodes and subjected to electrical pulses of high voltage (ranging from 1 to 80 kV/cm) for short periods (from a few milliseconds to microseconds), operating at temperatures below 30–40°C (Wibowo et al., 2019). This technique is commonly employed for microbial destruction and enzyme inactivation due to electroporation (Silva et al., 2020). However, few studies have investigated the effectiveness of PEF in enhancing colloidal stability. The findings indicate that PEF disaggregates coagulated particles, modifying their volume without altering the particle size (Manzoor et al., 2019; Taha et al., 2022). This effect may be attributed to the partial dissociation of particles during the process (Manzoor et al., 2019). Although PEF treatment decreased the size of fat globules, it also formed a weak gel, creating a three-dimensional network where denatured soluble proteins entangle larger aggregates of lipid–protein particles (Manzoor et al., 2019). Furthermore, Hemar et al. (2011) stated that the reduction in particle size and viscosity following PEF treatment was due to the high shear experienced during processing (circulation of samples in the system).

Manzoor et al. (2019) reported that the PEF intensities ranging from 7 to 28 kV/cm significantly increased apparent viscosity, indicating stronger intermolecular interactions among denatured molecules in weak transient networks. Increased protein aggregation further contributed to greater viscosity (Zhang et al., 2005). Although samples treated at 7, 14, and 21 kV/cm showed phase separation after 24 h, the 28 kV/cm treated sample remained stable for 48 h. Collectively, these results suggest that although PEF is effective for microbial destruction and enzyme inactivation, it is less effective for stabilization.

6 | DEVELOPMENT PATHWAYS

Based on the review of existing extraction methods, a framework for millet milk development is presented in Figure 2. In summary, the millet milk development process begins with selecting millet/s. Then, millets are preprocessed primarily to reduce antinutrient concentration and soften the tissues facilitating extraction (Geetha & Preethi, 2020; Pan et al., 2019). Wet extraction methods are commonly employed, as they readily form a suspension during grinding or blending, in contrast to dry extraction, where millet flour tends to settle, hindering suspension formation. The resulting extract is typically filtered using muslin cloth to remove larger particles and debris. However, there is lack of literature detailing filtration techniques for millet milk. Notably, the extraction method influences subsequent steps. For example, when millet milk is obtained through enzymatic hydrolysis, two heat treatments are involved—enzyme inactivation (at enzyme-specific temperature) and pasteurization (75°C for 10 min) (Shunmugapriya et al., 2020). Following this, stabilization is crucial to prevent phase separation and sedimentation, ensuring uniform consistency and consumer appeal. Additionally, millet milk can undergo further processes such as fermentation, drying, or blending with other PBMAs to produce value-added products such as fermented beverages, millet milk powder, and blended vegan milk.

7 | COMPARATIVE NUTRITIONAL PROFILE OF MILLET MILK

This section outlines the nutritional profile of millet milk in comparison to PBMAs and cow milk. The essential

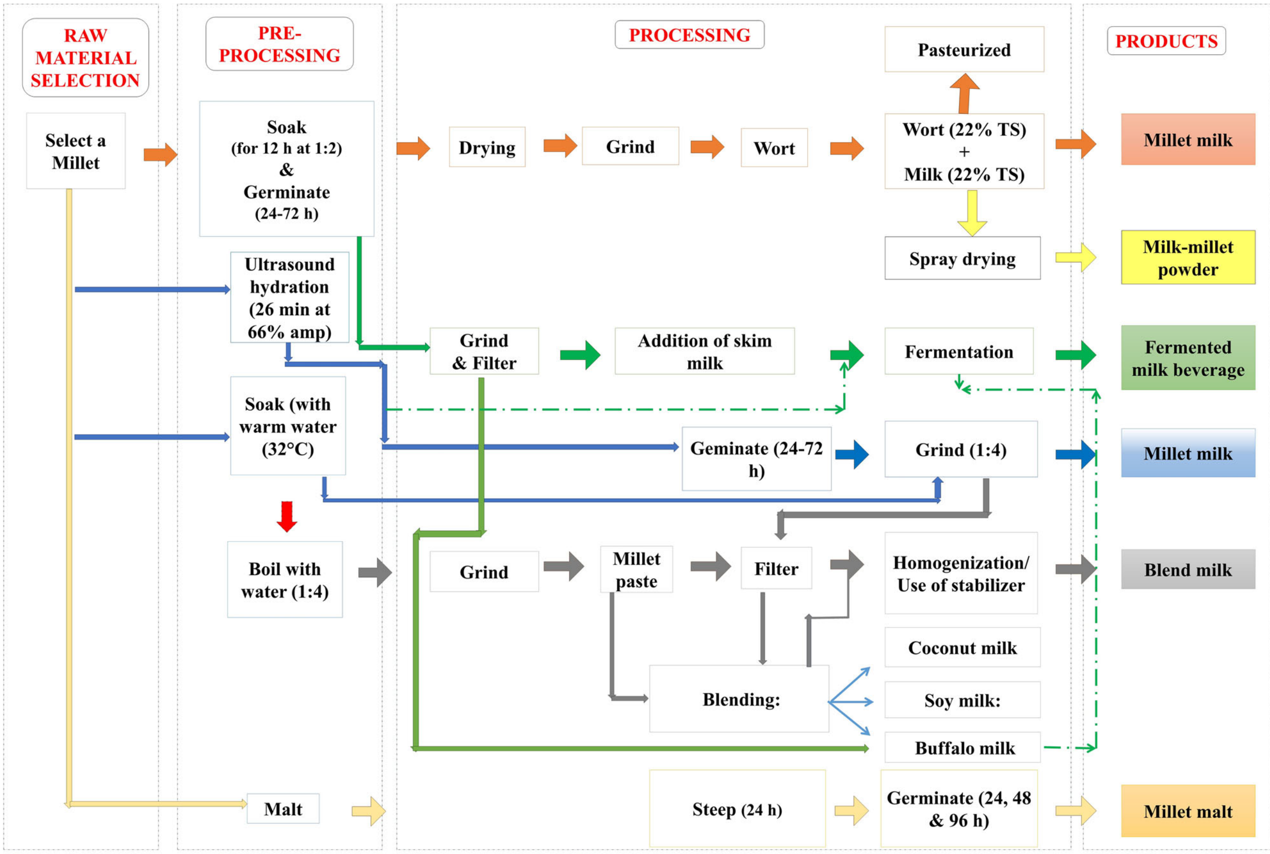

FIGURE 2 Millet milk development pathway as detailed in reviewed literature.

nutrients that must be considered when evaluating milk alternatives are protein (high biological value), calcium, iron, iodine, and vitamins B6, B12, A, and D (Table 3A). The nutritional profile of different PBMAs varies significantly depending on the source material, preprocessing techniques (e.g., soaking, sprouting, and blanching), and post-processing techniques used for stabilization, flavor enhancement, or antinutrient inactivation (Reyes-Jurado et al., 2023). As a result, establishing a consistent nutritional composition for PBMAs is challenging. Many PBMAs are fortified with micronutrients like phosphorus, calcium, vitamin B12, and vitamin D to better match the nutrient content of cow milk, as PBMAs are typically not nutritionally equivalent to cow milk (Reyes-Jurado et al., 2023; Harmer et al., 2025). Nevertheless, some PBMAs contain certain bioactive components (Table 3B) that may provide health benefits, such as promoting brain development, reducing cardiovascular disease risk, and exhibiting anticancer properties (Table 3B) (Reyes-Jurado et al., 2023; Scholz-Ahrens et al., 2020). The health benefits of these bioactive compounds arise from their diverse mechanisms of action. Their antioxidant activity helps neutralize free radicals and reduce oxidative stress, which can prevent chronic diseases like heart disease and cancer (Gani et al., 2012). Compounds such as phytosterols and β-glucan lower cholesterol levels by inhibiting its absorption and facilitating excretion (Liu, 2004). Moreover, many of these compounds have anti-inflammatory effects, support digestive health by promoting regular bowel movements, and may influence hormonal balance, particularly lignans for hormone-related cancers (Gani et al., 2012). The synergistic effects of these compounds enhance their health benefits, contributing to chronic disease prevention and overall well-being.

Harnessing the potential of these bioactive components paves the way for expanding PBMAs that offer health benefits beyond basic nutrition. Table 3B outlines the key components, bioactive compounds, and associated health benefits of millet, soybean, almond, oat, and coconut milk. It is important to note that many of these milk alternatives contain allergenic compounds like soy protein (β-conglycinin, globulin, and vicilin) (Wiederstein et al., 2023), nut proteins (2S albumins, legumins, and vicilins) (Geiselhart et al., 2018), and gluten. In this context, millet milk emerges as a hypoallergenic alternative for individuals with allergies. Its low fat, carbohydrate, and glycemic index

TABLE 3A Nutritional composition of millet milk and its comparison with various plant-based milk alternatives (PBMAs) cow milk.

	Millet milk	Cow milk	Soy milk	Almond milk	Oat milk	Coconut milk
Proximate composition						
Protein (%)	0.5–9.69	3.5	6.75–6.84	3.2	1–2	2.14–2.97
Fat (%)	0.08–2.1	3–4	3.5–3.9	6.85	1.5–3	18.83–21.09
Fiber (%)	0.86–0.9		0.14–0.16		0.8–2	
Carbohydrate (%)	2.52–6.01	4.9	6.02–6.05	2.44	6.6–8	6
Ash (%)	0.05–0.35	0.7	0.84–0.86	0.43		0.63–0.96
Vitamins						
Vitamin C (mg)	NA	1.5	–	–	–	–
Thiamine (mg)	NA	0.04	0.08	–	–	–
Riboflavin (mg)	NA	0.16	0.24	0.19	–	–
Niacin (mg)	NA	0.08	0.28	–	–	–
Vitamin B6 (mg)	NA	0.04	0.096	–	–	–
Folate, DFE (μg)	NA	5	33.6	19.2	–	19.2
Vitamin B12 (μg)	0.25	0.36	0.68	1	–	0.75
Vitamin A (μg)	NA	33	32.57	77.14	31.56 (47.1 IU)	60
Vitamin E (mg)	NA	–	4	3.84	–	–
Vitamin D (μg)	0.25	–	1.86	2.32	1.3	2.92
Minerals						
Ca (mg)	4.17–91.31	119	205.86	325.29	130.4	244.75
Fe (mg)	0.43–1.54	0.05	0.84	0.18	–	0.1
Mg (mg)	NA	13	49	21	–	35
P (mg)	NA	93	108	48	–	–
K (mg)	NA	151	364.29	65	150	46.67
Na (mg)	37.9	49	65	146.42	41.7	63.75
Zn (mg)	NA	0.38	0.75	0.56	–	0.66
Physicochemical properties						
pH	6.2–6.7	6.64	6.62	6.92	6.0–6.4	6.62–6.88
Titratable acidity (%)	0.5–0.83	0.16	0.17	0.39	0.45	0.02
Total solids (%)	2–15	12.62	11.45	27.96	11.39	12.5–12.7

Abbreviation: NA, not available.
Source: Data obtained from Sudha et al. (2016), Vanga and Raghavan (2018), Geetha and Preethi (2020), Scholz-Ahrens et al. (2020), Shunmugapriya et al. (2020), De et al. (2022), Cui et al. (2023), Kundukulanagara Pulissery et al. (2023), Zhou et al. (2023), Yu et al. (2023).

make it a valuable option for those concerned with hypercholesterolemia, diabetes, or a low-calorie diet. Further research is needed to explore the comprehensive nutritional profile of millet milk, including its vitamins and minerals.

8 | KEY TAKEAWAYS AND FUTURE TRENDS

The review identified challenges and opportunities in millet milk development, emphasizing the need for standardization to promote millet milk alongside other PBMAs. A summary of key takeaway points to guide future researchers in the millet milk development process is provided below:

1. Soaking and sprouting millets reduce antinutrients and enhance the bioavailability of essential nutrients, improving the overall nutritional profile of millet milk.
2. Blanching, although useful in enzyme inactivation and softening tissue for easier extraction, increases viscosity and reduces protein content and total solids.
3. Ultrasound pretreatment, though ineffective in reducing antinutrients, has shown potential in promoting the growth of probiotics.

TABLE 3B Overview of selected plant-based milk alternatives (PBMAs): key nutrients, bioactive components, and its associated health benefits.

PBMAs	Major components	Potential allergens	Bioactive components	Health benefits
Millet milk[a]	Iron, calcium and magnesium Low calorie	Nil	Polyphenols, flavonoids and tannins	Hypoallergenic, low glycemic index, and reduce risk of cardiovascular disease
Soybean milk [b]	Proteins, essential amino acid and calcium	Soy protein	Isoflavones phytosterol α-tocopherol	Alleviate menopause symptoms, properties of lowering cholesterol, decreases the risk of prostate and colon cancer, functions as anti-inflammatory agent
Almond milk[d]	Calcium	Nut protein	Arabinose, α-tocopherol, phytosterols, and flavonoids	Prebiotic properties, decreases lipid peroxidation
Oat milk[c,d]	B-glucan and fiber	May contain gluten	Phytosterols and β-glucan	Lowers plasma cholesterol, and management of body weight and blood pressure
Coconut milk[c,d]	Saturated fats	Nut protein	Medium chain triglycerides, and lauric acid	Decreases LDL cholesterol and increases HDL cholesterol, maintains elasticity of blood vessels, and promotes brain development

Source: Data obtained from (a) Shunmugapriya et al. (2020), (b) Paul et al. (2020), (c) Scholz-Ahrens et al. (2020), (d) Reyes-Jurado et al. (2023).

4. Enzymatic hydrolysis breaks down starch into simpler sugars, whereas electrolysis treatment aids protein release.
5. Novel stabilization techniques are still underexplored for millet milk.
6. Efficiency of homogenization depends on applied pressures (usually 100–200 MPa) and the number of passes with excessive pressures leading to particle aggregation.
7. Ultrasound treatment at optimal conditions has been shown to enhance stability.
8. Microfluidization, though effective in stabilizing millet milk, faces limitations due to high capital and operating costs. Additionally, although PEF can reduce fat globule size, their impact on the overall stabilization of PBMAs is limited.
9. There is limited evidence on the micronutrient composition of millet milk. Future studies should focus on systematically reporting the levels of vitamins and minerals in millet milk.

9 | CONCLUSION

Millet milk is still in its early stages of development, as evidenced by the limited number of studies available. This review has attempted to organize the existing literature and classify potential extraction, processing, and stabilization techniques for millet milk. It also guides the selection of appropriate technologies for millet milk development based on its impact on quality attributes. However, this review highlights significant research gaps such as a lack of comprehensive nutritional profile and application of novel stabilization techniques. Furthermore, it was also noted that limited studies exist on the filtration, packaging, and shelf life of millet milk presenting an important avenue for future investigation to make it commercially viable.

AUTHOR CONTRIBUTIONS

Nagarajan Meena: Writing—original draft; methodology; conceptualization. **N. U. Sruthi**: Writing—review and editing. **Pramesh Dhungana**: Writing—review and editing. **Hayder Al-Ali**: Writing—review and editing. **Pavuluri Srinivasa Rao**: Writing—review and editing; conceptualization; supervision; visualization. **Rewati Raman Bhattarai**: Conceptualization; writing—review and editing; visualization; supervision.

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CONFLICT OF INTEREST STATEMENT

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