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Sustainable development and comparative evaluation of probiotic lassi, porridge, and gruel from sorghum, pearl, and finger millet using a traditional curd-based unified fermentation approach

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This study uses a traditional Indian fermentation method with fresh curd made through household back-slopping as the only inoculum to create millet-based probiotic foods. Three types of fermented products: lassi, porridge, and gruel from sorghum, pearl millet, and finger millet were prepared. The process reflects established home practices while incorporating modern evaluation methods. A total of 36 formulations were systematically designed by changing millet type, substrate type (flour, extract, or residue), and pretreatments, including germination, gelatinization, and adding dairy milk. This approach enabled targeted assessment of how each variable affects nutritional, functional, and sensory qualities. Fermentation improved probiotic quality (LAB $>10^6$ CFU/mL), mineral bioavailability (Fe, Mn, Cu, Zn), antioxidant capacity, reducing sugars, and protein content. Germination raised phenolic and antioxidant levels with increased water and oil absorption. Gelatinization enhanced texture and stability, especially in porridge and gruel. Both germination and fermentation reduced sedimentation, boosting product stability. Adding dairy milk improved sensory acceptance, particularly in lassi. Following circular bioeconomy principles, the insoluble residue from extracting millet milk is converted into gruel. This ensured complete use of raw materials and minimized waste. By extending a familiar and tested dairy fermentation method to underused millets, this work connects traditional knowledge with scientific support. It offers functional, probiotic-rich foods that promote nutritional security and zero-waste processing while encouraging small-scale, home-based food ventures.

Keywords: Beverage, Curd, Dairy milk, Fermentation, Millet-milk

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Millets, which are small-grained cereal crops having enormous nutritional benefits, grow in marginal or low-fertility soils and do not need high input of fertilizers and pesticides. It is worth mentioning that these grains provide the country with food and nutritional security and can be called nutri-cereals because of their vital nutrient content that is important to the human health. Millets were a staple crop in India and other parts of India and Africa and its origins are many centuries old. They are grown as rain-fed crops hence their significance in low-rainfall areas. Millets include the widespread sorghum (jowar), pearl millet (bajra), and finger millet (ragi) and lesser varieties, like foxtail millet (kangni/ Italian millet) and others, including those in some African nations such as fonio and tef. Their historical origins date back to Asia and Africa as one of the earliest domesticated crops of the human race, millets became world cultures, with a short growing period of 2-4 months, and the ability to adapt to different systems of cropping, and the change of the environmental conditions, especially during the monsoon seasons. This has made them well adapted to drought stress as they do not need a lot of water, unlike rice and wheat which need at least 700 mm of rainfall to grow compared to the 450 mm limit of maize cultivation[1].

Millets, celebrated for their nutritional density, encompass a spectrum of health-promoting properties essential for maintaining optimal well-being. The gradual digestion of carbohydrates obtained by means of millet contributes to a slow release of glucose into the blood, which balances blood sugar levels and reduces the likelihood of diabetes and associated metabolic disorders[2]. In addition to their digestive properties, millets are practically reservoirs of minerals and antioxidants (phenolic compounds and flavonoids) which are essential in maintaining overall good health[3]. Previous studies on prebiotic, probiotic,

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and synbiotic product development have shown that nutritional aspects may be increased through germination and fermentation of millets[4-7], but there are no comprehensive studies utilizing a unified method for product formulation covering multiple millet types. In most beverages, significant amount of residue is obtained following extraction of “millet milk” from millets[7]. However, the sustainable use of this residue has not been studied yet, although the notion of sustainability has been growing in terms of its importance to be explored.

The ancient Indian method of fermentation in the dairy industry, e.g., curd and lassi, has long been a household process whereby milk is fermented by back-slopping, with a small part of a preceding batch acting as the starter. This ancient technique maintains microbial communities that are naturally safe, strong, and adapted to local environmental conditions. Although preparation of lassi at domestic and community levels is still common, little systematic research has been done on the application of this process to underutilized millets. The International Year of Millets (IYOM) has brought renewed international attention to these crops but, most of the new literature has focused on isolating novel microorganisms to prepare millet-based fermented products instead of considering the classical starter cultures. In the current experiment, fresh curd was selected to deliberately serve as the only inoculum to ferment millet-based substrates with and without dairy milk, therefore, extending a time-tested fermentation method to a new setting. This methodology conserves the originality of the native fermentation methods and utilizes the nutritional capability of ragi (*Eleusine coracana*), jowar (*Sorghum bicolor*), and bajra (*Pensisetum glaucum*). Moreover, by leveraging the soluble fraction of the millet milk, and the insoluble residue to make lassi, porridge, and gruel, the work is in line with the principles of the circular bio economy, which entail the minimization of waste and the recovery of maximum nutrients. A combination of these traditional practices, with a structured physicochemical, microbiological, and sensory assessment gives a scientific ground to the maintenance and adaptation of indigenous food technologies to modern nutritional and sustainability requirements.

The objective of this study is to develop sustainable, millet-based, beverage-like fermented products (lassi, porridge and gruel) using both the millets and the residue produced by extraction of millet milk, focusing on *Eleusine coracana* (ragi), *Sorghum vulgare* (jowar), and *Pennisetum glaucum* (bajra), as the starter culture is fresh curd. The objectives are to investigate the influence of germination and fermentation on the selected nutritional and functional properties of these millets and to examine the effects of dairy milk addition to the fermentation of a blend of millets and dairy milk on a beverage.

Materials and Methods

Chemicals and materials

Three millet varieties were used in this study: ragi (*Eleusine coracana*), bajra (*Pennisetum glaucum*), and jowar (Sorghum vulgare), which were procured at the local markets in Agartala, Tripura (5 kg each). Local sourcing was also done in terms of toned milk (Amul, Tetra Pak) and fresh curd. Chemicals used in analysis were of the grade of analytical reagents (AR).

Germination of millets

The millet grains were cleaned, sorted, and soaked in distilled water for 6 hours to initiate germination. After soaking, the grains were transferred onto a moistened muslin cloth and incubated at 30°C up to 48 h. Moisture was maintained by spraying water 2-3 times daily. The germinated grains were then dried at 50°C, milled, and sieved to obtain uniform flour. Both germinated and ungerminated flours were stored in airtight containers[5].

Preparation of products

Three types of fermented products lassi, porridge, and gruel were prepared. Porridge was made using millet flour, while lassi and gruel were formulated from extracted millet milk and its residue (Fig. 1). Multiple formulations were prepared as described in (Table 1).

Preparation of porridge

To prepare porridge, 10 g of millet flour (germinated or ungerminated) was mixed with 100 mL of distilled water and autoclaved at 121°C for 15 min. After cooling to 40°C, 5 g of fresh curd was added as the inoculum, and the mixture was incubated at 37°C for 8 h under shaking conditions (120 rpm).

Preparation of lassi and gruel

Millet milk was extracted following a method adapted from Saxena *et al.*[5]. In brief, 10 g of flour was soaked in 40 mL of water, ground using a mixer-

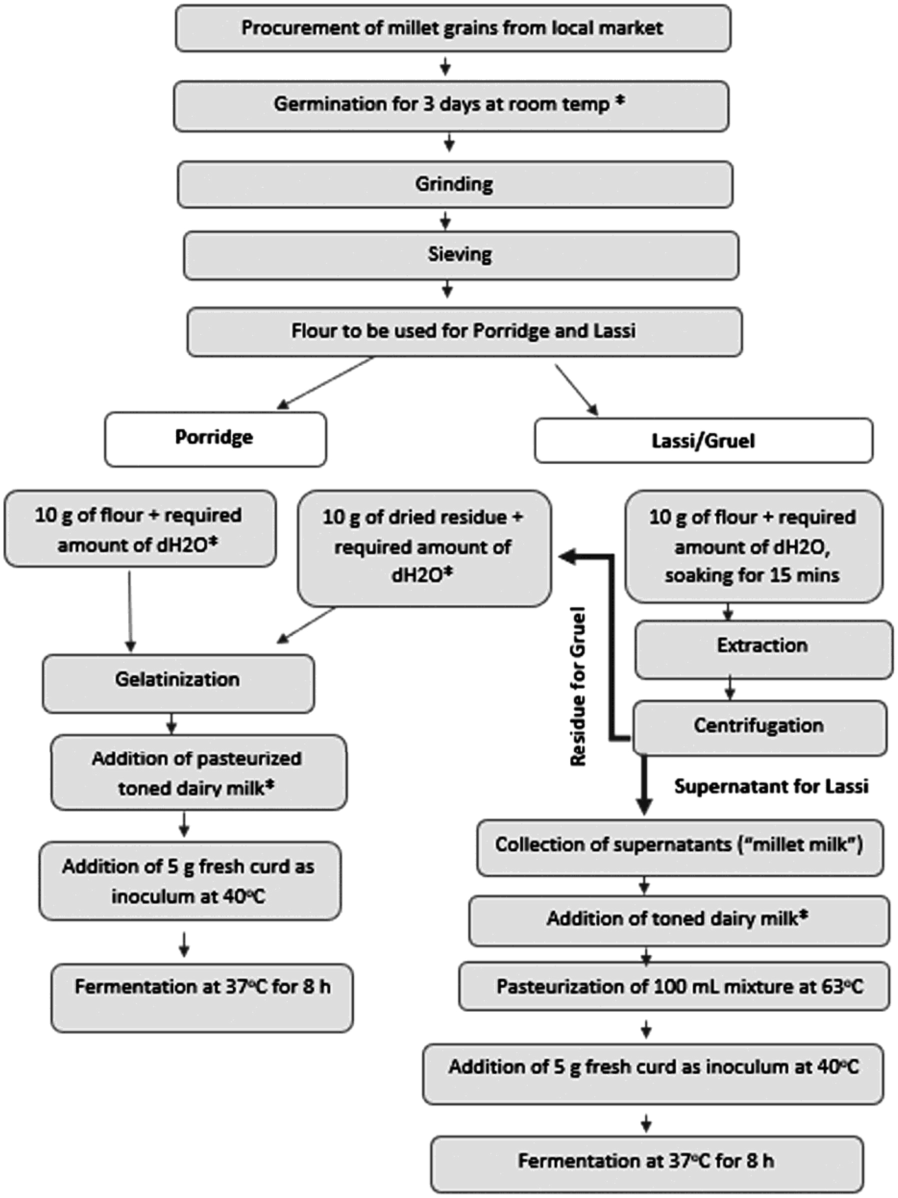

Fig. 1 — Preparation of millet-based lassi, gruel and porridge

grinder (Bajaj GX3701, 750W, India), and centrifuged at 10,000 rpm for 10 min. The resulting residue was re-extracted twice with 30 mL water each time. All supernatants were pooled and used as "millet milk," while the residue was dried for use in gruel formulations.

Lassi was prepared by blending millet milk with different volumes of dairy milk (Table 1). The mixture was pasteurized at 63°C for 10 min, cooled to room temperature, inoculated with 5 g of curd, and fermented at 37°C for 8 h with shaking (120 rpm).

Gruel was prepared using 10 g of residue, mixed with the required amount of water (Table 1), and autoclaved at 121°C for 15 min. After cooling, milk was added, followed by curd inoculation. Fermentation conditions were the same as those used for lassi. All samples were subjected to physicochemical, functional, microbiological, and sensory evaluation.

Physicochemical properties

pH

The pH of the products was measured using a digital pH meter (Labman LMPH-10). Prior to measurement, all samples were homogenized thoroughly[3].

Table 1 — Formulations of Porridge, Lassi, Gruel and their product codes

Product Name	Base Materials	Code	Gelatinization	Germination	Volume of dairy milk (mL)	Volume of distilled water/ millet milk (mL)
Porridge	Millet flour	NGR_NGL	No	No	0	100
		GR_NGL	No	Yes	0	100
		NGR_GL	Yes	No	0	100
		GR_GL	Yes	Yes	0	100
Lassi	Millet Milk	NG_0	No	No	0	100
		G_0	No	Yes	0	100
		NG_25	No	No	25	75
		G_25	No	Yes	25	75
		NG_50	No	No	50	50
		G_50	No	Yes	50	50
Gruel	Residue	GRGL_0	Yes	Yes	0	100
		GRGL_10	Yes	Yes	10	90

Titratable acidity

Titratable acidity was determined by titrating 10 mL of each sample against 0.1 N NaOH using phenolphthalein as the indicator. Acidity was calculated and expressed as grams of lactic acid per 100 mL[7].

Protein content

Protein content was measured by the Bradford method[8]. A 500 µL diluted sample was mixed with 1 mL of Bradford reagent, incubated in darkness for 5 min, and absorbance was read at 595 nm using a UV-Vis spectrophotometer (Thermo Scientific Genesys 10S, USA).

Reducing sugar content

Reducing sugar content was estimated by the dinitrosalicylic acid (DNS) method described by Miller *et al*.[9]. The diluted sample was treated with DNS reagent, boiled for 10 min, cooled, and then mixed with Rochelle salt. The absorbance was measured at 540 nm.

Total phenolic content

Total phenolic content was determined using the Folin–Ciocalteu (FC) reagent method, modified from Adebeyi *et al*.[10]. The diluted sample was reacted with FC reagent and sodium carbonate, incubated in the dark for 10 min, and absorbance was measured at 765 nm. Gallic acid was used to generate a standard calibration curve (10-100 µg/mL).

Antioxidant activity

Antioxidant activity was evaluated by the ferric reducing antioxidant power (FRAP) assay according to the method given by Kalam *et al*.[11]. The sample was mixed with phosphate buffer and potassium ferricyanide and kept at 50°C for 30 min. Next, it was reacted with trichloroacetic acid (TCA), distilled water, and ferric chloride. The absorbance was recorded at 700 nm.

Mineral content

To determine bioavailable mineral content, HCl-extractable Mn, Zn, Cu, and Fe were measured. Samples were digested with 0.06 N HCl at 37°C for 1 h, filtered through Whatman No. 42 filter paper, and analyzed by atomic absorption spectroscopy (AAS)[12].

Functional properties

Water absorption capacity (WAC)

Water absorption capacity (WAC) was determined following the method of Kumar *et al.*[13]. One gram of sample was mixed with 10 mL of distilled water in a pre-weighed centrifuge tube. After vortexing, the mixture was allowed to stand for 30 min and centrifuged at 3000 rpm for 10 min. The supernatant was discarded, and the sediment was dried at 50°C and weighed. WAC was calculated as the difference in weight before and after absorption as per Eq. (1):

$$\text{WAC (g/g)} = \text{((tube weight after drying – empty tube weight) – sample weight)/sample weight} \quad \dots (1)$$

Oil absorption capacity (OAC)

Oil absorption capacity (OAC) was measured using the same procedure, replacing water with 10 mL of sunflower oil. The final weight after drying was used to calculate oil absorbed per gram of sample as per Eq. (2):

$$\text{OAC (g/g)} = \text{((tube weight after draining excess oil - empty tube weight) - sample weight) / sample weight} \quad \dots (2)$$

Sedimentation volume

Sedimentation volume and wheying-off were measured by keeping 15 mL of each sample undisturbed at 4°C for 24 h. After the standing period, the sediment volume was recorded using a graduated cylinder. The remaining volume, considered as whey, was calculated by subtracting the sediment volume from the total volume[5].

Microbiological analysis

Lactic acid bacteria (LAB) counts were determined by spread plating on MRS agar. Samples were serially diluted up to 10^{-6} using sterile saline, and 0.1 mL aliquots from appropriate dilutions were plated onto sterilized MRS agar plates. The plates were incubated at 35°C for 24 h. After incubation, colonies were counted manually and expressed as colony-forming units per milliliter (CFU/mL) using standard microbial enumeration formulas[2].

Sensory analysis

A semi-trained group of five panel members was selected to perform sensory evaluation. Samples were randomly presented in a coded manner to eliminate bias. The products were evaluated by the panelists based on appearance, aroma, taste, and general acceptability on a five-point hedonic scale, with 1 implying ‘extreme dislike’ and 5 implying ‘extreme liking’. The average scores were used to compare the sensory attributes among different formulations.

Statistical analysis

All experiments were carried out in triplicate, and results are presented as mean ± standard deviation. Statistical analysis was performed using one-way analysis of variance (ANOVA) followed by Tukey’s multiple comparison test. The differences among formulations within each product category and millet type were considered statistically significant at $p<0.05$.

Results and Discussion

Physicochemical properties

The pH and titratable acidity of all fermented samples were monitored over 22 h. In all cases, the blank control containing no millet showed negligible changes in pH and titratable acidity, confirming that the observed acidification was due to millet fermentation. Fermentation reduced pH (to 4.2-4.9) and increased titratable acidity (1.7-3.4 g lactic acid/100 mL) across all products by 8 h (Supplementary Fig. S1 & Fig. S2), matching fermentation profiles in Saxena *et al.*[5] and Byresh *et al.*[4]. This validated our 8-h endpoint, as the lowest pH and highest titratable acidity were reached at that time. Protein concentration increased significantly (0.049-1.06 mg/mL), especially in germinated porridge (Fig. 2a), correlating with total solids from millet milk (Supplementary Fig. S3). This increase is likely due to microbial protein synthesis during fermentation, enzymatic hydrolysis of complex proteins into soluble peptides, and reduction of anti-nutritional factors that improve protein bioavailability. Reducing sugars (0.96-10.4 mg/mL), phenolics (5.39-139.52 µg/mL), and antioxidant activity (up to 0.51 mg/mL) all increased

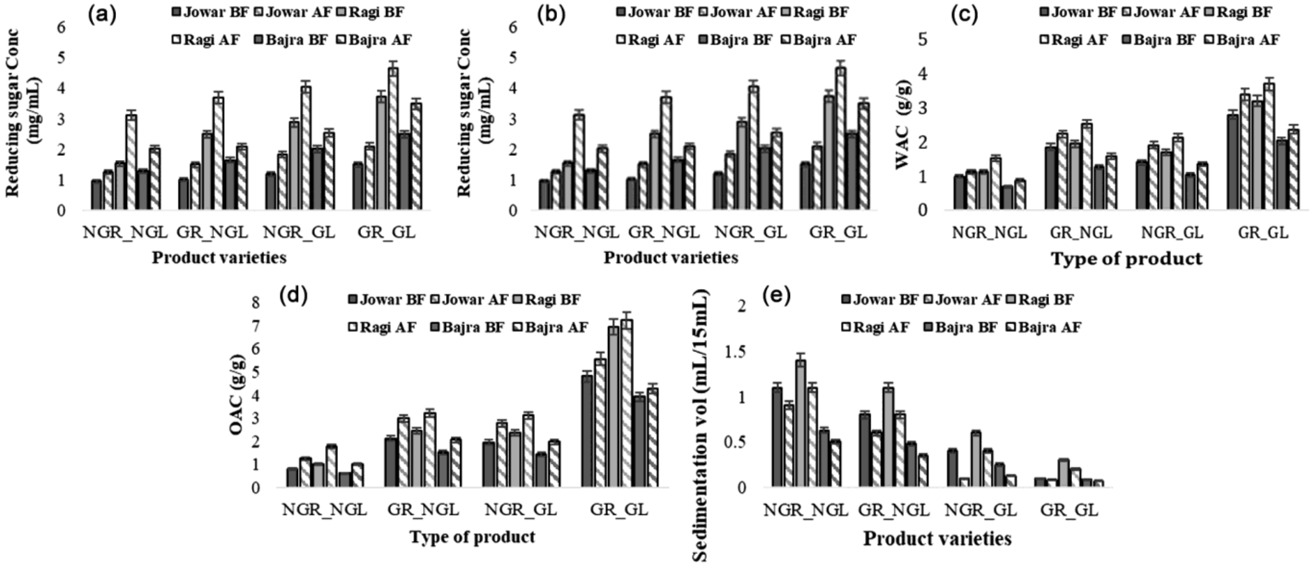

Fig. 2 — Properties of porridge: (a) Protein concentration (b) Reducing sugar concentration (c) Water absorption capacity (d) Oil absorption capacity (e) Sedimentation volume

with germination and fermentation, particularly in ragi-based formulations (Fig. 2b, Fig. 3b-d & Fig. 4b-d). In germinated samples, this rise was more pronounced due to activation of endogenous amylases during sprouting, which break down starch into fermentable sugars that also support LAB proliferation. The alterations are an indication of the enzymatic breakdown of complex carbohydrates and proteins to

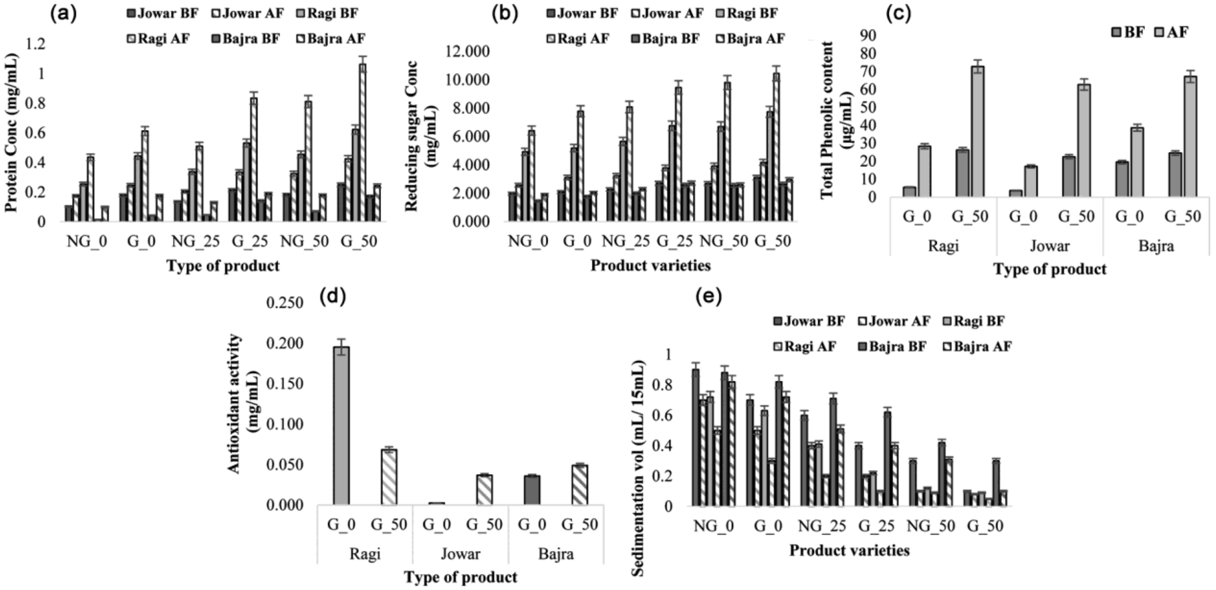

Fig. 3 — Properties of Lassi: (a) Protein concentration (b) Reducing sugar concentration (c) Total phenolic content (d) Antioxidant activity (e) Sedimentation volume

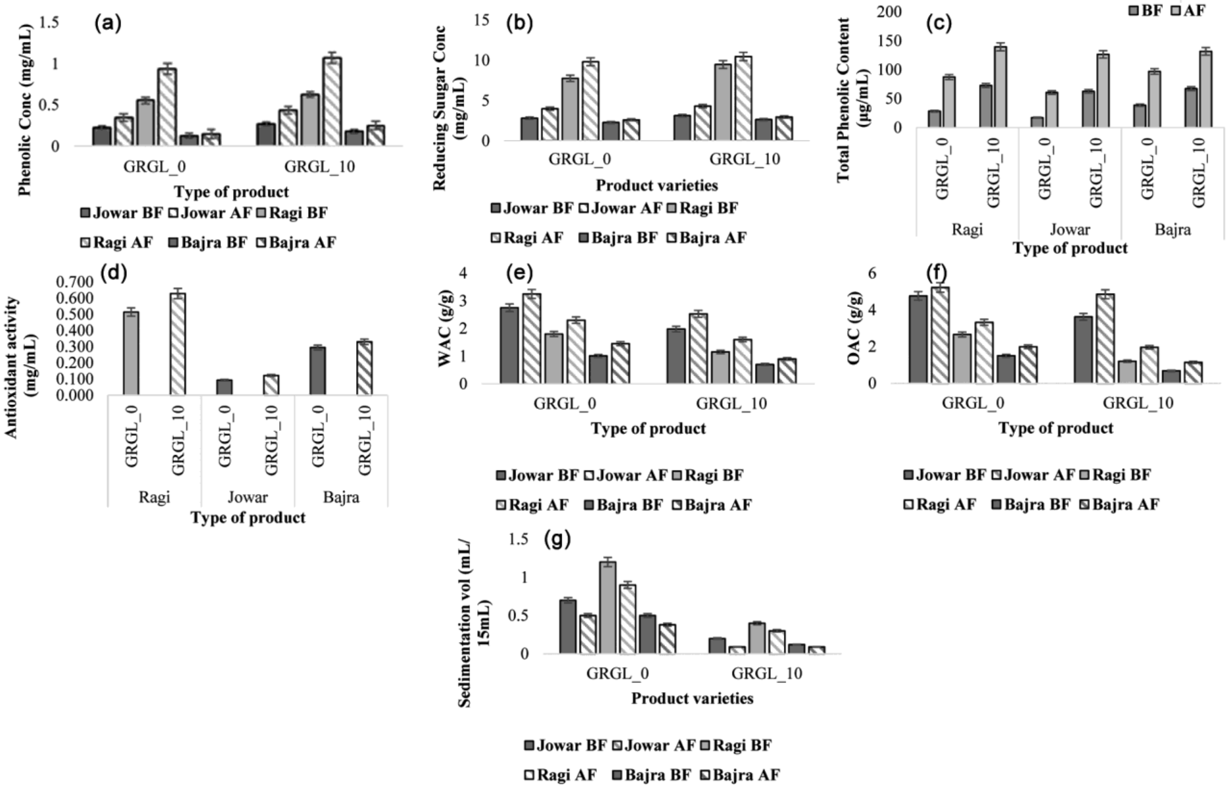

Fig. 4 — Properties of Gruel: (a) Protein concentration (b) Reducing sugar concentration (c) Total phenolic content (d) Antioxidant activity (e) Water absorption capacity (f) Oil absorption capacity (g) Sedimentation volume

release soluble nutrients. Saxena *et al.*[5] reported a 92% increase in phenolics and >30% in FRAP activity post-germination, consistent with our antioxidant trends. Similar to this study, Sudha *et al.*[6] also observed reduced sedimentation and improved nutrient retention. Byresh *et al.*[4] also reported the contribution of sprouting in probiotic support and accessibility of nutrients. Ragi consistently performed better due to richer intrinsic profile and higher fermentability as observed in all the four studies.

Mineral bioavailability

Fermentation improved HCl-extractable Fe, Mn, Cu, and Zn across all products (Fig. 5). The enhancement in metal bioavailability was observed irrespective of millet type, although the magnitude varied by both the specific mineral and the product matrix. Ragi lassi showed highest Fe and Mn (~5.8 and 3.7 mg/L), while bajra led in Zn and Cu. For all metals except Zn, products without dairy milk (G_0) showed higher mineral content than those with 50% dairy milk (G_50), indicating a dilution effect caused by the lower mineral content of dairy milk compared to millet milk. Milk reduced Fe, Mn, and Cu levels in G_50 but increased Zn, a trend also noted in Saxena *et al.*[5] who tracked mineral behaviour post-germination and blending. This reverse trend for Zn is likely due to dairy milk itself being a relatively richer source of Zn,

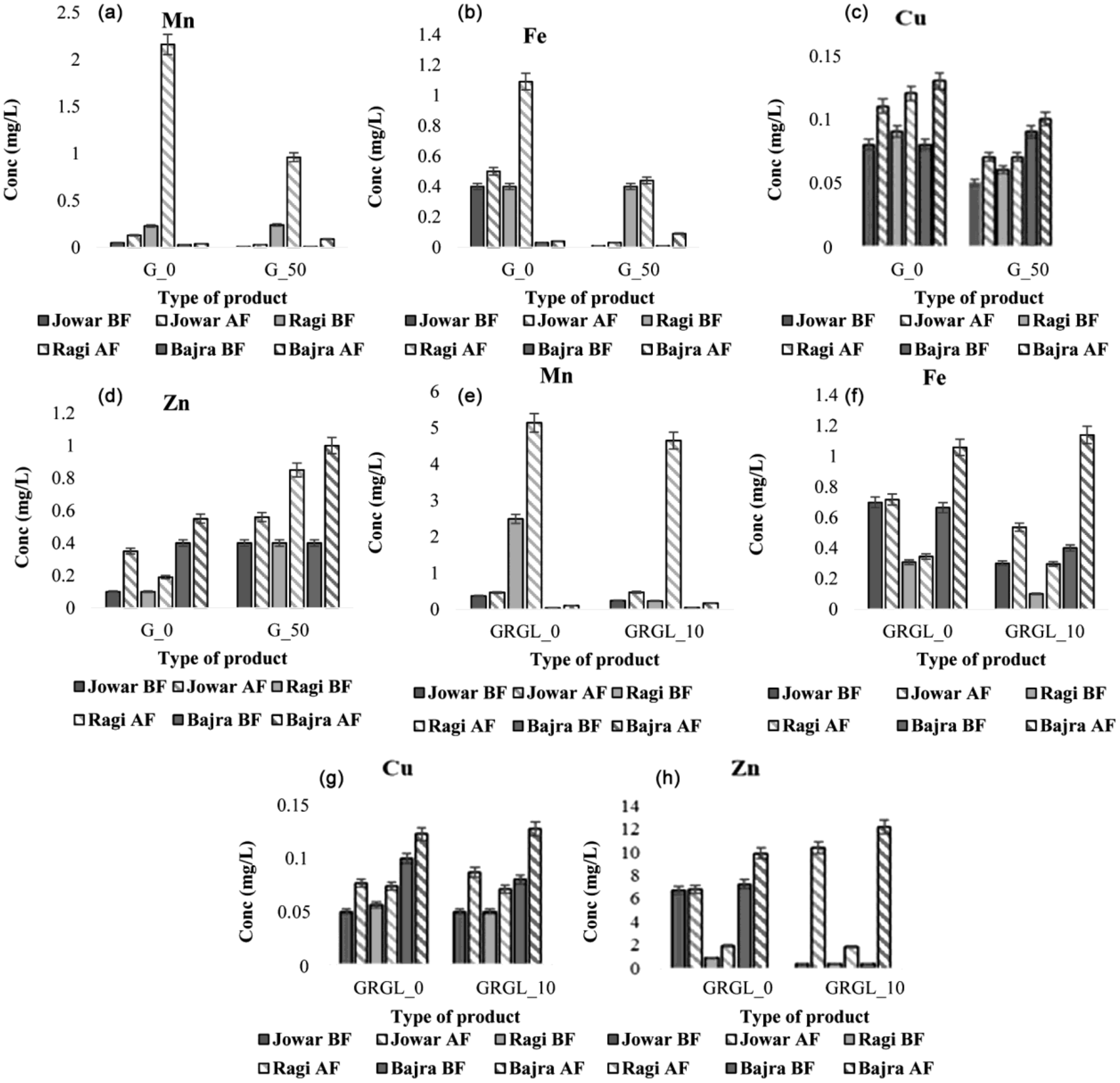

Fig. 5 — Mineral concentration of different varieties of Lassi (a-d) and Gruel (e-h)

combined with possible interactions between milk proteins and Zn that enhance its extractability. These findings confirm that fermentation breaks down phytates and enhances the solubility of minerals, and that milk selectively contributes to Zn. The effect of dairy milk was not as pronounced in gruel formulations since a smaller percentage of milk was added to the formulation, and this minimized the degree of mineral dilution. The combination of sprouting, fermentation, and controlled dairy blending enhances nutritional quality while moderating dilution effects.

Effect of milk addition

Milk altered acidity, protein, polyphenols, and sensory outcomes. As the proportion of dairy milk was increased in lassi formulations, millet-based bioactive compounds were become diluted. In lassi, protein was increased from ~0.17 mg/mL in G_0 to >0.9 mg/mL in G_50 (Fig. 3a), while titratable acidity was reduced from ~3.4 to ~2.0 g/100 mL (Fig. S2). This protein rise was partially caused by the high protein content of dairy milk which was mixed with millet milk. Phenolic compound was reduced from ~139 µg/mL to ~95 µg/mL (Fig. 3c) and reducing sugars was increased at G_25 (Fig. 3b). The decline in phenolic compound reflects the absence of these compounds in dairy milk, leading to a proportional reduction when replacing millet milk. The increase of reducing sugar in G_25 implies an optimal carbohydrate balance for microbial activity. The Zn content increased in G_50 (Fig. 5d), while Fe and Mn decreased due to dilution effect. Similar result was found by Malleshi *et al.*[14] and Saxena *et al.*[5] where blending millet with milk led to dilution of plant-derived bioactives but it improved texture and protein content. Our data also indicated that higher milk addition enhances the smoothness and reduces sedimentation, which may increase consumer acceptability despite slight nutrient trade-offs. Our study further extended to find an optimal balance at 50% dairy milk in lassi as sensory gains offset minor nutritional compromises.

Functional properties

Water absorption (up to 3.25 g/g) and oil absorption (3.5 g/g) capacities were highest in porridge (Fig. 2c-d). Both properties were significantly higher in germinated and fermented products compared to their ungerminated and unfermented counterparts. This indicates that both germination and fermentation improved the grains' ability to bind water and oil. Sedimentation value was reduced to 0.05 mL in lassi and porridge (Fig. 3e & Fig. 2e). This reduction in sedimentation suggests that germination and fermentation improved the structural integrity of the colloidal system. Fermentation disintegrated large starch granules and proteins into smaller, more soluble components leading to stability of suspension for longer duration. Similar observations were noted from Saxena *et al.*[5], who reported up to a 3-fold rise in WAC and OAC after germination. Germination also increases these properties by loosening grain matrices and exposing hydrophilic and lipophilic residues. Fermentation further contributes by producing organic acids and microbial enzymes that modify the surface characteristics of starch and protein leading to increased capacity to interact with water and oil molecules. Byresh *et al.*[4] emphasised these gains as critical for improving stability and mouth feel in vegan beverages.

Microbiological analysis

After 8 h, all of the fermented products had counts of more than 10^6 CFU/mL LAB (Supplementary Fig. S4). Porridge and gruel had higher counts than milk-rich lassi. The 22-h observation showed that the populations of LABs grew steadily until they reached their peak at 8 hours. After that, the growth stopped or slowed down. This suggests that this hour is the best balance between microbial activity and product quality. Even though milk had lactose, which helped LAB grow, the millet-based substrates, especially when they were germinated or gelatinized, had a wider range of fermentable sugars, dietary fiber, and prebiotic compounds. This may have helped microorganisms grow even better. During germination, complex polysaccharides are broken down into simple sugars. This makes starch more available, which can speed up microbial metabolism. The nutrient availability of sprouted millet likely enhanced microbial metabolism, which milk alone could not support. Byresh *et al.*[4], reported analogous trends, noting increased LAB activity in fiber-rich millet beverages. Saxena *et al.*[5] also showed that germination helps microbes to survive by making more fermentable substrates available and lowering anti-nutritional factors. In general, the processes of germination and fermentation not only increase the number of probiotics, but they also make them more stable in the final product. Germination breaks down complex polysaccharides into simple sugars, and

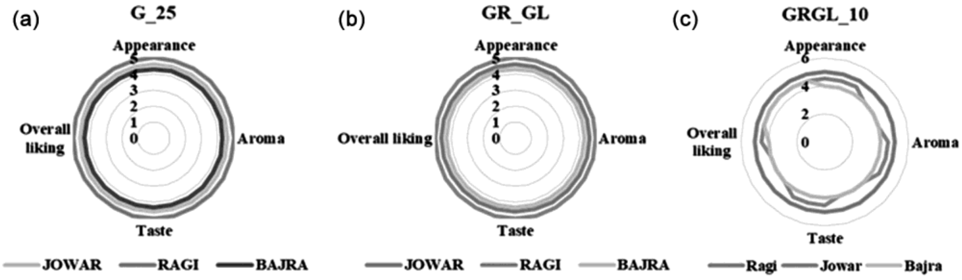

Fig. 6 — Sensory analysis of different varieties of (a) Lassi (b) Porridge (c) Gruel

gelatinization makes starch more available, which speeds up microbial metabolism. This process makes these drinks more useful.

Sensory evaluation

The G_50 lassi received the highest sensory scores, followed by the GR_GL porridge and the GRGL_10 gruel (Fig. 6). The G_50 lassi received the highest sensory scores, followed by the GR_GL porridge and the GRGL_10 gruel (Fig. 6). Panellists consistently claimed that the G_50 blend had a well-balanced flavor, creamy texture, and acceptable aroma, which meant that the 50:50 mixture of millet milk and dairy milk had reached the optimal balance between acidic and creamy characteristics. The Ragi products were always superior in taste, texture, and general acceptability. This can be explained by the natural richness in flavor and the presence of high mineral and phenolic content of ragi that was further augmented by germination and fermentation. These preferences align with Saxena *et al.*[5], who reported high consumer ratings for germinated millet milk blends, and Sudha *et al.*[6], who achieved a 7.1/9 score in optimized sprout-milk beverages. Byresh *et al.*[4] showed that acid-balance and matrix softness drive acceptability. This is consistent with our findings that gelatinization and milk blending improved smoothness, while ragi's natural richness enhanced flavor. For porridge, the germinated and gelatinized formulation (GR_GL) was preferred, likely because germination enhanced flavour complexity while gelatinization produced a thicker, more uniform consistency. In the case of gruel, the GRGL_10 formulation with a small proportion of dairy milk provided mild creaminess while maintaining the characteristic millet flavour, making it more acceptable to the panellists.

Statistical analysis

To improve clarity and avoid overcrowding of graphical representations, the outcomes of statistical comparisons are summarized in (Table 2). Table 2 lists all non-significant comparisons, including both control-based and inter-sample comparisons among formulations. Most non-significant comparisons were observed for protein content in lassi formulations. All other comparisons not listed in this table were found to be statistically significant.

Table 2 — Non-significant comparisons among formulations ($p > 0.05$)

Product	Property	Comparison	Millet	Type
Lassi	Protein	NG_25 vs NG_0	Jowar	Control
Lassi	Protein	NG_25 vs NG_0	Bajra	Control
Lassi	Protein	NG_50 vs G_25	Ragi	Inter-sample
Lassi	Protein	NG_50 vs G_25	Jowar	Inter-sample
Lassi	Protein	G_0 vs NG_50	Bajra	Inter-sample

Conclusion

Fermentation, germination, and gelatinization significantly improved the physicochemical and functional properties of beverages derived from jowar, bajra, and ragi millet, including protein content, reducing sugar content, phenolic compounds, antioxidant properties, mineral bioavailability, water/oil absorption, and sedimentation stability. The LAB count was more than 10^6 CFU/mL for all beverages. The GR_GL porridge, GRGL_10 gruel, and G_50 lassi had the best sensory scores of all the treatments. Ragi formulations consistently outperformed jowar and bajra. The study offers a sustainable method for millet-milk fermentation by converting the extraction residue into fermented gruel. These products, especially the enriched lassi, could be used in both home-based businesses and functional food markets, where they would compete with traditional dairy-based options.

Supplementary Data

Supplementary data associated with this article is available in the electronic form at https://nopr.niscpr.res.in/jinfo/ijtk/IJTK_25(4)(2026)406-415_SupplData.pdf

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Author Contributions

TD: Experimental Investigation and Data Analysis, Writing – original draft, KD: Writing – original draft, AC: Writing - review & editing, Supervision, SS: Writing - review & editing, Supervision. All authors read and approved the final manuscript

Conflict of Interest

The authors have no relevant financial or non-financial interests to disclose.

Ethics Statement

The sensory evaluation conducted in this study involved voluntary participation of panelists for assessment of food products. The study did not involve any invasive procedure or clinical intervention, and it was carried out following standard ethical practices for sensory food evaluation.

Informed Consent

Informed consent was obtained from all participants prior to the sensory evaluation.

Data Availability

The data sets generated and analyzed in this study are available upon request from the corresponding author.

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