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Enhancing the Bio-Availability in Barnyard Millet Through Various Processing Technique and its Functional Food Applications

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Abstract

Barnyard millet (*Echinochloa frumentacea*) is a nutrient-dense and climate-resilient minor millet with considerable potential for functional food development. However, its wider utilization is limited due to anti-nutritional factors such as tannins and phytates, which reduce mineral bioavailability. The present study evaluated the effect of traditional processing methods on the nutritional, anti-nutritional, functional, and sensory characteristics of barnyard millet. Raw barnyard millet grains were subjected to soaking, roasting, and steaming, followed by drying, milling, and analysis of proximate composition, micronutrients, tannin, and phytate content using standard analytical methods. The data were statistically analysed, and differences were considered significant at $p < 0.05$. Based on nutrient retention and anti-nutrient reduction, the optimum processed flour was selected for functional property assessment and value-added product development. Processing significantly influenced the nutritional profile of barnyard millet. Moisture decreased from 9.23% in raw grains to 7.82% after steaming, while crude protein increased from 6.15% to 7.32% after soaking. Crude fibre increased from 5.50% to 6.60% after roasting. Iron declined significantly from 11.00 to 3.00 mg/100 g after roasting and steaming, whereas calcium increased from 22.70 to 27.90 mg/100 g after soaking. Tannin content reduced significantly, with maximum reduction after roasting from 126 to 40 mg/100 g. Phytate showed only marginal, non-significant reduction from 652 to 616–618 mg/100 g. Soaked flour showed desirable functional properties, including water absorption capacity of 93.33%, oil absorption capacity of 105.75%, swelling power of 6.59 g/g, and bulk density of 0.88 g/ml. Sensory evaluation showed highest overall acceptability for beetroot cutlet with 10% beetroot powder and banana muffin with 10% banana powder. Soaking was identified as the most suitable processing method for improving the nutritional, functional, and sensory quality of barnyard millet for value-added product development.

Keywords: Anti-Nutritional Factors, Barnyard Millet, Functional Properties, Soaking, Value-Added Products

1. Introduction

Millets are growing rapidly as they are nutrient-dense, climate-resilient with enormous potential to improve global food and nutritional security, especially in situations with limited resources. Among these, barnyard millet (*Echinochloa frumentacea*), an ancient Poaceae crop native to Asia, has recently become more well-known for its ability to adapt to marginal environments and its rich nutritional profile, which includes vital micronutrients like iron and zinc along with roughly 68–70% carbohydrates, 10–12% protein, 3–4% fat, and 12–13% dietary fiber (Yadav *et al*., 2025; Singh *et al*., 2025) [32, 28]. Despite these advantages, its utilization is limited because of its anti-nutritional factors such as phytates and tannins that reduce nutrient bioavailability. Traditional Processing techniques such as soaking, germination, roasting, and fermentation play a crucial role in enhancing nutritional quality by reducing anti-nutrients and improving bioaccessibility (Santhosh *et al*., 2024; Chandraprabha & Sharon, 2021) [22, 4]. Scientifically, these processes improve techno-functional characteristics like viscosity, water absorption, and gelatinization behavior by resulting in biochemical and structural changes, such as the enzymatic breakdown of anti-nutrients and changes in starch–protein interactions (Bhatt *et al*., 2022) [2]. Additionally, processing effects the metabolic reponses, as evidenced by variation in glycemic index of barnyard millet- based products under different processing methods (Jinnappa *et al*., 2024) [10]. The present study aims to systematically investigate processing induced improvements in the nutritional and functional properties of barnyard millet to identify optimal strategies for its effective utilization in functional food applications.

1.1 Effect of Processing on Barnyard Millet

Processing significantly affects the proximate composition, mineral content, and phytochemical profile of barnyard millet. Processing improves protein digestibility and lower anti-nutrients (Sharma *et al*., 2022). Thermal processing, particularly cooking, leads to losses in carbohydrates, fats, and iron mainly through leaching and heat degradation, whereas roasting causes comparatively lowers nutrient loss (Rana *et al*., 2023) [17]. In contrast, germination improves the proximate composition by increasing protein and fiber content and enhances the bioavailability of minerals like iron and calcium by reducing anti-nutritional factors such as phytates (Manasa & Shekhara, 2024) [12]. Processing also alters antioxidant components; while heat treatments may reduce certain vitamins, they can increase total phenolics and tannins due to structural changes, whereas germination effectively lowers phytate levels and improves overall nutrient accessibility (Nazni & Devi, 2016). Overall, processing makes a balance between nutrient loss and improved bioavailability and make nutritionally enhance for consumption.

1.2 Objectives

This study was carried out to achieve the following objectives:

- To assess the impact of processing on the nutritional and anti-nutritional profile of barnyard millet.
- To identify the optimal processing method based on nutrient enhancement and anti-nutrient reduction.
- To evaluate the functional properties of the selected processed flour and its suitability for the development of value-added product.

2. Methods and Materials

2.1 Study Design

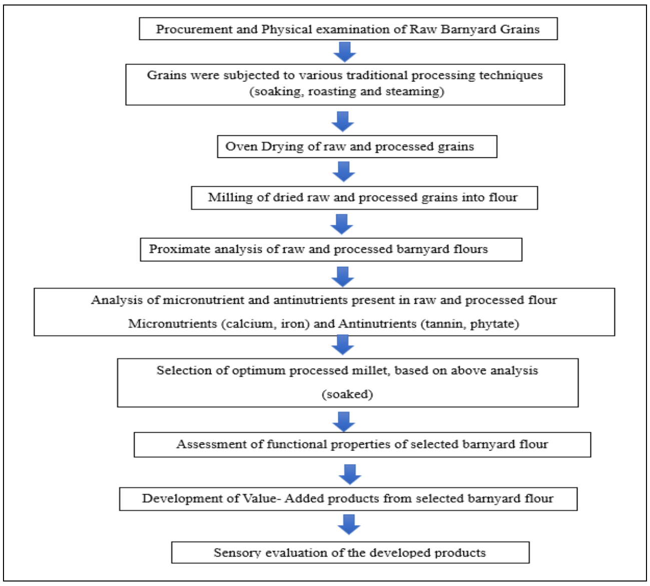

Fig 1: Sample preparation

Barnyard millet grains procured from the retail market of Jaipur city were thoroughly cleaned to eliminate dirt, hair, wilted grains and other impurities. Thereafter, the grains were subjected to various processing techniques i.e soaking (Shanmugapriya and Nazni 2020) [23], roasting (Mohd. *et al.,* 2023) [13] and steaming (Iralepatil *et al.,* 2024) [9] to reduce the antinutritional factors and improve the nutritional value of the millet. The processed millet grains were dried in a hot air oven at 105°C for 72h (Obi *et al*., 2015) later they were ground to powder for analysis.

2.2 Chemical Analysis of Samples

The flours of raw and processed barnyard grains were subjected to analysis of proximate composition (moisture, ash, crude protein, crude fat, crude fiber) [AOAC,2023], mineral content (iron, calcium) [Raghuramulu, 2003] and antinutritional component (tannin, phytate) [RPT/MT/FRK/2023/001 *et al*., 2023] [19] using standard analytical methods. The data obtained was statistically analyzed, and the differences were considered significant at 5% level of significance. Carbohydrate content was calculated by difference using the formula: Carbohydrate (%) = 100 - (moisture + ash + protein + fat + fibre). The estimations were carried out in the Research laboratory, Department of Home Science, IIS (deemed to be University), Jaipur, Rajasthan.

On the basis of the nutritional and antinutritional profile of the processed grain flours, the soaked grain was identified as the best, so, the flour obtained from dried soaked barnyard grains was used to develop value added products.

2.3 Sensory Evaluation

The developed products were evaluated for the sensory characteristics by a panel of 12 semi-trained judges selected through sensitivity threshold test. The sensory parameters like colour, flavour, texture, taste, and overall acceptability were assessed using nine-point hedonic scale.

3. Results and Discussion

Raw barnyard millet grains were subjected to selected traditional processing methods, namely soaking, roasting, and steaming, followed by oven drying and milling into flour. The raw and processed flour samples were analysed for proximate composition, micronutrient content, and anti-nutritional factors using standard analytical procedures. The obtained data were statistically analysed to determine the effect of processing on the nutritional quality of barnyard millet.The results for the macro nutrients, micronutrients and antinutrients factors were describe below.

3.1 Nutrient Analysis

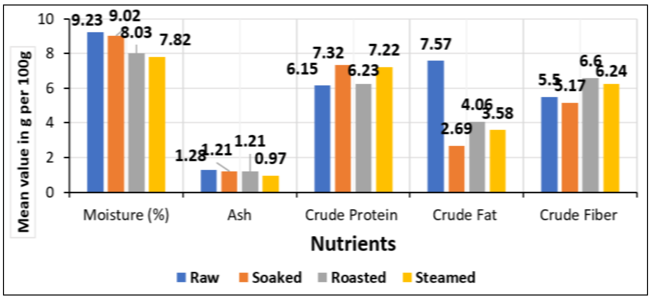

Fig 1: Proximate composition of raw and processed barnyard millet flour

Moisture Content

The moisture content decreased significantly from approximately 9.23% (raw) to about 9.02% (soaked) and 8.03% (roasted) in processed barnyard millet samples (Fig 1). This reduction is attributed to heat induced evaporation and structural changes that enhances water loss. Similar findings were reported where roasting of barnyard millet resulted in a significant moisture reduction of about 14.22% (Mohd. *et al* 2023) [13]. Additionally, studies on minor millets, including barnyard millet, show that hydrothermal treatments alter moisture depending on processing intensity, often leading to reduced final moisture after drying (Iralepatil *et al*., 2024) [9].

Ash Content

Ash content decreased slightly during processing (~1.6% to ~1.2–1.5%), with no significant difference ($p > 0.05$), which is consistent with mineral leaching during soaking. In barnyard millet and minor millets, processing treatments such as soaking and hydrothermal treatment have been shown to reduce ash content due to dissolution of minerals into soaking water, although the changes were often minimal and statistically insignificant (Iralepatil *et al*., 2024) [9]. Conversely, some studies reported that during roasting there is a slight increase in ash content because concentration is affected after the loss of moisture, highlighting that the ash content is based on the processing method that is used (Shinde *et al*., 2023).

Protein Content

The protein content was reported to increase from ~10.2% to ~12.5% after the combined effect of processing. This is consistent with other findings based on barnyard millet and other pseudo-cereals where processing enhances protein concentration and digestibility. For instance, roasting of barnyard millet improves amino acid content and overall protein quality due to denaturation and breakdown of anti-nutritional factors (Mohd. *et al* 2023) [13]. Similarly, studies on minor millets have shown that processing treatments can alter protein levels depending on method, with some treatments a measurable increase in protein content has been reported due to concentration effects (Iralepatil *et al*., 2024) [9].

Fat Content

A reduction in crude fat content from ~4.8% to ~3.0% was observed after soaking and heat treatment. This reduction is consistent with lipid loss during soaking (leaching) and thermal degradation. In contrast, a few studied based on roasting of barnyard millet reported slight increases in fat content due to concentration after moisture loss (e.g., 4.38% to 5.08%), indicating that fat changes depend strongly on processing conditions (Mohd. *et al* 2023) [13]. However, hydrothermal treatments in barnyard millet have been shown to decrease fat content, supporting the observed trend (Iralepatil *et al*., 2024) [9].

Crude Fiber Content

The crude fiber content was reported to increase from ~2.9% to ~4.2% after processing. Other studies have supported it by justifying it as roasting and processing increase fiber content due to concentration effects and structural breakdown of cell walls. For example, processing treatments have been shown to increase fiber content in barnyard millet due to the removal of soluble components and enhanced detectability of insoluble fiber fractions (Shinde *et al*., 2023).

Carbohydrate Content

A slight increase in the carbohydrate content from ~68.0% to ~72.5% was observed. Other studies on barnyard millet reported that roasting and processing increases the carbohydrate proportion due to reductions in moisture, fat, and other components, leading to relative concentration of carbohydrates (Shinde *et al*., 2023). Additionally, hydrothermal treatments in millets have been shown to increase carbohydrate content, further supporting this observation (Iralepatil *et al*., 2024) [9].

3.2 Micronutrient Content

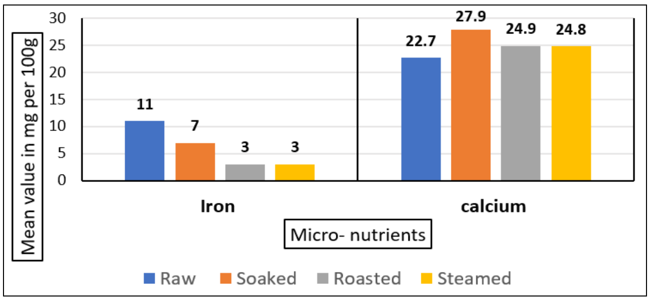

Fig 2: Micronutrient content of raw and processed barnyard millet flour

Iron Content

Fig 1 represents that iron content declined progressively from 11.00 mg/100 g (raw) to 7.00 mg/100 g after soaking and further to 3.00 mg/100 g in the case of roasting and steaming of barnyard grains, indicating significant processing-induced losses ($p<0.05$). These reductions are primarily attributed to leaching of iron into the soaking water and heat-induced structural changes in the grain matrix that reduce mineral retention (Saleh *et al*., 2013 [20]; Devi *et al*., 2014). These findings align with the reported iron content ranging from 15.6–18.6 mg/100 g in raw barnyard millet grain across different varieties (Saleh *et al*., 2013; Renganathan *et al*., 2020) [20, 18], and are consistent with iron values of 2–8 mg/100 g commonly reported for the processed millet grains (Singh *et al*., 2025) [28]. Also, soaking reduces the anti-nutritional factors such as tannins (2.21–2.96 mg/100 g) and phenolic compounds (5.20–5.31 mg/100 g) in barnyard millet, which indirectly influences the iron retention through their role in mineral binding (Bhatt *et al*., 2022) [2].

Calcium Content

Unlike iron, calcium content increased from 22.70 mg/100 g (raw) to 27.90 mg/100 g after soaking ($p<0.05$), and remained elevated in roasted (24.90 mg/100 g) and steamed (24.80 mg/100 g) grains as compared to the raw grains (Fig 2). Similar findings were reported for raw barnyard grains (20–23.16 mg/100 g) by Gopalan *et al*., 2007; Saleh *et al*., 2013 [20], confirming that soaking enhances calcium extractability beyond baseline levels. This increase is attributed to the reduction of phytates during soaking, which releases bound calcium into a measurable and bioaccessible form (Saleh *et al*., 2013 [20]; Devi *et al*., 2014). Krishnan *et al*. (2012) [11] reported that processing of minor millets increases bioaccessibility of calcium by 15 g/100 g, through reduction of phytate and polyphenol content, further supporting the observed trend. The phytate content of the barnyard millet has been reported as 3.30–3.70 mg/100 g in raw grain (Renganathan *et al*., 2020) [18]. Soaking-induced reduction of phytate could be a primary reason for increase in calcium content.

3.3 Ant Nutrients Factors

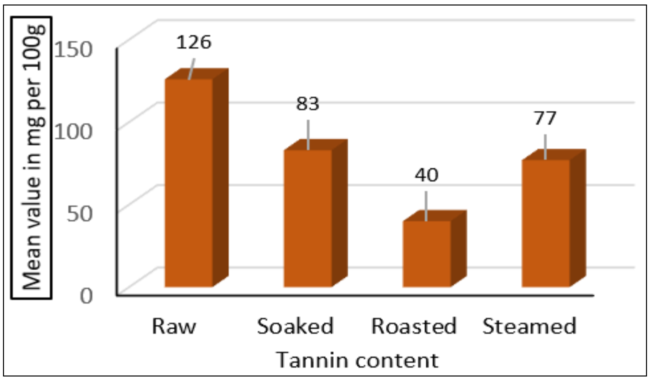

Fig 3: Mean tannin content of raw and processed barnyard millet

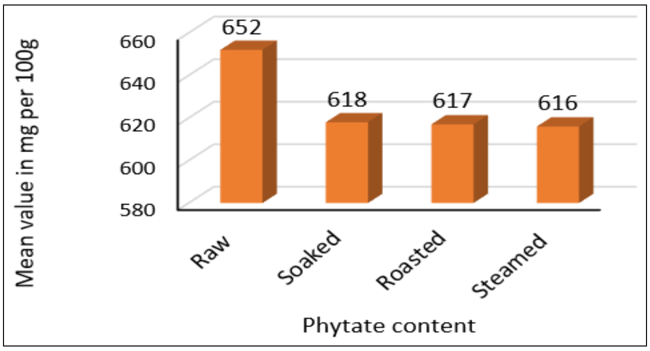

Fig 4: Mean phytates content of raw and processed barnyard millet

Tannin Content

Among all the processed grains of barnyard millet (*Echinochloa frumentacea*), tannin content declined significantly ($p<0.05$). The tannin content of raw grains was 125.00 mg/100 g, soaked 83.00 mg/100 g (33.6%), steamed 80.00 mg/100 g (36.0%), and roasted 38.00 mg/100 g (69.6%) (refer Fig 3). The findings were supported by Shanmugapriya and Nazni (2020) [23], soaking reduced tannin content of barnyard millet to 2.21–2.96 mg/100 g and roasting to an average of 1.9 mg/100 g (1.54–2.17 mg/100 g). Sharma *et al*. (2021) [25] reported 5–70% reductions in anti-nutritional factors, including tannins, during bioprocessing of barnyard millet, attributing these reductions to enhanced endogenous enzymatic activity. Singh *et al*. (2025) [28] reported 46% reduction in phytic acid content, confirming the broad susceptibility of tannins in this species to processing. The reduction in tannin content is nutritionally significant, as tannins form stable complexes with divalent mineral cations including Fe^{2+} and Ca^{2+}, inhibiting their gastrointestinal absorption.

Phytate Content

Fig 4 represents the phytate content of barnyard millet in the raw grain as 652.00 mg/100 g. All three processing treatments resulted in only marginal and statistically non-significant ($p>0.05$) reduction in phytate content: soaking reduced it to 618.00 mg/100 g (5.2%), dry roasting to 617.00 mg/100 g (5.4%), and steaming to 616.00 mg/100 g (5.5%), with no significant difference observed among the three processed samples however significant ($p>0.05$) differences were seen in raw and soaked samples. Millets were recognized as low-phytase grains, and soaking at ambient temperature is therefore substantially less effective in reducing phytate as compared to high-phytase cereals such as wheat, rye, and barley (Samtiya *et al*., 2021) [21]. Decortication decreases phytic phosphorus content by only 23% in barnyard millet, while roasting has been reported to reduce phytate by 28.4% in millet systems (Samtiya *et al*., 2021) [21], both values exceeding the reductions observed in the present study, suggesting that the processing duration and conditions applied were insufficient to substantially hydrolyse the phytate matrix. Phytate content in barnyard millet grain has been reported as 3.30–3.70 mg/100 g following dehulling (Panwar *et al*., 2016) [16], indicating that physical removal of the seed coat which concentrates phytate in the pericarp and aleurone layers is a more effective strategy than aqueous or thermal processing alone for phytate reduction (Renganathan *et al*., 2020) [18]. The persistence of high phytate levels across all processing treatments has direct nutritional implications, as phytic acid forms stable, insoluble complexes with divalent cations including Fe^{2+} and Ca^{2+}, limiting their intestinal bioaccessibility despite measurable improvements in total extractable mineral content (Sharma *et al*., 2021; Singh *et al*., 2025) [25, 28].

Selection of processed barnyard grains

Soaking leads to measurable improvements in the nutritional quality of barnyard millet which further influences the sensory attributes. The increase in protein and calcium availability, along with the reduction in fat and antinutritional factors, contribute to improved texture, taste, and overall acceptability of the the products developed from soaked grains. Specifically, reduction in phytate and tannin content minimizes bitterness and astringency, resulting in a milder flavor and better mouthfeel. Enhanced hydration during soaking also softens the grain structure, leading to improved cooking quality and palatability. Sensory evaluation studies on barnyard millet have reported higher scores for taste, texture, and overall acceptability in soaked samples compared to raw ones, supporting the observed nutritional improvements (Verma *et al*., 2014; Singh & Raghuvanshi, 2012) [31, 29]. Thus, it was concluded that soaking not only enhances nutrient bioavailability but also significantly improves sensory quality, making the product more acceptable for consumption.

Functional Properties of Soaked barnyard millet

Functional properties such as water absorption capacity, fat absorption capacity, emulsion activity, and emulsion stability are important indicators of the processing behaviour of barnyard millet flour. These properties directly influence product texture, appearance, stability, and overall sensory acceptability (Shrestha & Srivastava, 2017). A clear understanding and optimization of these functional attributes can support the development of value-added products such as extruded snacks, breakfast cereals, and other healthy millet-based foods, thereby strengthening the potential of barnyard millet for wider application in mainstream food processing industries (Sharma *et al*., 2024) [24].

Table 1: Functional properties of processed barnyard flour

Functional Properties (g/g)	Amounts
Bulk Density (g/ml)	0.88±0.0017
Water Absorption Capacity	93.33±0.01
Oil Absorption Capacity	105.75±1.02
Swelling Powder	6.59±0.1
Foaming Capacity	9.79±0.17

Table 1 represents the functional properties of processed barnyard flour developed after soaking the grains. The bulk density value (0.88 g/ml) lies within the commonly reported range of about 0.70–0.90 g/ml, indicating that the flour has a suitable compactness for food preparation and formulation (Verma *et al*., 2015). The reported water absorption capacity (93.33%) lies within the typical range of 80–120%, showing that soaking improves the ability of the flour to hold water, which is important for better texture and cooking quality (Chandra *et al*., 2016) [3].

Similarly, the observed values for oil absorption capacity (105.75%) fall in a range of 90–110% in millets, suggesting that the flour can effectively retain flavor and improve mouthfeel in food products (Singh & Raghuvanshi, 2012) [29]. The swelling power (6.59 g/g) also lies within the expected range of 5–8 g/g, indicating normal starch behavior after soaking, where the grains absorb water and swell moderately during cooking (Verma *et al*., 2014) [31]. The foaming capacity (9.79%) is relatively low but still falls within the typical range of 8–15% reported for millets, because millet proteins generally have limited foaming ability compared to other protein sources (Chandra *et al*., 2016) [3].

Development of Value-added product

Based on the improved nutritional and functional characteristics of processed barnyard millet flour (soaked), value-added food products were developed to enhance its practical utilization and consumer acceptability. The processed flour was incorporated into selected food formulations to improve the nutritional profile, texture, and overall quality of the products.

Sensory Evaluation of value-added food products

Sensory evaluation is a critical aspect of product development, as it helps determine consumer acceptability based on organoleptic properties (Pandey & Saxena, 2025) [15] A semi-trained panel of judges selected through sensitivity threshold test, assessed the developed food products on a 9-point hedonic scale, focusing on attributes like appearance, texture, taste, colour and overall acceptability.

Two products were formulated using processed barnyard millet namely cutlet (fried) and muffins(baked). In these two products beetroot and banana powder were added to develop value added products.

Barnyard Beetroot Cutlet

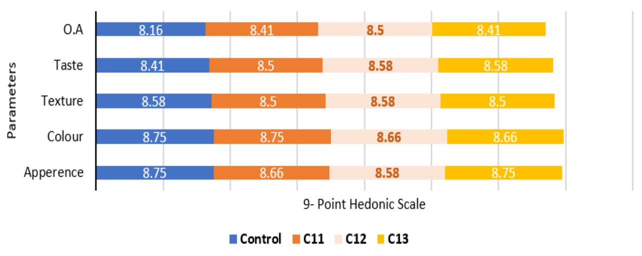

Fig 5: Mean sensory score of developed Cutlet

Firstly, cutlets were developed and the recipe was standardized using potato and vegetables. In the standardized recipe, processed barnyard millet was added in varied proportion i.e 25%, 50%, 75% and 100%. Among these 4 variations, cutlets containing 50% of processed barnyard flour (soaking) was found to be highly acceptable.

In this standardized recipe, beetroot powder was added in different proportion - 5% (C11), 10% (C12) and 15% (C13). The sensory evaluation revealed that the overall acceptability of cutlet containing 10% (C12) of beetroot powder was highest with a value of 8.50 as compared to control (8.16), followed by C12 (5%) and C13 (15%) having same value of 8.41. The variation C12 obtained highest for taste (8.58) and texture (8.58) also, identifying 10% as the optimal incorporation level. The improvement in colour and appearance with increasing beetroot powder is attributed to natural betalain pigments of beetroot, while the decline beyond 10% reflects excessive darkening from pigment accumulation at higher concentrations. Bhatt *et al.* (2023) [2] reported that 10% beetroot powder in a millet-based premix achieved the highest overall acceptability (7.5), colour (7.8), and taste (7.3) scores, confirming consumer preference for this incorporation level in millet-based products. Tangariya *et al.* (2023) [30] further demonstrated that textural properties of beetroot-incorporated snack bars were optimized at 10% beetroot powder, declining significantly ($p<0.05$) at 15% and 20%, consistent with the texture drop at C13 in the present study. Barnyard millet-based products have been established as sensorially comparable to conventional cereal-based products across all key sensory attributes (Dayakar Rao *et al*., 2015). Overall, C12 (10%) is the most preferred formulation, recording the highest combined scores for overall acceptability, taste, and texture among the other developed variations.

Barnyard Banana Muffin

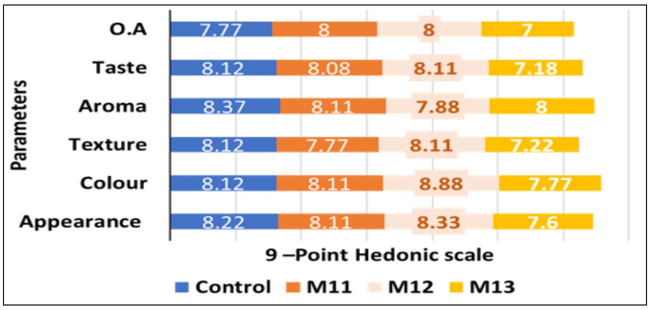

Fig 6: Mean sensory score of developed Muffin

Muffins prepared with 100% wheat flour served as the control formulation. Processed barnyard millet flour was then incorporated into the standardized muffin recipe at 25%, 50%, 75%, and 100% replacement levels of wheat flour to develop value-added millet-based muffins. Among these 4 variations, muffin containing 50% of processed barnyard flour (soaking) was found to be highly acceptable. In this variation banana powdered was added in varied proportion 5% (M11), 10% (M12) and 15% (M13). Fig 6 represents the mean sensory score of banana muffin. The overall acceptability of M12 (8.33) was found to be highest, followed by control (8.22), M11 (8.11), and M13 (7.60), identifying M12 as the most acceptable variation. The variation M12 recorded highest for colour (8.88) and taste (8.11) attributing to the characteristic volatile compounds of ripe banana enhancing the flavour profile. The appearance of M13 (7.00) recorded lowest values due to excessive surface browning at higher incorporation. Texture of the control sample (8.37) recorded highest values, but the values progressively decreased with the increase in the amount of banana flour, reflecting banana-induced softening of the muffin. Barnyard millet muffins have been reported to score 7.09 in overall acceptability, confirming the suitability of barnyard millet as a base for fortified baked products (Goswami *et al*., 2015) [7]. Harastani *et al*. (2021) [8], who reported that muffins incorporating 10% green banana flour maintained acceptable sensory scores with high purchase intent among consumers, while simultaneously achieving improved nutritional quality through enhanced fibre contribution. The overall acceptance declined at M13 (7.60) indicating over-incorporation, negatively affecting overall product balance. Overall, M12 was the found to be the most preferred formulation, recording the highest combined scores for overall acceptability, flavour, and taste.

4. Conclusion

The study evaluated the impact of soaking, roasting, and steaming on the nutritional, antinutritional, and functional properties of barnyard millet (*Echinochloa frumentacea*) and its suitability for product development. Processing improved protein and crude fiber content, while decrease in moisture and fat due to the effect of heat; carbohydrates showed a slight increase due to concentration. Iron content declined significantly (11.00 to 3.00 mg/100 g) after roasting and steaming whereas calcium increased (22.70 to 27.90 mg/100 g) after soaking due to phytate breakdown. Tannins were substantially reduced, especially by roasting (69.6%), while phytates showed minimal reduction (~5%), indicating limited effectiveness of conventional processing for phytate removal. Among treatments, soaking emerged as the most balanced method, improving nutrient availability while maintaining functional quality. The processed barnyard flour obtained after soaking showed desirable functional properties (WAC: 93.33%, OAC: 105.75%, swelling power: 6.59 g/g, bulk density: 0.88 g/ml), suitable for food applications. Sensory evaluation of developed value added products revealed that the beetroot cutlet with 10% incorporation (C12; OA: 8.50) and banana muffin at intermediate level (M12; OA: 8.33) were reported to be most acceptable. Overall, soaking is a simple and effective method to enhance the nutritional and sensory quality of barnyard millet, with potential for value-added product development. Further improvement may be achieved through combined processing methods such as germination or fermentation

5. Acknowledgment

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