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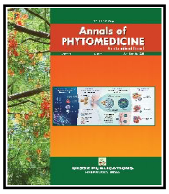

Original Article : Open Access

Optimization of finger millet milk by different green extraction methods and analyze its physicochemical, nutritional and sensory properties

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Abstract

Plant milk substitutes have seen an increase in demand because of lactose intolerance, allergy to milk proteins, prevention of cholesterol and the growing popularity of vegan diets. In this research, physicochemical, nutritional and sensory properties of finger millet milk that was extracted using four varied methods that included conventional extraction method (CEM), ultrasonic assisted extraction (UAEM), microwave assisted extraction (MWAEM) and enzyme assisted extraction (EAEM) were assessed. The protein content (2.10 ± 0.07 g/100 ml) of UAEM extracted finger millet milk was found to be significantly ($p<0.05$) higher than that of CEM (1.51 ± 0.04 g/100 ml), which would be an increase of 39%. Level of calcium (53.02 ± 0.21 mg/100 ml) and iron (1.34 ± 0.09 mg/100 ml) were also significantly ($p<0.05$) higher in UAEM than CEM (50.58 ± 0.21 and 1.07 ± 0.09 mg/100 ml, respectively) than EAEM and MWAEM, respectively. There were more color and appearance (8.8 ± 0.2), consistency (8.9 ± 0.2), flavor (8.6 ± 0.2) and overall acceptability (8.7 ± 0.2) in UAEM milk than in the EAEM and MWAEM finger millet milk than in CEM ($p<0.05$). These results indicate that ultrasonic assisted extraction is a promising and sustainable option to the conventional methods of processing since it improves nutritional, physicochemical and sensory quality of finger millet milk.

1. Introduction

Recently, there has been a growing global demand for dairy free alternatives due to serious health issues associated with certain nutrients found in milk (Granato *et al*., 2010). The production of plant-based milk has a lower carbon footprint compared to dairy milk, supporting both food security goals and environmental sustainability objectives (Coluccia *et al*., 2022). Clinical studies have demonstrated that certain components of milk are linked to negative health effects including lactose intolerance, cow's milk allergy and coronary heart diseases (Kneepkens *et al*., 2009). Avoiding milk products that contain these components can minimize these risks. Due to these issues related to cow's milk and increasing preferences for vegan diets, health-conscious consumers suitable options for dairy free alternatives. Most of the plant sources are rich in health promoting compounds like dietary fiber, vitamins, minerals and antioxidants, which contribute to nutraceuticals and functional foods (Das *et al*., 2012). According to Euromonitor, the Food Institute reported that sales of plant-based milk products increased by 6% in 2022, reaching a market value of $19.1 billion. The production of these milk alternatives involves dispersing plant materials, resulting in particles that vary in composition and size. The physical characteristics of these particles, as well as the shelf stability of the final product, are influenced by factors such as the raw material source, the method of disintegration and storage conditions (Sethi *et al*., 2016).

The finger millet (*Eleusine coracana* L.) is a healthy nutri-cereal crop and is a popular crop in many parts of Africa and India (Ramashia *et al*., 2019). It is a widely used staple crop in Indian cuisine, which is usually eaten without dehulling. India is also a major producer with almost 60 per cent of finger millet in the world. The crop can be characterized by the small dark brown grains and has much more polyphenol than such cereals as barley, rice, maize and wheat. It is a nutritious grain and has high levels of dietary fiber, starch, calcium and iron among others millets. Finger millet has a calcium content between 220 and 450 mg/100 g of the grain and iron content of 3% to 20% (Lokur *et al*., 2023). Finger millet is one of the leading cereals that are grown in Asia and Africa, the others being sorghum, pearl millet and foxtail millet. Finger millet is produced annually in amounts of about 4.5 million tons globally, 2.5 million tons of which are produced by Africa and 1.2 million tons of which is produced by India. It is important to note that sub-Saharan Africa contributes approximately 5560 per cent of the total output worldwide (Antony Ceasar *et al*., 2018).

Finger millet is rich in a wide range of phytochemicals that comprise of tannins, steroids, polyphenols, alkaloids, terpenoids, cardiac glycosides, balsams, lignans, phytoestrogens and phytocyanins. It also includes some prominent phenolic acid derivatives

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(hydroxybenzoic acids, gallic, protocatechuic, *p*-hydroxybenzoic, vanillic and syringic acids) and hydroxycinnamic acids (ferulic, trans-cinnamic, *p*-coumaric, caffeic and sinapic acids). Besides, finger millet contains flavonoid compounds such as quercetin, proanthocyanidin and condensed tannins. These bioactive compounds confer various health-promoting actions, such as wound healing, antiageing, antimetabolic disorders, blood pressure, and a lower likelihood of diabetes (Kalsi *et al*., 2022).

The application of emerging food processing technologies is focused on development of palatable, safe, nutritious, healthy and minimally processed foods. The need to seek alternative means has also led to the non-thermal technologies, which are used in maintaining flavours and nutrition of foods in the production process. One such method is also called ultrasonication which involves the conversion of large particles into smaller ones by use of sound waves of high frequency. High power ultrasound has been reported to be used in the food industry in the extraction (releasing of plant material), inactivation of microorganisms, enzyme inhibition, enzyme homogenization, enzyme emulsification, filtration, crystallization/deforming and enzyme inactivation. Ultrasonication is a technique which involves the use of sound energy to mix the particles of a sample between the frequency of 20 kHz to 100 kHz. Due to compression and refraction of sound waves, small vacuum or cavity bubbles are developed in the sonication process. When such bubbles meet, extremely high temperatures (3000 k up to above 10,000 k) and pressures (over 100 MPa) are produced within a fraction of a second. This is referred to as cavitation effect and it causes changes in the samples during the process (Shanmugam *et al*., 2012).

Microwave-assisted extraction (MAEM) uses microwave energy to quickly heat polar molecules, mainly water, inside the plant matrix, which leads to cell wall rupture and production of nutrients and bioactive compounds are released efficiently. As a result, this method selectively extracts polar components, thereby lowering extraction time, solvent consumption and energy usage to a great extent, thus being a green and resource-efficient way of producing plant-based milk (Varghese *et al*., 2019).

Enzyme-assisted extraction (EAEM) is a more environmentally friendly method of producing milk from plant sources as it employs hydrolytic enzymes to specifically degrade cell wall polysaccharides at the most favorable conditions. The enzymatic action changes substrate structures, allows for efficient interaction with plant materials and eases the binding of bioactive and nutritional compounds, thereby enhancing the quality of the final product. In the production of non-dairy beverages from cereals, the use of enzymes is geared towards the application of liquefying enzymes, especially during gelatinization. This process transforms the semi-crystalline starch structure into an amorphous form, making it more digestible by amylases. Enzymatic liquefaction not only improves yield but also reduces viscosity and increases total solid content by converting starch into maltodextrins (Mehany *et al*., 2024).

This research is about millet-based milk as a cheaper, healthy and environment-friendly substitute for cow's milk. Four different methods such as conventional extraction (control), ultrasonic-assisted, microwave-assisted and enzyme-assisted were used to prepare finger millet milk. The study also measured the changes in the physicochemical properties, nutritional composition, antinutritional factors, and sensory attributes of finger millet milk to understand the impact of these different extraction methods.

2. Materials and Methods

2.1 Materials

The study was carried out at the Department of Food Science and Nutrition, Community Science College and Research Institute, Madurai. Finger millet (*Eleusine coracana* L.) of the ATL 1 variety was obtained from the Centre of Excellence in Millets, Athiyandal, Tiruvannamalai District, Tamil Nadu. It produces compact brown ear heads with bold grains and exhibits good resistance to blast disease. This variety is noted for its high calcium, iron and dietary fibre content, along with a balanced amino acid composition, making it suitable for value-added and functional food applications. All chemicals used in this study were of analytical grade.

2.2 Ultrasonic assisted extraction (UAEM), microwave assisted extraction (MWAEM), enzyme assisted extraction (EAEM) and conventional method (CEM) extraction of finger millet milk preparation

The experimental design for ultrasonic, microwave and enzyme-assisted extraction of finger millet milk was formulated using a central composite design (CCD) under response surface methodology (RSM). For UAEM, the variables studied were soaking time (14-20 h), sonication time (5-30 min) and sonication temperature (30-45°C). For MWAEM, the factors included soaking time (14-20 h), microwave time (1-3 min) and microwave temperature (70-90°C). For EAEM, enzyme concentration (0-0.5%), incubation time (50-60 min) and incubation temperature (60-75°C) were optimized. The effects of these parameters were evaluated based on milk yield (%), protein content (g/100 ml), viscosity (cP/100 ml) and overall acceptability.

For each extraction method, 20 experimental runs were performed, with process variables chosen from preliminary analyses. Each response was averaged from three replicates. A quadratic model was used to assess variable interactions and ANOVA evaluated the significance of coefficients at $p<0.05$. Based on RSM results, the ultrasonic, microwave and enzyme-assisted extraction conditions for finger millet milk were optimized. The detailed procedures for each extraction method are provided below.

Finger millet grains were first cleaned to remove broken kernels and impurities, then thoroughly washed with water. For experimental preparations, 100 g of grains were soaked and after draining, germinated at room temperature for 24 h. The germinated grains were blended for 120 sec to form a slurry, which was then subjected to different pretreatments ultrasonication, microwave or enzyme-assisted extraction according to the RSM-determined experimental conditions. After pretreatment, the slurry was filtered through muslin cloth, homogenized at high speed for 15 min and double-pasteurized at 85°C for 15 min. The resulting finger millet milk was stored in glass bottles at 4°C for further analysis.

For conventional extraction, 100 g of grains were soaked for 19 h, germinated for 24 h at room temperature, and blended for 120 sec. The slurry was filtered, homogenized for 15 min, double-pasteurized at 85°C for 15 min and stored at 4°C in glass bottles for subsequent analysis.

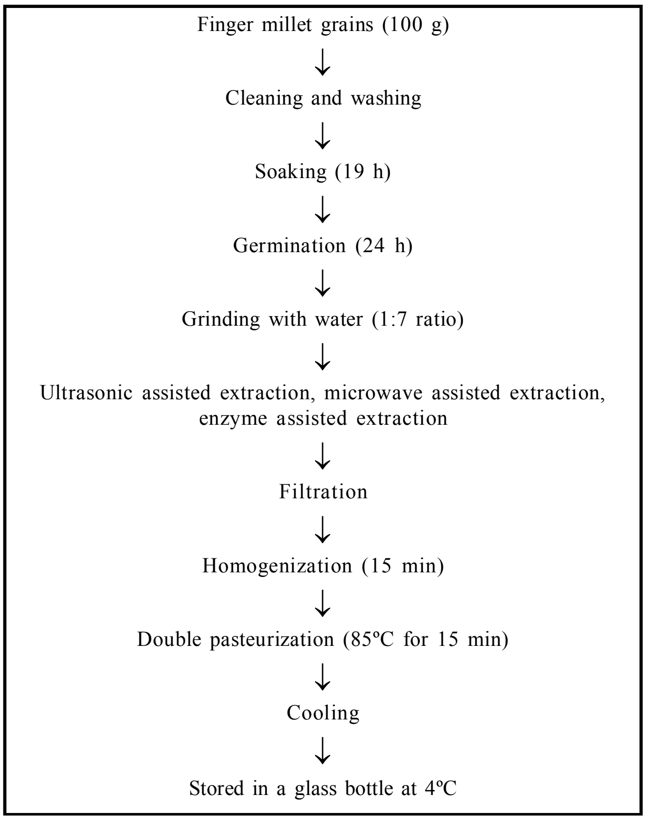


Figure 1: Flow chart for the preparation of ultrasonic, microwave and enzyme assisted extraction of finger millet milk.

2.3 Physicochemical and nutritional composition analysis

The pH of the finger millet milk samples was estimated by using a handheld digital pH meter, Total soluble solids were analyzed by refractometer (Erma, Tokya, Japan), total acidity was determined as per Ranganna (1986), viscosity of the finger millet milk samples was estimated by Brooke field viscometer using spindle 62 at 100 rpm, Acid value were determined as per (Sadasivam, 1996), colour values (L* a* b*) of the samples were measured by using a Hunter Laboratory chromometer (Model # Lovibond RT 100) with the Lovibond RT colour software (Version 3.0). The sedimentation index was determined and expressed as g of sediment/volume of centrifuge tube as per the (Jeske *et al*., 2017), Syneresis was determined as per Howard *et al*. (2010), Total solids were determined as per (AOAC, 2012). Total carbohydrate content by anthrone method was determined as per Sadasivam (1996), Protein content of the finger millet milk was analyzed by the Microk Jeldhal method (AOAC, 2005). Fiber content was analyzed by (Sadasivam, 1996), fat content of the samples was estimated as per (Howard *et al*., 2010), minerals, *viz*., calcium, iron and phosphorous were estimated by using triple acid digestive method (Ranganna, 1986).

Total phenolic content (TPC): Determined using the Folin-ciocalteu method. Milk samples were reacted with Folin-ciocalteu reagent and sodium carbonate, incubated in the dark for 30-60 min and absorbance measured at 765 nm. Results expressed as mg GAE/100 ml (Bao *et al*., 2005).

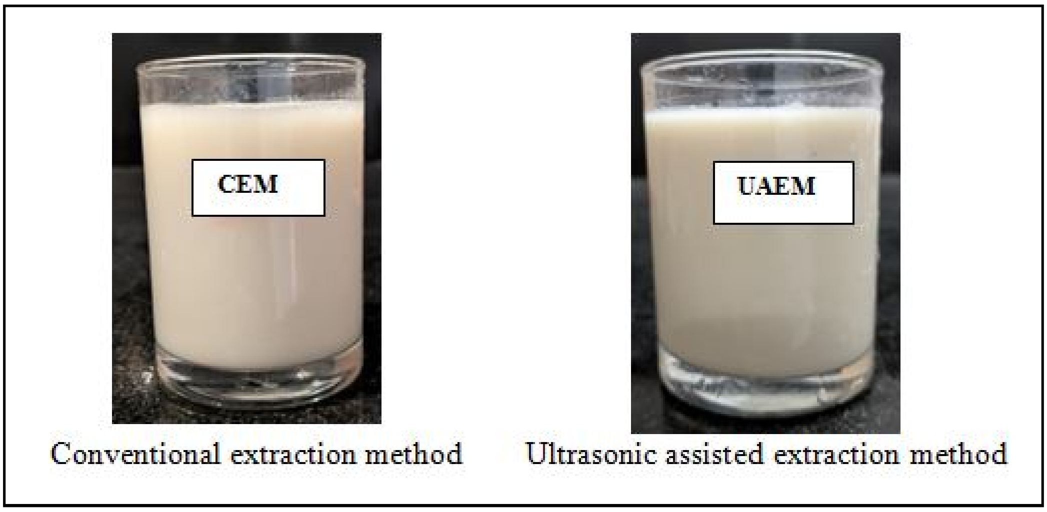
Total flavonoid content (TFC): Measured using aluminum chloride colorimetry. Samples were mixed with NaNO, , AlClƒ and NaOH, and absorbance recorded at 510 nm. Expressed as mg CAE/100 ml (Ribarova *et al*., 2005).

Total antioxidant activity (TAA): Evaluated by DPPH radical scavenging assay. Milk samples were incubated with DPPH solution for 30 min in the dark, and absorbance measured at 517 nm. Expressed as %RSA (Sadasivam, 1996).

Tannin content: Determined using the Folin-denis method. Samples reacted with reagent and sodium carbonate, incubated, and absorbance recorded at 760-765 nm. Expressed as mg TAE/100 ml (Sadasivam, 1996). All measurements were performed on centrifuged or filtered samples to avoid turbidity interference, with standard curves used for quantification.

2.4 Sensory evaluation

Finger millet control, ultrasonic assisted, microwave assisted and enzyme assisted extracted finger millet milk samples were evaluated for organoleptic characteristics by a panel of 30 semi trained members using a 9-point Hedonic rating scale (Ranganna, 1997). Sensory evaluation of UAEM, MWAEM, EAEM and CEM finger millet milk samples assessed color, appearance, flavor, taste, consistency and overall acceptability using a 9-point hedonic scale (1 = extremely dislike, 5 = neither like nor dislike, 9 = extremely like).



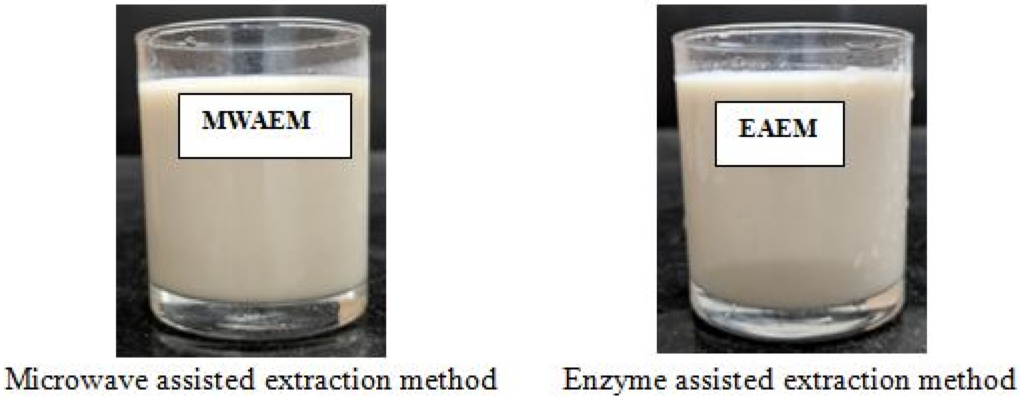


Figure 2: Conventional and green extraction of finger millet milk.

2.5 Statistical analysis

Data were analyzed using a paired t-test in a completely randomized design with three replications, employing WASP (Web agricultural statistical packages) software for statistical analysis.

3. Results

3.1 Optimized extract condition for extracting finger millet milk from conventional, ultrasonic assisted, microwave assisted and enzyme assisted extracted finger millet milk

This study evaluates the effect of various extraction methods on finger millet milk production, with process optimization performed using response surface methodology (RSM). Treatments included conventional extraction (CEM), ultrasound-assisted (UAEM), microwave-assisted (MWAEM) and enzyme-assisted extraction (EAEM). Independent variables were soaking time, extraction temperature and extraction technique, while dependent variables measured were milk yield, protein content, viscosity and overall sensory acceptability.

Table 1: Optimized extract condition for extracting finger millet milk using response surface methodology

Treatments	Independent variables	Dependent variables				Desirability value
		Milk yield (%)	Protein (g/100 ml)	Viscosity (cP/100 ml)	Overall acceptability	
CEM-Control	Soaking in water - 600 ml soaking time-14 h, soaking temperature-32°C	66.2^{d}	3.92^{d}	23.76^{c}	7.3^{c}	NA
UAEM	Soaking time-19 h, Sonication temperature-45°C, sonication time-20 min	76.67^{a}	5.45^{a}	26.85^{a}	8.7^{a}	1
MWAEM	Soaking time -16 h, microwave temperature - 85°C and Microwave time-2 min	70.68^{c}	4.67^{c}	26.98^{a}	7.2^{c}	1
EAEM	Enzyme concentration- 0.5%, Incubation temperature- 62°C, Incubation time-56 min	74.32^{ab}	5.43^{b}	24.27^{b}	8.1^{b}	1
	Statistical value					
CD (0.01)	4.331		0.345	2.492	0.637	
CD (0.05)	3.045		0.242	1.752	0.448	
CV %	3.045		2.729	3.806	3.134	

Each value is expressed as the mean ± standard deviation (SD) based on three replicate analyses (n=3). CEM-Conventional extraction method; UAEM-Ultrasonic assisted extraction method; MWAEM-Microwave assisted extraction method; EAEM-Enzyme assisted extraction method.

The results showed that UAEM produced the highest milk yield (76.67%), followed by EAEM (74.32%), MWAEM (70.68%) and CEM (66.2%), with UAEM and EAEM significantly outperforming the conventional method. Protein content was highest in UAEM (5.45 g/100 ml) and EAEM (5.43 g/100 ml), exceeding MWAEM (4.67 g/100 ml) and CEM (3.92 g/100 ml). Viscosity was greatest in MWAEM (26.98 cP/100 ml), closely followed by UAEM (26.85 cP/100 ml), then EAEM (24.27 cP/100 ml) and CEM (23.76 cP/100 ml), with differences statistically significant. Sensory evaluation showed UAEM had the highest overall acceptability (8.7), followed by EAEM (8.1), while CEM (7.3) and MWAEM (7.2) scored lower.

Statistical analysis confirmed that UAEM-based finger millet milk significantly outperformed the control across all evaluated parameters, with coefficient of variation (CV) values demonstrating minimal variability and strong reliability of the sensory data. Furthermore, the desirability value of 1 obtained for UAEM, MWAEM and EAEM validates their suitability as optimized extraction techniques within the RSM framework.

3.2 Nutritional, antinutritional and antioxidant activity of different green extraction techniques of finger millet milk analysis

Figure 2 presents the nutritional composition of finger millet milk prepared by different extraction methods conventional extraction method (control), ultrasound-assisted extraction (UAEM), Microwave-assisted extraction (MWAEM) and enzyme-assisted extraction (EAEM). The results indicate that ultrasonication significantly enhanced the nutritional profile, particularly increasing the levels of protein, dietary fiber, iron, calcium, and phosphorus compared with the control.

In terms of carbohydrate (CHO) content, the highest value was recorded in UAEM milk (9.59 g/100 ml), followed by EAEM (9.40 g/100 ml), MWAEM (9.00 g/100 ml), and the control (8.67 g/100 ml). Finger millet milk showed significantly higher protein content in UAEM (5.45 g/100 ml) compared to the control (3.92 g/100 ml), with EAEM (5.20 g/100 ml) and MWAEM (4.57 g/100 ml) also showing notable increases. The significant enhancement in protein yield achieved through ultrasonication can be explained by the formation and collapse of cavitation bubbles, which generate localized high shear forces and turbulence. These mechanical effects disrupt cell wall and membrane structures, thereby facilitating the release of intracellular proteins and soluble compounds into the medium.

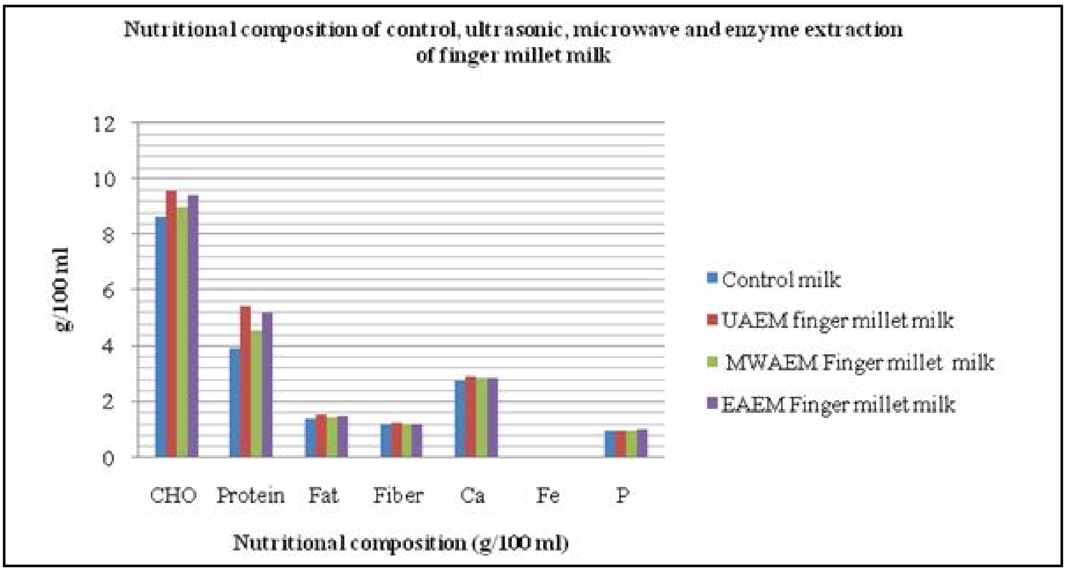


Figure 2: Nutritional composition of conventional method, ultrasonic, microwave and enzyme assisted extracted finger millet milk.

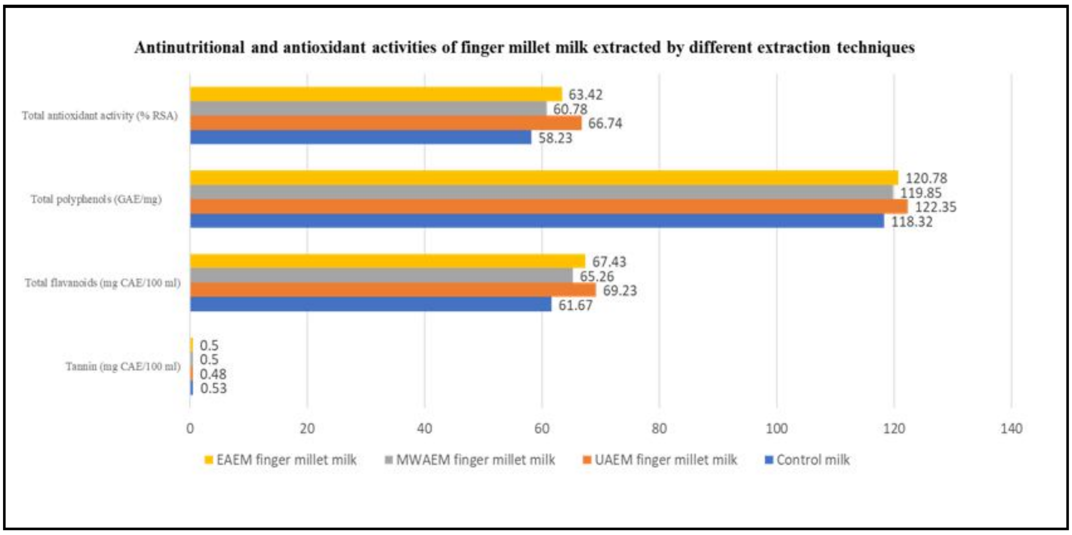


Figure 3: Antinutritional and antioxidant activity of conventional method, ultrasonic, microwave and enzyme assisted extracted finger millet milk.

The fat content of finger millet milk varied with extraction method, with UAEM yielding the highest (1.53 g/100 ml), followed by EAEM (1.49 g/100 ml), MWAEM (1.45 g/100 ml), and CEM (1.42 g/100 ml). Fiber content showed a slight increase with advanced extraction techniques, with UAEM at 1.25 g/100 ml, EAEM 1.23 g/100 ml, MWAEM 1.22 g/100 ml and the control at 1.21 g/100 ml.

The mineral content of finger millet milk was significantly affected by the extraction method. Milk obtained *via* ultrasound-assisted extraction (UAEM) showed the highest calcium level (289.36 mg/100 ml) compared to CEM, EAEM and MWAEM. Similarly, UAEM milk had the highest iron content (0.048 g/100 ml), followed by MWAEM (0.046 g/100 ml), EAEM (0.044 g/100 ml), and CEM (0.042 g/100 ml). Phosphorus content was slightly higher in UAEM (0.994 g/100 ml) than in CEM (0.987 g/100 ml).

Figure 3 illustrates a comparative evaluation of the antinutritional and antioxidant properties of finger millet milk prepared using different extraction methods: Conventional method (CEM control), ultrasound-assisted extraction of milk (UAEM), microwave-assisted extraction of milk (MWAEM) and enzyme-assisted extraction of milk (EAEM). The results showed that UAEM finger millet milk had the highest total antioxidant activity (% RSA) at 66.74%, followed by EAEM (63.42%), MWAEM (60.78%) and the control (58.23%).

The total polyphenol content (mg GAE/100 ml) was highest in UAEM milk (122.35 mg GAE/100 ml), followed closely by EAEM (120.78 mg GAE/100 ml), MWAEM (119.85 mg GAE/100 ml) and the control (118.32 mg GAE/100 ml). Total flavonoid content (mg CAE/100 ml) showed a similar pattern, with UAEM at 69.23 mg CAE/100 ml, EAEM 67.43 mg CAE/100 ml, MWAEM 65.26 mg CAE/100 ml and the control 61.67 mg CAE/100 ml. Tannin content (mg CAE/100 ml) remained relatively consistent across all methods, ranging from 0.48 mg in UAEM to 0.53 mg in the control.

3.3 Physicochemical characteristics of conventional method and ultrasonic, microwave and enzyme assisted extracted finger millet milk

Table 2 is a summary of the influence of ultrasonic-assisted, microwave-assisted, enzyme-assisted and conventional extraction technique on physicochemical characteristics of finger millet milk (ATL 1 variety) in terms of pH, TSS, acidity, specific gravity, viscosity, acid value, color, sedimentation rate, syneresis and total solids.

The pH of finger millet milk was observed to be slightly lower in the ultrasound-assisted extraction (UAEM) sample (pH 5.5) compared to the conventionally extracted milk (pH 6.2), indicating a mildly acidic environment. Total soluble solids (TSS) is a key physicochemical parameter in plant-based milk, representing the concentration of dissolved substances and directly influencing the flavour, mouthfeel and overall texture of the product. In this study, TSS was highest in microwave assisted extraction milk (MWAEM) at 5º Bx, followed by ultrasound-assisted extraction milk (UAEM) at 4.4º Bx, while conventional extraction (CEM) and enzyme-assisted extraction (EAEM) showed similar values around 4º Bx. The elevated TSS in MWAEM and UAEM samples suggests that both microwave and ultrasonication techniques improve the extraction and solubilization of dissolved solids, resulting in a higher concentration of soluble compounds in the final milk product.

Table 2: Physicochemical characteristics of conventional and ultrasonic, microwave and enzyme assisted extracted finger millet milk

Parameters	CEM finger millet milk	UAEM finger millet milk	MWAEM finger millet milk	EAEM finger millet milk	CD @ 0.05 %	CV (%)
pH	6.2 ± 0.18[a]	5.5 ± 0.10[b]	6.1 ± 0.03[b]	5.7 ± 0.12[b]	0.230	2.131
TSS (°Bx)	4 ± 0.019[b]	4.4 ± 0.14[a]	5 ± 0.001[a]	4 ± 0.003[b]	0.267	3.495
Acidity (%)	0.34 ± 0.009[a]	0.31 ± 0.006[b]	0.34 ± 0.00[a]	0.34 ± 0.58[a]	0.017	2.798
Viscosity (cP)	23.76 ± 0.16[b]	26.85 ± 0.12[b]	27.52 ± 0.23[a]	25.46 ± 0.15[b]	0.951	2.069
Specific gravity	1.027 ± 0.00[c]	1.033 ± 0.002[a]	1.029 ± 0.67[b]	1.030 ± 0.32[a]	1.140	1.402
Acid value (mg KOH/g)	0.10 ± 0.00[a]	0.07 ± 0.0004[c]	0.09 ± 0.002[a]	0.08 ± 0.001[b]	0.236	1.631
Colour value						
L*	63.21 ± 0.04[c]	67.36 ± 2.10[a]	65.32 ± 0.03[b]	66.45 ± 1.13[b]	NS	2.669
a*	0.87 ± 0.01[c]	1.2 ± 0.03[a]	0.95 ± 0.05[c]	1.0 ± 0.03[b]	0.049	2.755
b*	22.25 ± 0.43[a]	19.53 ± 0.43[b]	19.58 ± 0.40[d]	20.68±0.18[c]	0.831	2.169
Sedimentation rate (g/40 ml)	1.52 ± 0.028[a]	0.83 ± 0.009[c]	0.86 ± 0.002[c]	0.90 ± 1.67[b]	0.032	1.256
Syneresis (ml/h)	41.28 ± 0.56[a]	38.24 ± 0.07[b]	39.45 ± 0.04[b]	39.01 ± 0.67[a]	1.461	2.332
Total solids	8.24 ± 0.13[b]	9.47 ± 0.12[a]	9.02 ± 0.10[b]	9.21±0.01[a]	0.781	2.176

Each value is Mean ± SD of three replicate analysis (n=3). The values mentioned in superscripts are significantly different at $p<0.05$ in the column.

The level of acidity of finger millet milk did not change much when using different extraction procedures, and its acidity was 0.34% and when using ultrasound assisted extraction (UAEM), the acidity was a slightly lower (0.31%). This decrease shows that ultrasonication might assist to stabilize the pH of the milk and lead to a less pronounced flavor profile and probably, increased palatability. The viscosity of the finger millet milk was significantly higher in those samples collected by means of the microwave-assisted extraction

(MWAEM, 26.85 cP/100 ml) and ultrasound-assisted extraction (UAEM, 26.85 cP/100 ml) compared to the control (CEM, 23.76 cP/100 ml). The specific gravity (UAEM) and EAEM (1.033 and 1.030) are much more dense signifying composition respectively. The outcome of UAEM process leaves a slightly dense milk of finger.

Finger millet milk acid value was minimum in the extraction conducted using ultrasound (UAEM, 0.07 mg KOH/g) justifying the extra stability of lipids. However, the traditional extraction (CEM) procedure displayed a larger acid value (0.10 mg KOH/g) indicating the presence of more free fatty acids probably because of higher lipid degradation and increased rancidity susceptibility. Finger millet milk was measured on the tintometer and L*, a* and b* were used to determine the color, where L is lightness, a is red-green axis and b is the yellow-blue axis. The milk produced in UAEM (L* 67.36) was also found to have greater L* value compared to the conventional extraction milk (CEM), which was 63.21, implying that the milk produced by UAEM had a lighter color, better clarity and less turbidity. The color of finger millet milk was assessed using the tintometer, where L* indicates lightness, a* the red-green axis and b* the yellow-blue axis. UAEM milk exhibited a higher L* value (67.36) than conventional extraction (CEM) milk (63.21), suggesting a lighter appearance, improved clarity and reduced turbidity.

The extraction method had a major effect on the rate of finger millet milk sedimentation. The lowest rates of sedimentation (0.86 g/40 ml) were observed in UAEM and MWAEM samples, meaning they have better colloidal stability and more dispersed suspended particles. Conversely, the highest sedimentation was recorded in conventionally extracted (CEM) milk (1.52 g/40 ml) which indicated lower dispersion efficiency with aggregation of greater particles. The increased stability of UAEM-treated milk could be explained by the fact that ultrasonication is quite effective to break the bigger particles and aggregates in order to get smoother and much more homogeneous beverage.

The rate of syneresis in finger milled milk was higher in conventionally extracted (CEM) extract (41.28 ml/h) than the UAEM extract (38.24 ml/h), showing that the whey was more separated into the milk matrix using the conventional method. Finger millet milk contained the highest amount of total solids using ultrasound-assisted extraction (UAEM), then EAEM, MWAEM, and the conventional extraction (CEM) (9.47 g/100 ml, 9.21 g/100 ml and 8.24 g/100 ml, respectively).

The statistical examination revealed significant impact of ultrasound-assisted extraction (UAEM) on the physicochemical characteristics of finger millet milk ($p \geq 0.05$) such as pH, total soluble solids (TSS), acidity, viscosity, color parameters (L* a* b*), specific gravity, rate of sedimentation, syneresis and total solids. This indicates that ultrasonication improves nutrient extraction and retention, and the stability, texture and overall quality of finger millet milk over conventional, microwave and enzyme assisted processes.

3.4 Sensory evaluation

Figure 3 presents a spider plot illustrating the sensory evaluation of finger millet milk based on colour, appearance, flavour, consistency, taste and overall acceptability. The results demonstrate that milk processed via ultrasound-assisted extraction (UAEM) consistently scored higher across most sensory attributes compared to conventional extraction (CEM), microwave-assisted extraction (MWAEM), and enzyme-assisted extraction (EAEM) methods. UAEM finger millet milk scored higher in color and appearance (8.6), flavor (8.5), and consistency (8.4) compared to CEM milk, which received lower ratings. Overall acceptability was also greater for UAEM milk (8.7) versus CEM (8.3), indicating a clear consumer preference. These results suggest that ultrasonication improves visual appeal, flavor retention, and texture, enhancing the overall sensory quality of the milk.

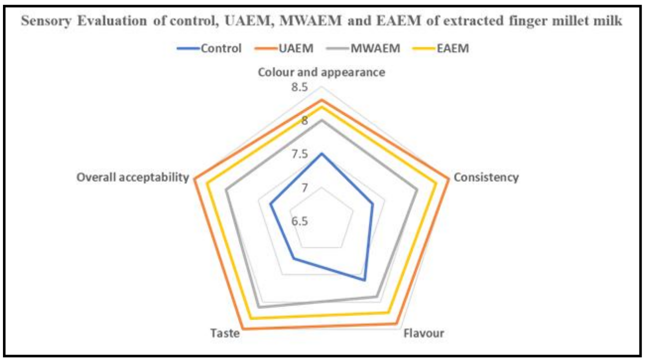


Figure 3: Sensory evaluation of control, UAEM, MWAEM and EAEM extracted finger millet milk.

The greatest differences were observed in overall acceptability, color, appearance, flavor and viscosity, partly due to variations in total solids (8.24 g/100 ml in CEM milk versus 9.47 g/100 ml in UAEM milk) and the effects of processing techniques. Both thermal and non-thermal methods, including pulsed electric fields, ultra-high-pressure homogenization, and ultrasonication, contribute to enhanced taste, consistency and flavor.

4. Discussion

The results demonstrate that the extraction method significantly affects the quality of finger millet milk. UAEM, MWAEM and EAEM showed improvements in milk yield, protein content, viscosity and sensory acceptability compared to the control (CEM), emphasizing the importance of optimizing processing parameters like soaking time and extraction temperature to maximize the nutritional and functional qualities of millet milk.

The improved extractability in UAEM is attributed to the mechanical effects of ultrasound, which disrupt cell walls and facilitate the release of intracellular nutrients, enhancing milk yield. Similar observations in previous studies on ultrasound-assisted plant-based milk confirm the technique's potential to improve process efficiency and product quality. Statistical analysis further highlights the effectiveness of ultrasound and enzyme treatments in enhancing protein solubility and extraction efficiency, consistent with findings reported by Vallath and Shanmugam (2022) in plant-based milk processing.

The comparatively higher viscosity in MWAEM is likely the result of microwave-induced structural modifications, particularly involving starch protein interactions, a phenomenon also noted in earlier studies on microwave-treated plant-based beverages. The significant differences in panel responses highlight that UAEM and EAEM markedly improved the sensory qualities of finger millet milk particularly in terms of flavour, taste, colour, and visual appearance. These findings are in agreement with earlier work by Rojas *et al.* (2022), who also reported superior sensory outcomes in ultrasound-treated plant-based milks. Among the tested methods, ultrasound-assisted extraction (UAEM) clearly emerged as the most effective, as it not only maximized milk yield and protein recovery, but also enhanced viscosity and consumer acceptability, establishing it as a promising green extraction technique for finger millet milk processing.

The carbohydrate content improvement observed in UAEM can be attributed to the mechanical effects of ultrasonication, which facilitate cell wall disruption and breakdown of polysaccharides, leading to the release of simple, soluble sugars. Although, this process reduces the proportion of complex carbohydrates, it simultaneously enhances the digestibility and bioavailability of carbohydrates. These findings are consistent with those reported by Julaluk and Khemacheewakul (2022), who demonstrated the effectiveness of ultrasound-assisted extraction in improving the recovery of bioactive compounds from green soybean pods. Similarly, the present study underscores the potential of UAEM as a green and efficient technique, not only for maximizing nutrient extraction from finger millet milk but also for improving the digestibility and nutritional accessibility of carbohydrates and other bioactive compounds.

Preece *et al*. (2017) reported that just one minute of ultrasonic treatment of soy slurry increased total solids and protein yield by about 10%. Notably, intact cells remained even after 15 min of ultrasound exposure, indicating that improved protein extractability resulted mainly from enhanced solubility rather than complete cell disruption. This demonstrates that ultrasound can optimize protein recovery efficiently and non-destructively, preserving cell structure while improving solubilization. Overall, these findings highlight ultrasound-assisted processing as a sustainable and effective approach for enhancing protein extraction in finger millet milk, with potential applications across other plant-based beverages.

The higher fat recovery in UAEM is attributed to the mechanical effects of ultrasonication, which disrupt cell walls and reduce particle size, facilitating the release of lipids. This process not only increases fat extraction but also enhances the emulsification, stability and texture of finger millet milk. Supporting evidence from Anitha and Manivannan (2023) showed that ultrasonic-assisted extraction of potato milk yielded 0.3% fat with a fatty acid profile rich in linoleic acid (41.2%), palmitic acid (23.22%) and oleic acid (6.6%). These results demonstrate that ultrasonication improves lipid recovery while preserving nutritionally important fatty acids, enhancing the overall quality of plant-based milks.

The observed enhancement can be attributed to the ultrasonic cavitation effect, which disrupts plant cell wall structures and loosens bound fibers. This process increases the solubilization of both soluble and insoluble dietary fibers, thereby improving their availability in the liquid phase of finger millet milk. Comparable findings were reported by Anitha and Manivannan (2023), where ultrasound-assisted extraction of potato milk resulted in a significantly higher fiber content (9 ± 0.234 g/100 ml) compared to untreated milk. This consistency in results highlights the efficiency of ultrasonication as a green processing technique to enhance fiber availability and functional quality in plant-based milk formulations.

The relatively lower calcium content observed in conventionally extracted milk may be due to incomplete breakdown of the grain structure, which limits the release of calcium that is tightly bound to phytates and dietary fiber. In contrast, ultrasonication effectively disrupts plant cell walls and breaks down protein-mineral and phytate complexes, thereby enhancing calcium release into the milk extract. These findings are consistent with the work of Lavrentev *et al*. (2024), who reported that ultrasonic-assisted extraction can significantly increase calcium levels in various plant-based milks including soy, rice, oats, wheat, peas, and pumpkin seed milks by 30 to 100% depending on the raw material. The present study similarly demonstrates that UAEM is an effective technique to maximize calcium bioavailability in finger millet milk, highlighting the potential of ultrasonication for improving the nutritional quality of plant-based beverages.

The superior iron content in UAEM-treated milk can be attributed to the high-frequency ultrasonic waves, which effectively disrupt phytate iron complexes, thereby enhancing the bioavailability of iron in the milk. These findings are in agreement with Flipp *et al*. (2024), who reported that ultrasonic-assisted treatment of plant-based milks led to a significant increase in iron and other mineral contents. Similarly, the present study demonstrates that UAEM improves the mineral extractability and nutritional quality of finger millet milk compared to conventional processing methods. Ultrasonic-assisted extraction may be somewhat more effective at releasing phosphorus from the grain matrix. This improvement can be attributed to the mechanical effects of ultrasonication, which disrupt plant cell walls and enhance the solubilization of bound minerals.

These observations are consistent with the findings of Ashwin *et al*. (2022), who reported that ultrasonication of plant-based milks such as soy and almond enhanced physical stability, improved overall nutritional composition (particularly micronutrients), increased emulsification efficiency, and reduced microbial load. Similarly, the current study demonstrates that UAEM enhances the micronutrient content and functional quality of finger millet milk compared to conventional extraction methods.

The observed enhancements in macronutrient and mineral content of finger millet milk obtained through advanced extraction techniques indicate improved nutrient bioavailability and extraction efficiency, positioning these methods as nutritionally superior alternatives to conventionally extracted milk. Statistical analysis further confirmed that ultrasound-assisted extraction (UAEM) significantly affects the nutritional profile including protein, fat, fiber, calcium, iron and phosphorus compared to other extraction methods (*p*d”0.05), highlighting its effectiveness in optimizing both the quantity and quality of nutrients in finger millet milk.

These findings underscore the effectiveness of UAEM in preserving and enhancing bioactive compounds especially antioxidants, polyphenols and flavonoids in finger millet milk. The improved extraction efficiency is attributed to cavitation-induced cell wall disruption, which promotes the release of bound bioactive molecules.

Nayak *et al*. (2024) reported that green extraction techniques such as ultrasound and microwave-assisted extraction are more effective for isolating bioactive compounds from plant sources. Similarly, Thomas *et al*. (2014) found that ultrasonic treatment increased antioxidant activity in Bacopa monnieri by approximately 9.08% compared to microwave-assisted and conventional extraction methods. Furthermore, Khemacheewakul (2022) demonstrated that ultrasound-assisted extraction of green soybean pods enhanced total flavonoid and polyphenol content by 35% and 28%, respectively, compared to conventional methods. These results indicate that ultrasound-assisted extraction (UAEM) not only improves the antioxidant capacity of finger millet milk but also preserves important bioactive compounds, making it a highly effective technique for producing nutritionally superior plant-based milk.

This slight decrease in pH may be attributed to the cavitation effects of ultrasonication, which can induce mild hydrolysis of macromolecules, potentially releasing fatty acids and amino acids into the milk. Such a shift in pH could contribute to enhanced microbial stability and safety of UAEM-treated finger millet milk. Similar trends have been reported by Anitha and Manivannan (2023), who found that potato-based milk processed with ultrasonication maintained a near-neutral pH (7.1 ± 0.001), consistent with other studies on plant-based beverages. These observations underscore the ability of ultrasonication to preserve or slightly modulate the pH of plant-derived milks without causing excessive acidification, thereby supporting product stability and shelf-life. These findings are consistent with Rojas *et al*. (2022), who reported that ultrasound processing is generally more effective than conventional thermal methods in preserving TSS and other bioactive components in plant-based beverages, contributing to enhanced flavor, consistency, and nutritional quality.

Similar observations have been reported by Shunmugapriya *et al*. (2020), who measured the acidity of enzyme-treated millet and pulse beverages, with values ranging from 0.50% to 0.83%, highlighting the influence of processing techniques on the acid content and sensory characteristics of plant-based beverages. These results suggest that UAEM not only preserves the nutritional quality but also modulates acidity to improve the sensory attributes of finger millet milk.

Total solid content increase can be attributed to the ability of microwave and ultrasound waves to more effectively disrupt cell walls, releasing additional soluble and suspended solids into the milk. The higher particle concentration contributes to a thicker consistency and enhanced mouthfeel. These observations are supported by Faccin *et al*. (2009), who reported that increased viscosity in rice bran beverages was largely due to starch retrogradation, indicating that starch components play a significant role in texture development. Similarly, the elevated viscosity in UAEM and MWAEM finger millet milk suggests that ultrasonication and microwaves can improve the textural properties and body of plant-based milks by modulating starch and suspended solids.

UAEM is more effective at extracting solutes, it leads to a higher concentration of dissolved or suspended particles in the final product compared to the conventional method. Ramon *et al*. (2021) reported that innovative manufacturing technologies, including ultrasound and high-pressure processing can alter the sensory and nutritional properties of plant-based milk and also potentially influencing the specific gravity of milk.

Acid value of the finger millet milk are consistent with findings from Isabel *et al*. (2021), who noted that the acid value of plant-based milks varies depending on the source, with soy milk generally exhibiting lower values compared to almond or oat milk. Similarly, Ramon *et al*. (2021) reported that ultrasonication and high-pressure processing can influence the acid value of non-dairy milks by affecting microbial activity and lipid stability during production. This parameter is particularly important as it directly impacts the taste, shelf life and overall quality of plant-based milks, highlighting that UAEM not only improves nutrient extraction but also enhances the chemical stability of lipids in finger millet milk.

In terms of the a* value, UAEM milk showed a slight shift toward a redder hue, suggesting a higher concentration of certain pigments extracted by the ultrasonication process. Conversely, the b* value for UAEM decreased relative to CEM, indicating a reduction in yellow pigmentation and a possible alteration in the pigment profile due to the extraction technique. These observations are comparable to findings by Oyedeji *et al*. (2018), who reported that the colour of soy milk was influenced by germination and soaking conditions, with L* values ranging from 78.9 to 83.21, a* values from -1.79 to -2.52, and b* values between 7.78 and 12.77. While the lightness and a* values of soy milk were similar to those of UAEM finger millet milk, the b* values were lower in soy milk, highlighting the unique pigment composition and extraction dynamics of finger millet milk.

These findings are consistent with Jeske *et al*. (2017), who reported that sedimentation rates in commercially available plant-based beverages varied from 0.20 ± 0.19 mm to 4.22 ± 2.9 mm, emphasizing the impact of processing techniques on particle dispersion and product stability. This suggests that CEM produces a less stable emulsion, whereas ultrasound-assisted extraction (UAEM) promotes better emulsion stability, reducing phase separation and improving the overall consistency of the milk. These findings are consistent with Vallath and Shanmugam (2022), who reported that ultrasonication (20 kHz at 130-195 W for 2-8 min) significantly enhanced the sedimentation and stability of chickpea-based beverages, highlighting the effectiveness of ultrasound in improving the structural and physicochemical properties of plant-based milk alternatives. This trend indicates that ultrasonication is more effective at solubilizing and retaining solids during the extraction process, leading to a nutritionally enriched and texturally improved milk product.

Similar observations were reported by Anitha and Manivannan (2023), who found that ultrasonic-assisted extraction of potato-based milk resulted in a total solids content of 7.34 g/100 ml, demonstrating the technique's ability to enhance solid retention. Additionally, Lavrentev *et al*. (2023) noted that ultrasonic pretreatment improved the total solids content in various plant-based milks including soy, rice and pea by optimizing extraction efficiency. These findings underscore the significance of total solids as a critical parameter influencing nutritional value, flavor and mouthfeel in plant-based milk alternatives.

These observations are in line with Sethi *et al*. (2016), who reported that soluble and insoluble fibers in plant-based milks significantly affect consistency, with insoluble particles contributing to a gritty or fluffy texture. In contrast, UAEM enhances particle dispersion, producing a smoother, more uniform milk with superior sensory qualities.

Five milk-based beverages were developed with malted finger millet and evaluated for sensory attributes by a semi-trained panel of 10 judges. Banana-based beverages containing 5% malted finger millet were the most preferred, showing the highest overall acceptability for color, appearance, flavor, consistency, and taste. Similar results were reported by Bansal and Kaur (2018) and Jain *et al*. (2016), who found that adding 5% malted finger millet flour to milk porridge significantly, improved sensory scores. Kundu *et al*. (2008) also noted that almond milk, as a dairy alternative, achieved high sensory acceptability due to its fat content, which enhanced mouthfeel and overall preference.

Statistical analysis further confirmed that the ultrasound-assisted extraction (UAEM) method significantly improves sensory attributes (*p*d”0.05), including colour and appearance, flavour, consistency, taste, and overall acceptability, compared to the conventional extraction method. This highlights the effectiveness of UAEM not only in enhancing nutritional and physicochemical properties but also in improving the sensory quality and consumer appeal of finger millet milk beverages.

5. Conclusion

This paper analyzes the physicochemical, nutritional and sensory characteristics of finger millet milk which is extracted via traditional extraction (CEM), ultrasonic-assisted (UAEM), microwave-assisted (MWAEM) and enzyme-assisted (EAEM). The findings show that UAEM finger millet milk contains more protein, fat, calcium, iron, and phosphorus, but slightly less total carbohydrates as compared to CEM, MWAEM and EAEM. The physicochemical parameters such as specific gravity, color, total solids, TSS, and viscosity were also better in UAEM milk. Sensory analysis revealed that UAEM milk scored better on overall acceptability as well as individual sensory properties in comparison with CEM milk. These results imply that ultrasonic-assisted extraction improves the nutritional and sensory properties of finger milk, and it can be proposed that it can be used as a healthy and consumer-friendly dairy substitute. Shelf stability and storage conditions critically affect the quality, safety, and nutrient retention of plant-based milks. Factors such as temperature, light exposure and packaging influence the microbial stability, viscosity, pH and sensory properties making their evaluation essential for commercial viability. Compared to commonly available plant-based milks like almond, soy and oat. UAEM finger millet milk offers superior mineral and protein content along with enhanced sensory attributes, establishing it as a nutritionally enriched and highly acceptable non-dairy alternative.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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