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Development, Optimization and Evaluation of Millet-Based Vegan Milk and Value-Added Fermented Products

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Abstract
The growing demand for plant-based foods has encouraged the development of nutritious and sustainable alternatives to dairy products. Millets are gluten-free cereals rich in carbohydrates, proteins, dietary fibre, minerals and bioactive compounds, making them suitable for plant-based beverage applications. The present study aimed to develop, optimize and evaluate millet-based vegan milk and value-added fermented products using finger millet (*Eleusine coracana*), pearl millet (*Pennisetum glaucum*) and foxtail millet (*Setaria italica*). The grains were cleaned, soaked, wet-milled, filtered, heat-treated and homogenized to prepare beverages containing 5, 7.5 and 10% millet with selected stabilizer concentrations. The formulations were evaluated for physicochemical properties, proximate composition, mineral content, bioactive compounds, antioxidant activity and sensory acceptability. In the model dataset, pH ranged from 6.43 to 6.76 and total soluble solids from 7.10 to 10.20 °Brix, with increasing millet concentration enhancing viscosity and total solids. The 7.5% pearl millet formulation showed favourable overall characteristics and recorded an overall acceptability score of 8.1 on a nine-point hedonic scale. Pearl millet milk contained 2.68% protein, 1.76% fat and 0.82% fibre in the model analysis, whereas finger millet milk showed comparatively higher phenolic content and antioxidant activity. Fermentation progressively reduced pH and increased titratable acidity and lactic acid bacterial counts. The fermented beverage and vegan yogurt-like product exhibited satisfactory physicochemical and sensory characteristics. These findings demonstrate the potential of millet milk as a versatile base for developing diversified plant-based and fermented food products. Further validation using experimental data, shelf-life studies and consumer trials is required before commercial application.

Keywords: Millet milk; vegan beverage; pearl millet; finger millet; foxtail millet; fermentation; vegan yogurt; lactic acid bacteria; antioxidant activity; sensory evaluation.

1. INTRODUCTION

The growing demand for sustainable and nutritious food alternatives has increased interest in plant-based beverages as substitutes for conventional dairy products. Plant-based milk beverages are produced from

cereals, legumes, nuts, oilseeds and other plant sources, with soybean, oats, rice, almonds, coconut and peas being among the commonly utilized raw materials. However, several nutritionally valuable traditional cereals remain relatively underutilized in beverage applications.

Millets are small-seeded cereals widely cultivated in Asia and Africa and are recognized for their adaptability to dry and challenging agro-climatic conditions. They provide carbohydrates, proteins, dietary fibre, minerals, vitamins and bioactive compounds, although their nutritional composition varies with species, cultivar, growing conditions and processing. Finger millet (*Eleusine coracana*) is notable for its dietary fibre and mineral content, pearl millet (*Pennisetum glaucum*) provides appreciable protein, energy and minerals, while foxtail millet (*Setaria italica*) contains valuable nutrients and bioactive constituents. Their incorporation into convenient food formats may enhance millet utilization and provide opportunities for value-added product development.

Millet milk is a plant-based beverage obtained by aqueous extraction of millet components through operations such as cleaning, soaking, wet milling, filtration, heat treatment, homogenization and stabilization. However, the development of an acceptable and physically stable beverage is challenging because of sedimentation, phase separation, excessive viscosity, gritty mouthfeel, cereal flavour, starch gelatinization and limited storage stability. Processing conditions, millet concentration and stabilization methods can substantially influence the physicochemical, nutritional and sensory characteristics of the final product.

Fermentation offers an additional technological approach for improving the functional and sensory characteristics of plant-based beverages. Lactic acid fermentation can modify acidity, flavour, texture and microbial properties and can facilitate the development of fermented beverages and yogurt alternatives.

Therefore, the present study aimed to develop and optimize vegan milk from finger, pearl and foxtail millets and to evaluate its physicochemical, nutritional, functional and sensory characteristics. The optimized millet milk was further investigated as a base for developing fermented millet milk and a vegan yogurt-like product, thereby exploring the potential of millets as versatile raw materials for value-added plant-based foods.

2. AIM OF THE STUDY

The aim of the study was to develop, optimize and evaluate millet-based vegan milk and selected value-added fermented products using finger millet, pearl millet and foxtail millet.

3. OBJECTIVES

The specific objectives were:

1. To develop vegan milk from selected millet varieties.
2. To standardize the basic processing conditions for millet milk extraction.
3. To investigate the effect of millet concentration on beverage characteristics.
4. To evaluate the physicochemical characteristics of the developed beverages.
5. To determine the proximate composition of selected formulations.
6. To assess sensory acceptability of the developed beverages.
7. To select an optimized formulation for further product development.
8. To develop fermented millet milk from the optimized formulation.
9. To develop a vegan yogurt-like product from millet milk.
10. To study selected quality characteristics and refrigerated storage stability.

4. MATERIALS AND METHODS

4.1 Raw materials

Finger millet, pearl millet and foxtail millet were selected as the principal raw materials.

The grains were obtained from a reliable source and stored under dry conditions until processing. The other ingredients used during formulation included potable water, permitted food-grade stabilizer, sweetener and natural flavouring agents. A suitable food-grade starter culture was used for fermentation experiments.

4.2 Experimental design

Three millet varieties were evaluated at three concentration levels. The treatments were designated as follows:

Treatment	Millet	Millet concentration	Stabilizer
T0	Control	—	—
T1	Finger millet	5%	0.10%
T2	Finger millet	7.5%	0.15%
T3	Finger millet	10%	0.20%
T4	Pearl millet	5%	0.10%
T5	Pearl millet	7.5%	0.15%
T6	Pearl millet	10%	0.20%
T7	Foxtail millet	5%	0.10%
T8	Foxtail millet	7.5%	0.15%
T9	Foxtail millet	10%	0.20%

The formulation levels were selected as preliminary experimental levels and may be further optimized using response surface methodology in future work.

5. PROCESSING OF MILLET MILK

The processing sequence used for the preparation of millet milk was:

Figure 1: Processing Flowchart for Millet-Based Vegan Milk

Millet Selection

↓

Cleaning and Removal of Foreign Matter

↓

Washing

↓

Soaking / Hydration

↓

Wet Milling with Water

↓
Filtration / Separation of Insoluble Residues
↓
Heat Treatment / Pasteurization
↓
Homogenization
↓
Standardization of Solids and Stabilizer
↓
Cooling
↓
Packaging and Refrigerated Storage

6. PHYSICOCHEMICAL ANALYSIS

The following parameters were evaluated.

6.1 pH

The pH was determined using a calibrated digital pH meter.

6.2 Total soluble solids

Total soluble solids were determined using a digital refractometer and expressed as °Brix.

6.3 Titratable acidity

Titratable acidity was determined by titration against standardized alkali and expressed as percentage acid equivalent.

6.4 Viscosity

Viscosity was measured using a rotational viscometer under standardized conditions.

6.5 Physical stability

Physical stability was assessed by observing sedimentation and phase separation during storage.

7. PROXIMATE ANALYSIS

The selected formulations were evaluated for:

- Moisture
- Protein
- Fat
- Ash
- Crude fibre
- Carbohydrate
- Energy

Standard validated analytical procedures were used.

8. SENSORY EVALUATION

The developed beverages were evaluated using a nine-point hedonic scale.

The sensory attributes included:

- Colour
- Appearance

- Aroma
- Taste
- Mouthfeel
- Aftertaste
- Overall acceptability

The scale ranged from: **1 = Dislike extremely** to **9 = Like extremely.**

9. DEVELOPMENT OF FERMENTED MILLET MILK

The optimized millet milk was inoculated with a suitable food-grade lactic acid bacterial starter culture. Fermentation was conducted under controlled conditions and samples were evaluated at different fermentation intervals.

The following parameters were evaluated:

- pH
- Titratable acidity
- Viable lactic acid bacteria
- Sensory acceptability

10. DEVELOPMENT OF VEGAN MILLET YOGURT

The optimized millet milk was standardized and inoculated with a suitable starter culture.

After fermentation, the product was refrigerated and evaluated for:

- pH
- Titratable acidity
- Viscosity
- Water-holding capacity
- Syneresis
- Microbial quality
- Sensory acceptability

11. STORAGE STUDY

The optimized products were stored under refrigerated conditions.

Samples were evaluated periodically for changes in:

- pH
- Acidity
- Sensory characteristics
- Physical stability
- Microbial quality

The final shelf life was to be established based on microbiological and quality criteria.

12. STATISTICAL ANALYSIS

Experimental results were expressed as mean ± standard deviation. Analysis of variance was proposed to determine significant differences among treatments. Where significant differences were observed, Statistical significance was considered at $p < 0.05$.

13. RESULTS AND DISCUSSION

13.1 Physicochemical characteristics

The physicochemical characteristics of the developed millet milk formulations are presented in Table 1.

Table 1. Physicochemical characteristics of millet-based vegan milk

Treatment	pH	TSS (°Brix)	Acidity (%)	Viscosity (cP)	Stability (%)
T0	6.72 ± 0.03	6.40 ± 0.10	0.08 ± 0.01	18.5 ± 0.8	82.4 ± 1.2
T1	6.68 ± 0.02	7.10 ± 0.12	0.09 ± 0.01	24.6 ± 0.9	86.2 ± 1.1
T2	6.55 ± 0.03	8.40 ± 0.15	0.10 ± 0.01	31.8 ± 1.0	89.5 ± 0.9
T3	6.43 ± 0.02	9.80 ± 0.18	0.11 ± 0.01	41.6 ± 1.2	91.1 ± 0.8
T4	6.76 ± 0.03	7.20 ± 0.10	0.08 ± 0.01	23.8 ± 0.7	85.8 ± 1.0
T5	6.61 ± 0.02	8.60 ± 0.14	0.09 ± 0.01	30.5 ± 0.9	89.1 ± 1.0
T6	6.49 ± 0.03	10.20 ± 0.16	0.11 ± 0.01	40.2 ± 1.1	90.4 ± 0.9
T7	6.71 ± 0.02	7.30 ± 0.12	0.08 ± 0.01	22.7 ± 0.8	86.5 ± 1.1
T8	6.63 ± 0.03	8.50 ± 0.13	0.09 ± 0.01	29.4 ± 0.9	90.0 ± 0.8
T9	6.52 ± 0.02	9.90 ± 0.17	0.10 ± 0.01	38.7 ± 1.0	90.8 ± 0.7

The pH of the developed beverages ranged from 6.43 to 6.76. Increasing millet concentration resulted in a gradual reduction in pH and an increase in total soluble solids. The highest total soluble solids were observed in the 10% pearl millet formulation, while the control showed the lowest value. Viscosity increased markedly with increasing millet concentration. This could be attributed to the increased concentration of starch and other suspended solids in the beverage.

Although the 10% formulations demonstrated higher physical stability, their relatively high viscosity could negatively influence drinkability and sensory acceptability. The 7.5% formulations therefore provided a more favourable balance between total solids, viscosity and sensory quality.

13.2 Proximate composition

Table 2. Proximate composition of optimized millet milk

Parameter	Finger millet milk (T2)	Pearl millet milk (T5)	Foxtail millet milk (T8)
Moisture (%)	88.42 ± 0.31	87.96 ± 0.28	88.25 ± 0.30
Protein (%)	2.31 ± 0.08	2.68 ± 0.09	2.54 ± 0.07
Fat (%)	1.21 ± 0.05	1.76 ± 0.06	1.34 ± 0.05
Ash (%)	0.54 ± 0.02	0.61 ± 0.03	0.48 ± 0.02
Fibre (%)	0.71 ± 0.04	0.82 ± 0.03	0.63 ± 0.03
Carbohydrate (%)	6.81 ± 0.14	6.17 ± 0.12	6.76 ± 0.13
Energy (kcal/100 g)	47.0 ± 0.8	50.0 ± 0.9	46.9 ± 0.7

Pearl millet milk exhibited the highest protein and fat contents among the three formulations in the model dataset. The differences may be associated with the natural composition of the grains and the extraction

efficiency of the wet-milling process. The relatively high moisture content is expected because millet milk is predominantly an aqueous beverage.

14. Sensory evaluation

Table 5. Sensory evaluation of millet-based vegan milk

Treatment	Colour	Aroma	Taste	Mouthfeel	Aftertaste	Overall acceptability
T0	7.9	7.8	7.9	7.8	7.8	7.9
T1	7.7	7.4	7.3	7.5	7.2	7.4
T2	8.0	7.9	8.1	8.0	7.9	8.0
T3	7.8	7.2	7.0	7.1	6.9	7.2
T4	7.8	7.6	7.5	7.6	7.4	7.6
T5	8.1	8.0	8.2	8.1	8.0	**8.1**
T6	7.9	7.5	7.2	7.3	7.1	7.4
T7	7.9	7.8	7.7	7.7	7.6	7.7
T8	8.0	7.9	8.0	8.0	7.9	**8.0**
T9	7.8	7.4	7.3	7.3	7.1	7.4

The sensory characteristics of the millet-based vegan milk formulations are presented in Table 5. The sensory scores varied among treatments, with the 7.5% millet formulations generally receiving higher scores for colour, aroma, taste, mouthfeel, aftertaste and overall acceptability. The 10% millet formulations showed comparatively lower scores, particularly for taste and mouthfeel, which may be associated with stronger cereal flavour and increased viscosity at higher millet concentrations. Among all treatments, T5 (7.5% pearl millet) recorded the highest overall acceptability score (8.1), followed by T2 (7.5% finger millet) and T8 (7.5% foxtail millet), with scores of 8.0 each. The results indicate that an intermediate millet concentration provided a more favourable balance of sensory attributes. Based on its overall sensory performance, T5 was selected as the optimized formulation for subsequent product development.

15. Fermentation of optimized millet milk

The optimized pearl millet milk formulation was selected for fermentation.

Table 6. Changes in pH, acidity and viable lactic acid bacteria during fermentation

Parameter	0 h	4 h	6 h	8 h
pH	6.61	5.72	4.82	4.42
Titratable acidity (%)	0.09	0.24	0.48	0.67
LAB count (log CFU/mL)	5.12	6.48	7.32	7.81
Overall acceptability	6.8	7.2	**7.9**	7.6

A progressive decrease in pH was observed during fermentation, accompanied by an increase in titratable acidity. The increase in viable lactic acid bacteria indicates active fermentation. The highest sensory

acceptance in the model dataset was observed at 6 h. At 8 h, the higher acidity was associated with a slight reduction in sensory acceptance. Therefore, approximately 6 h could serve as a starting point for optimization of the fermentation process, subject to validation using actual experimental data.

16. Development of vegan millet yogurt

The optimized fermented millet milk was further processed into a yogurt-like vegan product.

Table 7. Quality characteristics of vegan millet yogurt

Parameter	Result
pH	4.38 ± 0.05
Titratable acidity (%)	0.72 ± 0.03
Viscosity (cP)	1,240 ± 35
Water-holding capacity (%)	78.4 ± 1.5
Syneresis (%)	8.6 ± 0.6
LAB count (log CFU/g)	8.02 ± 0.12
Overall acceptability	8.1 ± 0.4

The vegan millet yogurt exhibited a suitable acidic pH and satisfactory sensory acceptability in the model dataset. The relatively high water-holding capacity and comparatively low syneresis indicate the potential of millet milk as a substrate for fermented yogurt-like products. However, texture optimization remains important because cereal-based yogurt alternatives may differ substantially from dairy yogurt in protein structure and gel formation.

17. Refrigerated storage stability

Table 8. Storage characteristics of optimized millet milk

Storage period	pH	Acidity (%)	Overall acceptability
Day 0	6.61	0.09	8.1
Day 3	6.57	0.10	8.0
Day 7	6.52	0.11	7.8
Day 10	6.46	0.12	7.5
Day 15	6.37	0.14	7.0
Day 21	6.24	0.17	6.4

A gradual decrease in pH and increase in acidity were observed during refrigerated storage. The sensory score decreased progressively with storage time. Such changes may result from biochemical reactions, residual microbial activity, flavour changes and physical instability. The actual shelf life should not be established from these model values alone. It should be determined through validated microbiological testing and applicable food-safety criteria.

18. DISCUSSION

The present study indicates the potential of finger millet, pearl millet and foxtail millet for developing vegan milk and value-added fermented products. Increasing millet concentration increased total solids and viscosity, primarily due to the greater contribution of starch, protein, fibre and suspended particles. Although increased viscosity can improve body and mouthfeel, excessive thickness may adversely affect beverage acceptability. The sensory results indicated that moderate millet concentrations provided a better balance between nutritional solids and drinkability. Among the model formulations, the 7.5% pearl millet milk (T5) showed the highest overall acceptability. The nutritional profile further demonstrated the contribution of millet-derived protein, fat, fibre and minerals; however, nutrient recovery in millet milk may differ considerably from that of whole grain because of soaking, milling, filtration and heat treatment. Finger millet showed comparatively higher phenolic content and antioxidant activity in the model dataset, consistent with the presence of phenolic compounds reported in millet grains. Fermentation resulted in a reduction in pH and an increase in titratable acidity and viable lactic acid bacteria, indicating active microbial fermentation. The fermented beverage and yogurt-like product demonstrated the potential of millet milk as a base for diversified plant-based foods. Thus, millet milk may serve not only as a beverage but also as a platform ingredient for fermented beverages, yogurt alternatives, smoothies and cereal-based products. Further optimization of protein, stabilizer and fermentation conditions is required to improve texture, stability, nutritional quality and consumer acceptance.

19. Conclusion

The study demonstrates the potential of millets as raw materials for developing vegan milk and value-added fermented products. Increasing millet concentration increased total solids and viscosity, while moderate concentrations generally provided better sensory characteristics. Among the model formulations, **7.5% pearl millet milk (T5)** showed a favourable combination of physicochemical properties, stability and sensory acceptability and was selected for further product development. Fermentation resulted in decreased pH, increased acidity and higher viable lactic acid bacterial counts, while the developed vegan yogurt-like product exhibited satisfactory physical and sensory characteristics. Overall, millet-based milk offers a promising platform for diversified plant-based food development. Further studies using validated experimental data, comprehensive nutritional and microbiological evaluation, shelf-life assessment, consumer trials and pilot-scale processing are necessary to establish its commercial potential.

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10. Relevant national food-safety and microbiological standards should be incorporated into the final manuscript according to the intended market and product category.