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Physicochemical, nutritional and sensory characteristics of enzyme-assisted extracted finger millet (*Eleusine coracana* L.) milk

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Abstract

The rising demand for dairy-free alternatives has driven interest in developing plant-based milks that are nutritious, sustainable, and consumer-friendly. Millets, particularly finger millet, are nutrient-dense cereals rich in dietary fiber, calcium, iron, and antioxidants, offering significant health benefits and environmental sustainability. This study evaluates the physicochemical, nutritional and sensory properties of finger millet milk prepared using conventional and enzyme-assisted extraction (EAEM) methods. EAEM was employed to enhance cell wall disruption and release bioactive components through enzymatic hydrolysis, resulting in improved extraction efficiency. These findings demonstrate that EAEM significantly increases protein (5.20 g/100 ml), fat (1.49 g/100 ml), calcium (0.226 g/100 ml), iron (0.045 g/100 ml), and phosphorous content (0.990 g/100 ml) in finger millet milk compared to conventional extraction method. Physicochemical properties, including specific gravity (1.033), total soluble solids (4.2°Brix), and viscosity (25.46 cP/100 ml) were also notably enhanced in EAEM finger millet milk. Sensory evaluation revealed superior overall acceptability for EAEM finger millet milk due to its enhanced taste, texture and appearance. These results found the potential of enzyme-assisted extraction in improving the nutritional and sensory quality of finger millet milk, making it a viable alternative to traditional dairy milk products. This study highlights the suitability of millet-based milk as an economical, eco-friendly, and consumer-preferred non-dairy beverage, contributing to food security and sustainability goals.

1. Introduction

The global demand for dairy-free alternatives has significantly increased the health concerns associated with certain nutrients in milk. Compared to dairy milk, plant-based milk production has a substantially lower carbon footprint, supporting food security and environmental sustainability goals. Clinical studies have linked components in cow's milk to adverse health effects such as lactose intolerance, cow's milk allergy, and coronary heart diseases. These risks can be reduced by choosing non-dairy alternatives (Coluccia *et al.*, 2022).

The rising prevalence of vegan diets and health-conscious lifestyles has made plant-based milk an appealing option for many consumers. Plant sources are typically rich in health-promoting compounds like dietary fiber, vitamins, minerals, and antioxidants, contributing to

their use in nutraceuticals and functional foods. According to Euromonitor, the Food Institute reported a 6% growth in plant-based milk sales in 2022, reaching a market value of \$19.1 billion. The production of plant-based milk involves dispersing plant material to create particles of varying sizes and compositions. Factors such as the source material, processing methods, and storage conditions influence the physical properties and shelf stability of these products (Sethi *et al.*, 2016).

Millets are nutrient-rich grains that provide numerous health benefits. They are naturally gluten-free, non-acidic and, have a low glycaemic index, making them easy to digest. Millets are a wholesome dietary choice, offering high levels of energy, protein, fatty acids, vitamins, minerals, dietary fiber and polyphenols. Although, millet proteins are relatively low in essential amino acids like lysine and threonine, they are abundant in sulphur-containing amino acids such as methionine and cysteine. Millets are rich in phytochemicals, micronutrients, and antioxidants, including phenolic acids and glycosylated flavonoids, which enhance their overall nutritional profile (Shah *et al.*, 2021). Globally, millet ranks as the sixth most productive grain, with a total output of approximately 28.4 million metric tonnes in 2021, of which India accounted for the largest share, producing 11.64 million metric tonnes (Ingle *et al.*, 2023).

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Finger millet (*Eleusine coracana* L.), commonly known as ragi, is a nutrient-dense cereal crop celebrated for its health benefits and is extensively cultivated in Africa and India (Ramashia *et al.*, 2021). A dietary staple in Indian households, finger millet is typically consumed without dehulling, with India contributing approximately 60% of global production. Recognized for its small, dark brown grains, finger millet boasts higher polyphenol levels than cereals such as barley, rice, maize and wheat. Nutritionally, finger millet is rich in dietary fiber, starch, calcium, and iron, making it increasingly popular among other millets. Its calcium content ranges from 220 to 450 mg per 100 g, while iron content varies from 3% to 20% (Gaikwad, 2024). Among cereals produced in Asia and Africa, finger millet ranks fourth, followed by sorghum, pearl millet, and foxtail millet. The finger millet crop has an annual global production of 4.5 million tonnes, with Africa contributing 2.5 million tonnes and India producing 1.2 million tonnes. Sub-Saharan Africa accounts for 55-60% of the global output (Ceasar *et al.*, 2024).

Innovative food processing technologies focus on developing palatable, safe, nutritious, healthy, and minimally processed foods. This has led to growing interest in non-thermal methods, which retain the flavor and nutritional value of foods during production. Enzyme-assisted extraction of plant-based milk extraction process can enhance cell wall disruption through hydrolytic activity under optimal experimental conditions. Enzymes alter the molecular structure at the active site of the substrate, improving their interaction with plant substrates. This enzyme action facilitates the release of active components by breaking down the cell walls. Additionally, hydrolytic enzymes degrade polysaccharides in cell walls, improving the nutritional quality of the final products (Fan *et al.*, 2024). Use of enzymes in preparing non-dairy beverages, including rice milk and other cereal-based drinks. This enzymatic process involves the use of liquefying enzymes, preferably during gelatinization. During gelatinization, the semi-crystalline structure of starch granules becomes amorphous, making starch more susceptible to digestion by amylases. The enzymatic liquefaction process not only increases yield but also reduces viscosity. Additionally, it enhances the total solid content as amylases break down starch, producing maltodextrins (Mehany *et al.*, 2024).

Finger millet contains 81.5% carbohydrates, 65-75% starch, 9.8% protein, 1-1.7% fat, 2.7% minerals, and 4.3% fiber, making its nutritional profile comparable to other millets and cereals like wheat and rice (Choudhury and Chaudhary, 2023). Natural compounds in fruits, vegetables, grains, millet especially finger millet offer benefits that extend beyond basic nutrition. Finger millet is a nutrient-rich and highly versatile grain; it is an excellent choice for gluten-free food (Banu *et al.*, 2024). It had a low glycemic index value, so it regulates blood sugar levels, reduces inflammation, and boosts immunity (Saidaiyah *et al.*, 2024).

Finger millet is a nutrient-dense grain with strong antioxidant, anti-diabetic, anti-inflammatory and antimicrobial properties due to its high phenolic, flavonoid, and antioxidant content. It helps regulate blood sugar, and cholesterol, prevents protein glycation and cataract formation, and supports digestive health by inhibiting harmful bacteria. Rich in iron and calcium it will enhance hemoglobin levels, strengthen bones, and prevent osteoporosis. Bioactive compounds present in the finger millet milk contribute to wound healing,

neurological health, and anti-ageing effects. Additionally, monacolin production through fermentation lowers cholesterol, making finger millet a highly functional and health-promoting food (Shingote *et al.*, 2021).

This study focuses on millet-based milks as an economical, nutritious, and environmentally friendly alternative to cow's milk. We prepared finger millet milk using both conventional (control) and enzyme-assisted extraction methods. The physicochemical properties, nutritional composition and sensory attributes were analyzed to evaluate the effects of enzyme-assisted treatment on finger millet milk extraction.

2. Materials and Methods

2.1 Plant material and authentication

This research was conducted at the Departemnt of Food Science and Nutrition, Community Science College and Research Institute, Madurai. The grains of finger millet (*Eleusine coracana* L. Gaertn., family: Poaceae), variety ATL 1, were procured from the Centre of Excellence in Millets, Athiyandal, Tiruvannamalai District, Tamil Nadu, India. ATL 1 finger millet is a high-yielding, drought-tolerant variety specifically developed for its nutritional quality and agronomic adaptability released by the Athiyandal Research Station. The plant material was authenticated based on morphological characteristics according to the standard descriptors. A Voucher Specimen has been retained in the Department of Human Development and Family Studies, Community science College and Research Institute, Madurai. All chemicals used in the study were of analytical grade.

2.2 Enzyme-assisted extraction (EAEM) and conventional extraction method (CEM) of finger millet milk preparation

For the preparation of finger millet milk, both enzyme-assisted extraction (EAEM) and conventional extraction (CEM) methods were used. The finger millet grains were cleaned to remove broken kernels and impurities, then washed thoroughly with water. A 100 g portion of the grains was soaked for 19 h, and after draining, they were germinated for 24 h at room temperature. The germinated grains were blended for 120 sec to create a slurry. For the EAEM process, the finger millet slurry was treated with heat-stable alpha-amylase enzyme across varying concentrations (0.5-1%), incubation temperature (60-75°C) and incubation time (50-60 min) to optimize extraction conditions based on CCD-RSM treatments allowed to hydrolysis for 2 h. The enzymatically treated slurry was filtered through a muslin cloth by hand pressing; the enzyme was inactivated by heating the milk to 100°C for 15 min, cooled then homogenized for 5 min, and pasteurized at 85°C for 15 min. The final enzyme-assisted finger millet milk was stored in a glass bottle at 4°C for further analysis.

In the conventional extraction process, finger millet (100 g) was soaked for 19 h and germinated for 24 h at room temperature. The germinated grains were blended into a slurry, filtered through muslin cloth and the extract was homogenized for 5 min, pasteurized at 85°C for 15 min, and stored at 4°C for analysis, serving as the control sample. The process flow chart for the preparation of enzyme-assisted extraction of finger millet and images was illustrated in Figures 1 and 2.

2.3 Procedure for the preparation of conventional and enzyme-assisted extraction of finger millet milk

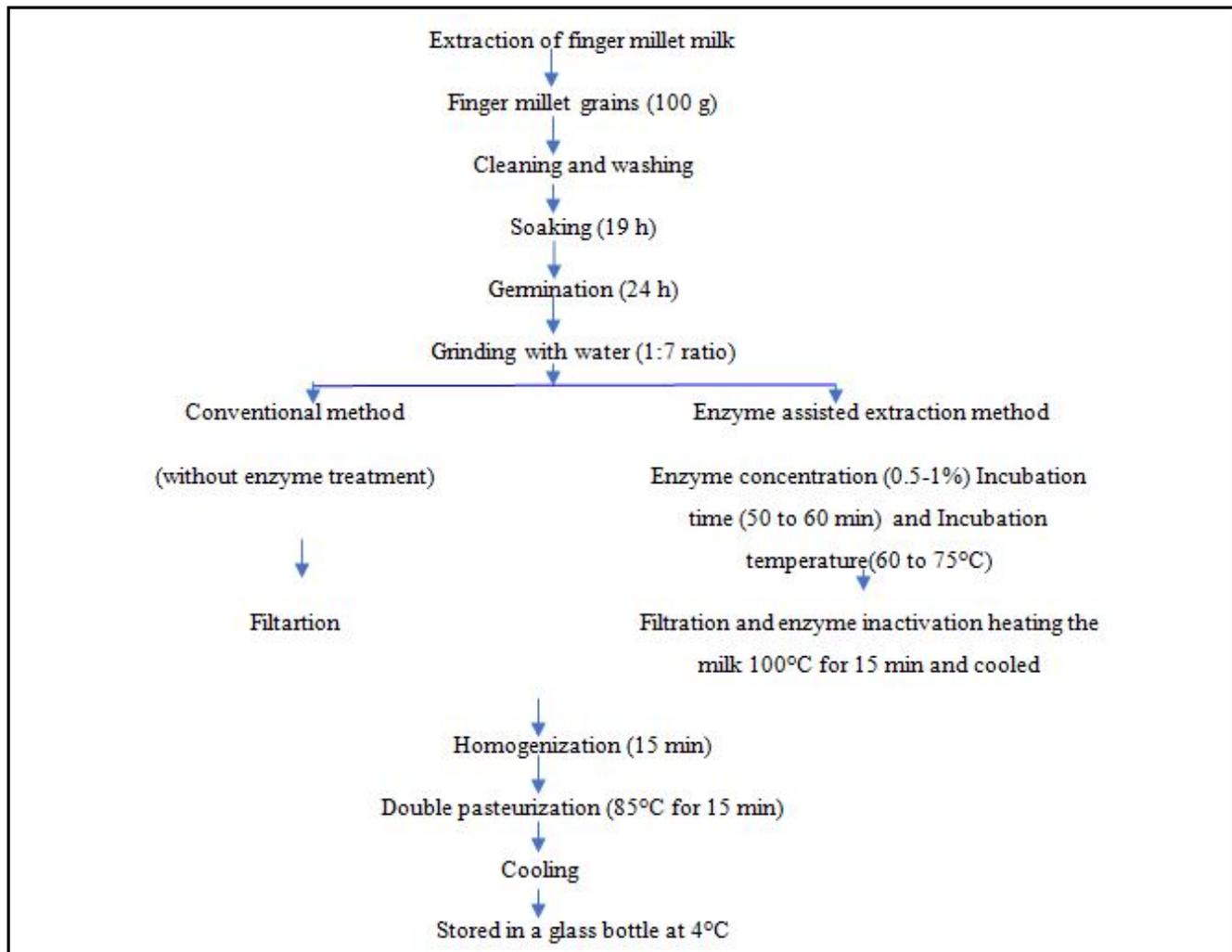


Figure 1: Process flow chart for the preparation of enzyme-assisted extraction of finger millet milk.



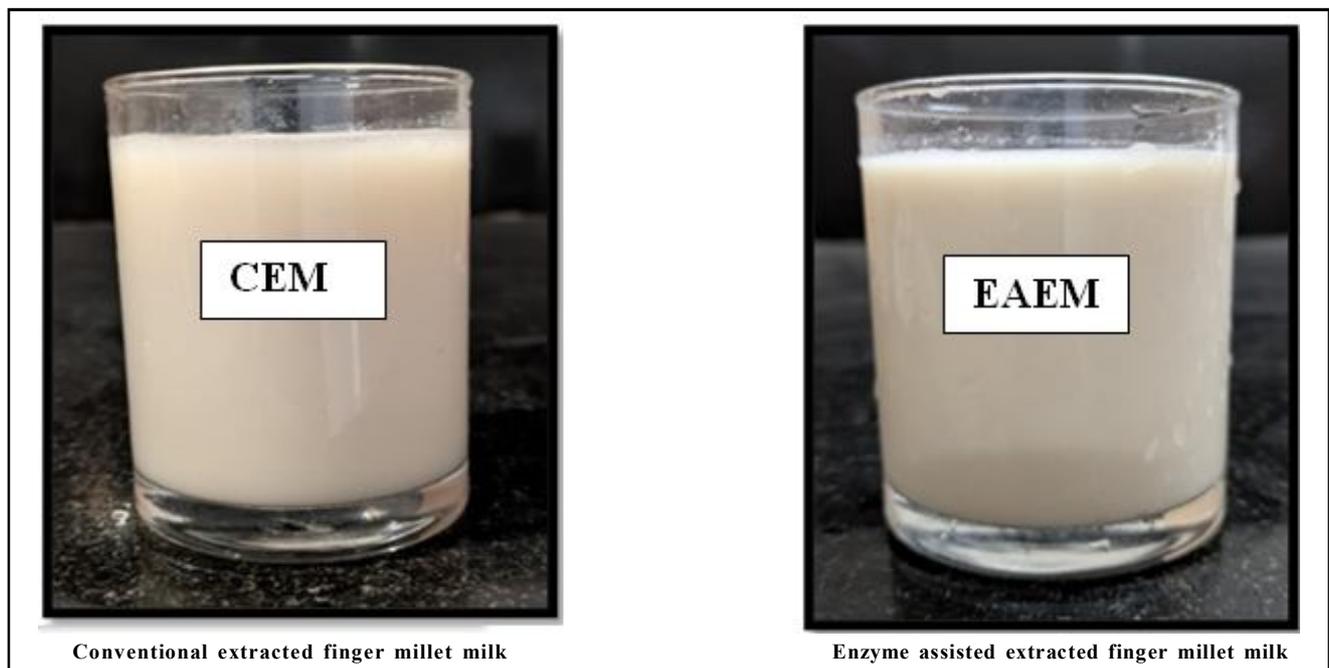


Figure 2: Conventional and enzyme-assisted extraction of finger millet milk.

2.4 Physicochemical and nutritional composition analysis

The following analytical methods were employed to evaluate the physicochemical properties of finger millet milk samples: The pH was measured using a digital hand-held pH meter. Total soluble solids (TSS) were determined using a refractometer (Erma, Tokyo, Japan). Total acidity was estimated following the procedure described by Ranganna (1986). Viscosity was measured using a Brookfield viscometer with spindle number 62 operated at 100 rpm. The acid value was determined according to the method outlined by Sadasivam (1996).

Colour parameters ($L^*a^*b^*$) were assessed using a Hunter lab colorimeter (Model: Lovibond RT 100) equipped with Lovibond RT colour software (version 3.0). The sedimentation index was evaluated and expressed as grams of sediment per volume of centrifuge tube, as per the method described by Jeske *et al.* (2017). Syneresis was determined as per Sadasivam (1996). The protein content of the finger millet milk was analyzed by the Microkjeldhal method (AOAC, 2005), fiber content was analyzed according to 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).

2.5 Sensory evaluation

The control and enzyme-assisted extracted (EAEM) finger millet milk samples were subjected to organoleptic evaluation by a panel of 15 semi-trained members using a 9-point Hedonic rating scale, as outlined by Ranganna (1986). The sensory assessment covered attributes such as colour and appearance, flavour, taste, consistency, and overall acceptability. Each parameter was rated on a scale where 1 indicated “extremely dislike”, 5 denoted “neither like nor dislike”, and 9 represented “extremely like.”

2.6 Statistical analysis

The data were statistically analyzed using a paired t-test under a completely randomized design (CRD) with three replications. The analysis was carried out using WASP software. Furthermore, a least significant difference (LSD) test was applied at a 5% significance level ($p \leq 0.05$) to identify any statistically significant differences between the samples.

3. Results

3.1 Physicochemical composition of conventional method and enzyme-assisted extracted finger millet milk analysis

Table 1 illustrates the effects of enzyme-assisted extraction and conventional extraction methods on various physicochemical properties of finger millet milk prepared from the ATL 1 variety. The evaluated parameters include pH, total soluble solids (TSS), acidity, specific gravity, viscosity, acid value, colour values, sedimentation rate, syneresis, and total solids.

Each value is expressed as the mean \pm standard deviation (SD) based on three replicate analyses ($n=3$). Superscript letters within the same column indicate values that are significantly different at $p < 0.05$.

CEM-Conventional extraction method; EAEM-Enzyme-assisted extraction method; a-Control sample without enzyme treatment; b-Optimized value derived from enzyme concentration (0.5%), incubation time (52 min) and incubation temperature (62°C); c-Values are approximate and not accompanied by standard deviation; °Bx-Degree Brix, cP-Centipoise.

The pH of enzyme-assisted finger millet milk (5.7) is slightly lower than that of the conventional method (6.2). This reduction is likely due to enzymatic hydrolysis releasing acidic byproducts such as

free amino acids. The TSS value of enzyme-assisted finger millet milk (4.2°Bx) is slightly higher than (4°Bx). This increase suggests that the enzymatic process improves the extraction of soluble solids, such as simple sugars, soluble fibers, and amino acids, from finger millet grains.

The acidity of enzyme-assisted finger millet milk (0.39%) is slightly higher than the conventional method (0.34%). The increase may result from enzymatic hydrolysis releasing organic acids during the breakdown of proteins and carbohydrates.

The physicochemical properties like pH, TSS, acidity of finger millet milk were compared with cow's milk. Cow's milk generally exhibits a pH of 6.6-6.8, while finger millet milk showed lower values it may be due to presence of inherent organic acids in finger millet and the

enzymatic hydrolysis of complex carbohydrates, which may release additional acidic compounds. TSS in cow milk, which range from 10 to 13°Bx due to the presence of lactose, proteins and minerals, were higher than in finger millet milk. Acidity in finger millet milk was notably higher than in cow milk (0.14-0.17%), possibly due to the production of lactic and phenolic acids during enzymatic treatment, which enhances nutrient release but also increases titratable acidity.

The viscosity of enzyme-assisted finger millet milk (25.46 cP/100 ml) is higher than that of the conventional method (23.76 cP/100 ml). The increase in viscosity can be attributed to enzymatic hydrolysis of macromolecules such as carbohydrates and proteins which improves water-binding capacity and solubilizes structural polysaccharides, thereby leading to a thicker consistency of the finger millet milk.

Table 1: Physicochemical characteristics of conventional and enzyme-assisted extraction method of finger millet milk

| Parameters | Conventional method (Finger millet milk) ^a | Enzyme assisted method (Finger millet milk) ^b | CD value (0.05) | %Change (c) |
|-------------------------------|---|--|-----------------|-------------|
| pH | 6.20 ± 0.018 | 6.0 ± 0.032 | 0.001 | 3.23 |
| TSS (°Bx) | 4.0 ± 0.02 | 4.2 ± 0.12 | 0.002 | 5.00 |
| Acidity (%) | 0.24 ± 0.02 | 0.29 ± 0.001 | 0.024 | 18.56 |
| Viscosity (cP/100 ml) | 23.76 ± 0.56 | 25.46 ± 0.72 | 0.835 | 7.15 |
| Colour value | | | | |
| L* | 63.21 ± 0.90 | 66.45 ± 2.03 | 0.005 | 5.13 |
| a* | 0.87 ± 0.02 | 1.0 ± 0.02 | 0.038 | 14.94 |
| b* | 22.25 ± 0.10 | 20.68 ± 0.04 | 0.723 | -7.05 |
| Sedimentation rate (g/100 ml) | 1.30 ± 0.028 | 0.56 ± 0.009 | 0.002 | 34 |
| Syneresis (ml/h) | 41.28 ± 0.56 | 38.24 ± 0.07 | 0.001 | 7.36 |
| Total solids | 8.24 ± 0.13 | 9.47 ± 0.12 | 0.002 | 14.92 |
| Specific gravity | 1.027 ± 0.00 | 1.033 ± 0.002 | 0.004 | 0.58 |
| Acid value (mg KOH/g) | 0.10 ± 0.001 | 0.07 ± 0.0004 | 0.003 | 28 |

The L* value of enzyme-assisted finger millet milk (66.45) is higher than the conventional method (63.21), indicating a lighter appearance. Enzymatic breakdown of pigments enhanced the solubilization of particulate matter, leading to a more uniform dispersion of light. Increased lightness is often associated with improved consumer appeal and a perception of freshness in non-dairy milk. The slight increase in the a* value (0.87 to 1.0) indicates a marginal shift toward red tones. This change might result from enzymatic hydrolysis affecting phenolic compounds naturally present in finger millet. The b* value decreased from 22.25 to 20.68 in enzyme-assisted milk, suggesting a reduction in yellowness. This could be due to the partial breakdown of yellow pigments, such as carotenoids, during enzymatic treatment. Lower yellowness may enhance the perception of uniformity in color, which is a desirable attribute in plant-based milk beverages for enhancing consumer acceptability.

The sedimentation rate of finger millet milk prepared using the enzyme-assisted method (0.56 g/100 ml) is significantly lower than that of the conventional method (1.30 g/100 ml). This reduction reflects the improved colloidal stability achieved through enzymatic hydrolysis, which breaks down more extensive, insoluble particles into smaller, more soluble components. Syneresis, an indicator of

when separation, is reduced in enzyme-assisted finger millet milk (38.24 ml/h) compared to the conventional method (41.28 ml/h).

The total solids content in enzyme-assisted finger millet milk (9.47%) is notably higher than in the conventional method (8.24%). This increase indicates better extraction efficiency, where enzymatic hydrolysis facilitates the release of soluble nutrients, including proteins, sugars, and peptides, from the finger millet matrix. The specific gravity of enzyme-assisted finger millet milk (1.033) is slightly higher than that of the conventional method (1.027). This increase is directly correlated with the higher total solids content, as the dissolved solids add to the density of the milk. The acid value of enzyme-assisted finger millet milk (0.007 mg KOH/g) was found to be lower compared to that obtained through the conventional method (0.10 mg KOH/g) a lower acid value indicates reduced lipid oxidation, suggesting better preservation of the milk's quality and stability during enzymatic processing.

3.2 Nutritional composition of conventional method and enzyme-assisted extracted finger millet milk

Figure 3 demonstrated the nutritional composition of finger millet milk extracted using conventional methods compared to enzyme-assisted extraction.

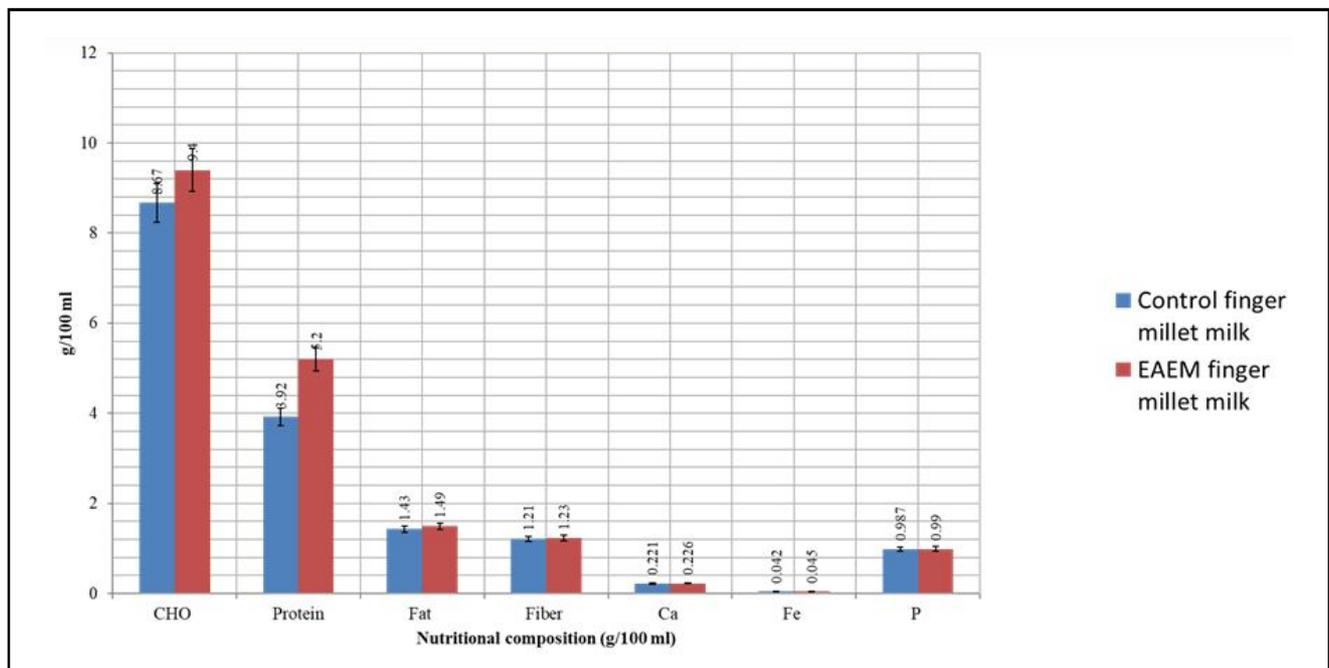


Figure 3: Nutritional composition of conventional and enzyme-assisted extraction method of finger millet milk.

The carbohydrate content of enzyme-assisted finger millet milk (9.40 g/100 ml) is higher than that of the conventional method (8.67 g/100 ml). This enhancement is due to the enzymatic breakdown of complex carbohydrates, such as starches, into simple and soluble sugars. Enzyme-assisted finger millet milk has a significantly higher protein content (5.20 g/100 ml) compared to the conventional method (3.92 g/100 ml). This increase is attributed to the enzymatic breakdown of protein carbohydrate and protein fiber complexes, enhancing protein solubility and extractability.

The fat content of enzyme-assisted finger millet milk (1.49 g/100 ml) is slightly higher than the conventional method (1.43 g/100 ml). This slight increase can be attributed to the enzymatic release of bound lipids from cell walls and protein-lipid complexes. Although the differences are small, the improved lipid availability can enhance the creaminess and overall sensory quality of the milk. The fiber content of enzyme-assisted finger millet milk (1.23 g/100 ml) is slightly higher than that of the conventional method (1.21 g/100 ml). This increase reflects the solubilization of dietary fiber fraction during enzymatic treatment. Enzymes can break down insoluble fiber components into soluble forms, improving their bioavailability.

Calcium content is slightly higher in enzyme-assisted finger millet milk (226 mg/100 ml) compared to the conventional method (221 mg/100 ml). This increase may be due to the enzymatic hydrolysis of calcium-bound phytates, leading to their breakdown which liberates calcium ions and improves their solubility and bioavailability. The iron content of enzyme-assisted finger millet milk (0.45 mg/100 ml) is slightly higher than that of the conventional method (0.42 mg/100 ml). Enzymatic treatment reduces the levels of phytates and tannins, which are known to bind iron and inhibit its absorption. The phosphorous content shows minimal difference between enzyme-assisted (0.990 mg/100 ml) and conventional (0.987 mg/100 ml) methods.

3.3 Sensory evaluation of conventional and enzyme-assisted extraction method of finger millet milk

The sensory evaluation of finger millet milk, conducted using a 9-point Hedonic scale, revealed that enzyme-assisted method significantly improved all sensory parameters compared to the conventional method. In terms of colour and appearance, the enzyme-assisted finger millet milk scored 8.2, better than the conventional method, which scored 7.5. The improved (L^* value) and reduced sedimentation enhanced the milk's clarity and visual uniformity, making it more appealing.

The consistency of enzyme-assisted milk secured 8.3 compared to 7.3 in the conventional method. The enzymatic hydrolysis facilitated the release of soluble fibers and proteins, improving viscosity and stability, which contributed to a smoother texture. The flavour of enzyme-assisted milk (8.2) also outperformed the conventional sample (7.6). Enzymatic hydrolysis released free amino acids, simple sugars, and flavour-enhancing volatile compounds, reducing bitterness and contributing to a sweeter, more appealing profile. The taste of enzyme-assisted milk (8.3) was also superior to the conventional method (7.2). The natural sweetness derived from the enzymatic breakdown of starch into maltose and glucose significantly enhanced palatability. The overall acceptability score for enzyme-assisted milk (8.3) was notably higher than that of the conventional method (7.3). This indicates that the combined improvements in color, consistency, flavor, and taste significantly enhanced the consumer preference for enzyme-treated finger millet milk. The most significant differences were observed in the overall acceptability, colour, appearances, flavour, and viscosity attributes, with CEM (Control) finger millet milk receiving lower scores compared to enzyme-assisted extracted finger millet milk (Figure 4).

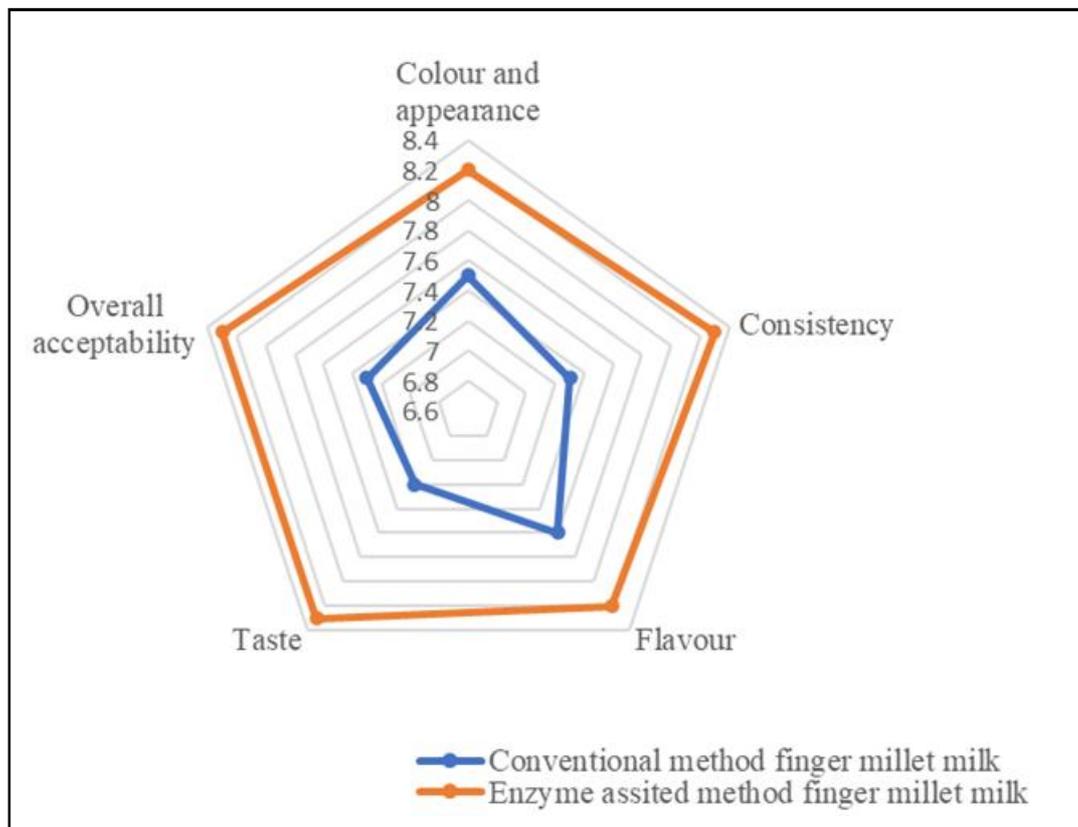


Figure 4: Sensory evaluation of conventional and enzyme-assisted extracted finger millet milk.

4. Discussion

Enzyme-assisted extraction (EAEM) enhances the yield and nutritional quality of finger millet milk by breaking down complex cell walls, improving nutrient and bioactive compounds release. Enzymatic treatment also affects macromolecule breakdown, acidity and buffering capacity with lower pH aiding microbial stability and preservation. According to Fuentes *et al.* (2024), enzymatic processing can influence pH and acidity levels in plant-based beverages improving their shelf-life and digestibility. Tong *et al.* (2024) observed similar reductions in pH during enzymatic treatment, highlighting improved functionality and stability in plant-based milk.

Enzyme-assisted extraction increased TSS in finger millet milk by converting complex molecules into soluble solids, enhancing yield. Similar increase in TSS in enzyme assisted millet-based beverages, attributing it to the enhanced solubilization of matrix-bound components (Zhang *et al.*, 2024). Jeske (2018) also found similar the TSS content in plant-based milk due to enzymatic treatments, which contribute to richer flavor and enhanced nutritional profile.

Our results are supported by earlier findings enhanced acidity could positively influence the microbial stability of the milk, reducing the likelihood of spoilage and extending shelf-life. A moderate increase in acidity in enzyme-treated oat and rice milk due to the release of hydrolysis by-products, such as lactic acid, improves microbial stability while maintaining sensory acceptability (Luo *et al.*, 2024). Enzymatic treatments of plant-based beverages showed increased acidity due to enhanced extraction of acidic compounds, which positively influenced the functional properties and stability of the final product (Jeske, 2018).

According to the cited literature viscosity of almond milk (4.63 mPas) is comparable to the viscosity range observed in millet-based milk. These values suggest that finger millet milk could achieve a slightly higher viscosity, contributing to its desired mouthfeel and textural properties (Paul *et al.*, 2020). The viscosity of finger millet beverages varied between 2.43 and 26.40 cP, which has been observed near the results of the present study (Shunmugapriya *et al.*, 2020). Enzyme-assisted extraction of almond milk significantly reduced viscosity compared to conventional methods by efficiently hydrolyzing insoluble fibers into soluble forms, improving fluidity while retaining essential nutrients (Shinde *et al.*, 2020).

McCl ements and Grossmann (2022) reported that enzyme-assisted extraction (EAEM) affects the colour of plant-based milk, as reflected in wide variations in CIELAB values (L^* : 23.29 -72.4, a^* : -39.27 to 1.71, b^* : 33.4-95.5). Studies on chlorophyll-based spinach extracts also showed EAEM significantly influences colorimetric properties. The findings of the previous researchers Mazzocchi *et al.* (2023) corroborate the results of lower extraction temperature (25°C) and shorter times (1 h) resulted in more intense green hues, with a^* values less than -30, indicating a shift towards green. This suggests that EAEM can be optimized to enhance desirable color attributes in plant-based milk.

Enzymatic treatments enhance solubility and suspension stability, preventing particle settling and ensuring uniform distribution. The sedimentation rate observed in the enzyme-assisted extracted finger millet milk is closely aligned with the findings reported by

Shumugapriya *et al.* (2020) that millet milk extraction compared various methods and found that EAE resulted in a sedimentation rate ranging from 0.93 to 1.13 g/40 ml, indicating enhanced stability compared to other techniques.

Lower syneresis in the enzyme-treated sample indicates improved water retention, likely due to enzymatic modification of carbohydrates and proteins, enhancing texture and sensory quality. The present study's findings on the syneresis rate of the enzyme-assisted finger millet milk were found to be in close accord with those of Tang *et al.* (2023) found that enzymatic treatment of soy milk resulted in a lower syneresis rate compared to conventional methods, attributed to improved molecular interactions between protein and water. The reduction in syneresis not only enhances the physical stability of the milk but also ensures a uniform texture and consistent sensory experience for consumers. These findings highlight the efficacy of EAE in mitigating syneresis in plant-based milk formulations like Finger millet milk, making it a promising approach for high-quality, staple beverages.

Higher total solids contribute to improved nutritional density and sensory attributes such as richness and mouthfeel. According to Zhou (2024), who optimized the extraction of plant-based milk from oats, the total solids content measured using the air-oven method after enzymatic hydrolysis demonstrated the effectiveness of enzyme-assisted extraction methods (EAEM) in releasing soluble components. These findings highlight that EAEM enhances extraction efficiency in plant-based milk, leading to higher total solids content and potentially improving the nutritional value and sensory attributes of the final product.

The increased specific gravity of enzyme-assisted finger millet milk suggests a denser, more nutrient-rich formulation, highlighting the efficiency of the enzymatic extraction in releasing essential components. A study on soybean milk production using an enzymatic approach demonstrated that EAEM can enhance the extraction efficiency and alter the physicochemical properties of the milk. The enzymatic treatment led to a higher yield and potentially affected the density of the final product, which is directly related to specific gravity (Kumar *et al.*, 2020).

Enzyme-assisted extraction (EAEM) helps minimize oxidative reactions, preserving fat quality and flavour. It also influences the acid value, an indicator of free fatty acids and oil quality. Polmann *et al.* (2019) reported an acid value of 0.13 g oleic acid/kg in peacan oil using EAEM comparable to mechanical pressing.

Amylase breaks down polysaccharides into maltose and glucose, boosting carbohydrate solubility, extraction efficiency, energy content, and sweetness of the milk. Cioni *et al.* (2024) highlighted the enzyme-assisted extraction method using cellulase achieved a carbohydrate content of 5.9 mg/ml, while pectinase-assisted soymilk recorded 6.2 mg/ml. In comparison, the mechanical extraction method produced a lower carbohydrate content of 4.9 mg/ml.

Enzymes degrade protein molecules into smaller peptides and individual amino acids, promoting their release from the finger millet matrix. According to Rashwan *et al.* (2023), enzyme-assisted extraction (EAEM) effectively enhances protein yield in plant-based milk by breaking down cell walls, enabling better protein release. It achieves extraction efficiencies of 86-95% while preserving functional properties. During the germination of finger millet, the crude protein and fiber content were increased (Choudhury and Chaudhary, 2023).

The enzyme-assisted extraction method using cellulase resulted in a fat content of 12 mg/ml, while the pectinase method produced a fat content of 13 mg/ml. However, the mechanical extraction method yielded a higher fat content of 14.2 mg/ml (Cioni *et al.*, 2024). Fiber significantly contributes to improving the functional properties of finger millet milk, including viscosity, stability and health benefits like supporting gut health. Enzyme-assisted extraction of plant materials has shown that enzymatic hydrolysis can efficiently break down plant cell walls, resulting in the release of bioactive compounds and fibers. These released components can be harnessed to enhance the functional qualities of plant-based milk (Cheng *et al.*, 2018).

The enhanced calcium content is crucial for enhancing the nutritional characteristics of finger millet milk, addressing micronutrient deficiencies, and supporting bone health. Unfortified soymilk may contain about 30-50 mg of calcium per 100 ml, while calcium-fortified soymilk contains 120-150 mg per 100 ml (Hardy, 2019). This small increase in iron content improves the product's nutritional quality, particularly for individuals prone to iron deficiency. Enzyme-assisted extracted almond milk which contains 1.21 mg/100 ml (Manzoor *et al.*, 2021). The negligible change suggests that phosphorous in finger millet milk is not significantly bound to anti-nutritional factors and similar results were reported by Cui *et al.* (2023).

Five milk-based beverages were formulated by incorporating 5% malted finger millet and were evaluated for sensory characteristics by a semi-trained panel of 10 judges. Among them, the banana-based beverage with 5% malted finger millet was the most preferred in terms of sensory appeal. Bansal and Kaur (2018) reported that adding 5% malted finger millet flour to milk porridge yielded the highest sensory scores. According to Shumugapriya *et al.* (2020) enzyme-assisted extracted finger millet milk had significantly ($p < 0.05$) improved sensory attributes, including color, flavor, texture and overall acceptability, compared to the conventional method.

5. Conclusion

This study mainly investigates the physicochemical, nutritional, and sensory characteristics of a novel plant-based milk alternative derived from finger millet grains, comparing the conventional extraction method (CEM) with the enzyme-assisted extraction method (EAEM). The findings reveal that finger millet milk produced using EAEM contains higher levels of protein, fat, calcium, iron, and phosphorous. Enzyme-assisted extracted finger millet milk exhibits enhanced physicochemical properties, including specific gravity, color value, total solids, total soluble solids, and viscosity. Sensory evaluation indicates that EAEM finger millet milk scores significantly higher in overall acceptability than its conventional method. These results suggest that enzyme-assisted extraction not only improves the nutritional and sensory quality of finger millet milk but also enhances its viability as a healthful, consumer-preferred alternative to traditional dairy products.

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Conflict of interest

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

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