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Nutritional Optimization and Sensory Characterization of Cookies Via Pearl Millet (*Pennisetum glaucum*) Flour Substitution: A Multivariate Analytical Approach

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ABSTRACT

Background: Given the escalating prevalence of malnutrition and diet-related non-communicable diseases, there is an urgent demand for nutritious, affordable, and sustainable food vehicles. The integration of underutilized, climate-resilient cereals—such as pearl millet—into widely consumed bakery products represents a strategic intervention to address food security and improve public health nutrition.

Objectives: This study aimed to evaluate the impact of substituting wheat flour with graded levels of pearl millet flour (PMF) on the physicochemical composition and sensory attributes of functional cookies.

Methods: Pearl millet flour was incorporated as a partial-to-total replacement for wheat flour at levels of 0% (control), 20%, 40%, 60%, 80%, and 100%. The resulting formulations were analyzed for nutritional composition using AOAC standardized protocols and for sensory attributes employing a nine-point hedonic scale. Statistical significance was determined via ANOVA and post-hoc mean separation tests ($p < 0.05$), while Principal Component Analysis (PCA) was applied to characterize multivariate nutritional patterns across the experimental groups.

Results: Increasing PMF inclusion led to significant linear improvements in crude protein, ash, dietary fiber, and essential mineral content ($p < 0.05$). Specifically, the 40% PMF substitution exhibited a significant nutritional fortification compared to the control without compromising overall sensory acceptability. While sensory evaluation confirmed that formulations containing 20–40% PMF were acceptable comparable to the wheat-based control, higher substitution levels ($\geq 60\%$) resulted in significantly lower scores for texture and visual appearance. Multivariate PCA demonstrated a distinct clustering of nutrient-dense profiles associated with increasing PMF levels, confirming a coordinated enhancement of the mineral and protein matrices.

Conclusion: The partial substitution of wheat flour with 20–40% pearl millet flour offers a viable approach for developing nutritionally superior cookies with high consumer acceptance. These findings support the broader application of PMF in the commercial bakery sector, school feeding programs, and therapeutic food formulation, contributing to both dietary diversity and agricultural sustainability.

Keywords: Pearl Millet Flour; Nutritional Fortification; Proximate Composition; Sensory Evaluation; Principal Component Analysis (PCA).

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1 INTRODUCTION

On a global scale, the prevalent "triple burden" of malnutrition—comprising undernutrition, micronutrient deficiencies, and the escalating prevalence of diet-related non-communicable diseases (NCDs)—affects over two billion individuals (FAO *et al.*, 2022; Kiani *et al.*, 2022). This public health crisis necessitates the development of accessible, nutrient-dense food vehicles. Given their global ubiquity across all demographic cohorts, bakery products, specifically cookies, represent a strategic medium for nutritional intervention. However, conventional formulations predominantly utilize refined wheat flour, resulting in products characterized by high glycemic indices and suboptimal micronutrient profiles (Pareyt & Delcour, 2008). The rising awareness of consumers towards healthier diets has led to the demand for functional bakery products with

enhanced nutritional density (Kaur *et al.*, 2019). With the global cookie market valued at USD 32.94 billion in 2022 and projected to maintain a compound annual growth rate (CAGR) of 5.3% (Grand View Research, 2023) a significant opportunity exists to integrate climate-resilient, nutrient-rich grains into mainstream food systems.

Pearl millet (*Pennisetum glaucum*) constitutes an underutilized cereal distinguished by its exceptional agronomic resilience and superior nutritional profile (Satyavathi *et al.*, 2021). As a C4 photosynthetic plant, it thrives in arid and semi-arid environments with minimal inputs, aligning with the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-Being), and SDG 12 (Responsible Consumption and Production). Nutritionally, pearl millet surpasses wheat in crude protein

content (9 – 13%), dietary fiber, and essential sulfur-containing amino acids (methionine, lysine, cysteine). Furthermore, it boasts significantly higher concentrations of critical minerals, including iron, zinc, calcium, and phosphorus (Priya et al., 2023; Rai et al., 2008; Saleh et al., 2013), while its rich phenolic compounds and antioxidants offers potential prophylactic health benefits (Bheemaiah Balyatanda et al., 2024; Chandrasekara & Shahidi, 2011).

Despite these advantages, the technological integration of pearl millet flour (PMF) into baked products can be technologically challenging. The absence of a gluten matrix fundamentally alters dough viscoelasticity, spread factors, and crumb texture. Moreover, its distinct aromatic profile and darker pigmentation may impede consumer acceptability at high inclusion thresholds (Bala et al., 2014; Yadav et al., 2012). While extant literature indicates that partial substitution (20 – 50%) of wheat with alternative cereal or legume flours can improve nutritional indices without influencing acceptable sensory quality (Kaur et al., 2019), these studies frequently rely on univariate statistical frameworks, and the entire substitution range of PMF has not adequately been investigated, nor has any multivariate analytical approach been applied to characterize nutrient interactions and product transformation.

A critical research gap regarding the systematic assessment of total wheat-to-millet replacement. Previous investigations have largely examined the partial substitution strategies but to an extent there is no systematic investigation of the entire range of substitution from 0% to 100% wheat–pearl millet flour replacement. Other studies often have concentrated on either the nutritional characterization or the sensory evaluation separately, with little regard for the combined evaluation of nutritional improvements in addition to consumer acceptability. This fragmented method cannot provide a total picture of how different levels of substitution affect the health promoting attributes and organoleptic characteristics of the final product in combination. Furthermore, the application of multivariate statistical techniques, specifically PCA, remains underutilized in millet-based product development. These methods are indispensable to study nutrient interrelationships and patterns for overall formulation behavior based on levels of substitution. By analyzing these multidimensional dynamics, researchers can better address "food neophobia"—the hesitancy toward novel ingredients, (Bialek-Dratwa et al., 2022, Pliner & Hobden, 1992) —and identify optimal substitution thresholds that harmonize nutritional goals with consumer preferences.

Accordingly, this study aims to characterize the nutritional composition and sensory attributes of cookies formulated with six levels of wheat-to-PMF substitution: 0% (Control), 20%, 40%, 60%, 80%, and 100%. The specific objectives of this study were: (i) to quantify macronutrient and micronutrient

flux across all treatments, (ii) to evaluate consumer acceptability via hedonic sensory profiling; and (iii) to employ PCA and correlation analysis to interpret the complex nutritional patterns associated with increasing PMF incorporation. The findings seek to validate the use of pearl millet as a sustainable and affordable strategy to mitigate malnutrition while promoting the diversification of functional bakery products.

2 MATERIAL AND METHODS

2.1 Materials and Sample Procurement

Pearl millet grains (*Pennisetum glaucum*) were procured from the Rajasthan State Seed Corporation (Jaipur, India). Refined wheat flour and the auxiliary baking ingredients—including sucrose, anhydrous butter, fresh eggs, vanilla essence, leavening agent (sodium bicarbonate-based baking powder), and sodium chloride were sourced from a Bureau of Indian Standards (BIS) certified outlet in Sikar, Rajasthan. All chemical reagents utilized for nutritional quantification were of analytical grade and obtained from Sigma-Aldrich (St. Louis, MO, USA).

2.2 Study Design

The study investigated the impact of incremental substitution of wheat flour with pearl millet flour (PMF) on the physiochemical, nutritional, and organoleptic properties of the resulting cookies.

2.2.1 Cookie Formulation

Six experimental treatments were established based on the PMF substitution level: (1) 0% PMF (Control), (2) 20% PMF, (3) 40% PMF, (4) 60% PMF, (5) 80% PMF, and (6) 100% PMF (Table 1). Formulations were developed in a laboratory setting utilizing a batch size of 1 kg. A Completely Randomized Block Design (CRBD) was employed, with the six substitution levels serving as the primary experimental blocks. Each formulation was prepared in triplicate (n=3), and data from proximate, mineral, and sensory analyses were subjected to ANOVA within this design framework.

2.2.2 Preparation Procedure

The dough was prepared using the standardized creaming method (AACC, 2010) with minor modifications. Butter and sugar were creamed in a planetary mixer at moderate speed for 3 minutes, followed by the addition of eggs and vanilla extract with continued mixing for 2 minutes. The composite flours and remaining dry ingredients were pre-sifted and incrementally incorporated at low speed to ensure the formation of a homogenous dough while avoiding gluten over-development.

Table 1. Cookie Formulations with Varying Pearl Millet Flour (PMF) Substitution Levels

Treatment Code	Wheat Flour (g)	Pearl Millet Flour (g)	Total Flour (g)	Sugar (g)	Butter (g)	Egg (g)	Baking Powder (g)	Vanilla Extract (g)	Salt (g)
Control (0% PMF)	100	0	100	50	50	1	2	2	1
S1 (20% PMF)	80	20	100	50	50	1	2	2	1
S2 (40% PMF)	60	40	100	50	50	1	2	2	1
S3 (60% PMF)	40	60	100	50	50	1	2	2	1
S4 (80% PMF)	20	80	100	50	50	1	2	2	1
S5 (100% PMF)	0	100	100	50	50	1	2	2	1

To allow hydration and firming, the dough was encapsulated in polyethylene and tempered at 4°C for 30 minutes. Post refrigeration, the dough was rolled to a uniform thickness of 5 mm and fabricated into circular forms (50 mm diameter). In a preheated convection oven, the cookies were baked at 180°C for 10 – 12 minutes until optimal browning was achieved. Following a 60-minute cooling period on wire racks at ambient temperature (25 ± 2°C), the samples were stored in hermetically sealed containers to maintain textural integrity prior to analysis.

2.2.3 Sensory Evaluation

Organoleptic properties were assessed using a 9-point hedonic scale (ranging from 1: "dislike extremely" to 9: "like extremely"). A semi-trained panel of 30 individuals (16 females and 14 males, aged 22 – 45 years) evaluated the samples for appearance, color, texture, flavor, taste, and overall acceptability. Assessments were conducted in individual sensory booths under standardized white fluorescent lighting at 25 ± 2°C. Samples were presented in a randomized order, served on neutral white plates, and identified by three-digit random codes.

To prevent cross-modal interference, panelists utilized deionized water and unsalted crackers for palate cleansing between samples. To minimize sensory fatigue, sessions were limited to three samples per interval, separated by a 15-minute recess. The protocol adhered to international ethical standards for human participation, ensuring informed, voluntary, and anonymous consent. Prior to analysis, samples were homogenized using a high-speed electric blender for 5 minutes and stored in airtight conditions.

2.2.4 Proximate Composition and Mineral Analysis

Proximate constituents, including moisture, crude protein, crude fat, ash, and crude fiber, were quantified according to the official methods of the AOAC, (2016). Moisture content was determined gravimetrically via oven-drying at 105°C until a constant mass was achieved. Protein content was determined using the Kjeldahl method. Crude protein was estimated using the micro-Kjeldahl method (Nitrogen factor: 6.25), while crude fat was quantified

through Soxhlet extraction utilizing petroleum ether. Ash content was determined by incineration in a muffle furnace at 550°C. Total carbohydrate content was calculated by difference: [100 - (moisture + protein + fat + ash + crude fiber)]. All analyses were performed in triplicate and results were expressed on a dry weight (DW) basis (g/100g), with the exception of moisture, which was reported on a wet basis.

Mineral analysis (Calcium, Phosphorus, and Iron) was conducted following AOAC, (2016) protocols. Samples underwent mineralization through dry ashing at 550 °C followed by acid digestion. Calcium (Ca) and Iron (Fe) concentrations were determined via atomic absorption spectrophotometry (Analytic gena). Phosphorus (P) was quantified colorimetrically using the vanado-molybdate method with a UV-Visible spectrophotometer (Model UV-1900i, Shimadzu, Japan) at 400 nm. All mineral data were reported in mg/100g DW.

2.2.5 Statistical Analysis

Data were subjected to one-way Analysis of Variance (ANOVA) using SPSS software (Version 26.0, IBM Corp., Armonk, NY, USA). Mean separation was performed using Duncan's Multiple Range Test (DMRT) at a significance level of $p < 0.05$. Results are presented as mean ± Standard Deviation (SD). Furthermore, Principal Component Analysis (PCA) was performed to elucidate multivariate correlations between the nutritional parameters and substitution levels.

3 RESULTS

3.1 Sensory Evaluation

The sensory attributes of cookie formulations incorporating varying substitution levels of Pearl Millet Flour (PMF) are delineated in Table 2, ranging from the control (0% PMF) to full substitution (100% PMF). Statistical analysis revealed significant differences ($p < 0.05$) across all organoleptic parameters, including appearance, color, texture, flavor, taste, and overall acceptability. A discernible downward trend was noted in overall acceptability, which declined progressively from a mean score of 8.20 in the control to 6.78 in the S5 treatment.

Alongside, appearance scores fluctuated between 7.6 (control) and 6.0 (S5), while color intensity exhibited a reduction from 8.1 to 6.0 along the substitution gradient. The textural profile demonstrated a notable decline from 8.9 (Control) to 7.1 (S5). Although flavor scores ranged from 8.2 to 6.9, taste perceptions remained comparatively stable, oscillating between 8.2 to 7.9. Superscript letters indicate statistical groupings, where values sharing the same letter are not significantly different (Table 2).

Table 2. Sensory Evaluation Across the Six Treatment Groups of Cookies with PMF Substitution as Per the Nine-Point Hedonic Scale

Treatment Code	Appearance	Color	Texture	Flavor	Taste	Overall Acceptability
Control (0% PMF)	7.6 ^a	8.1 ^a	8.9 ^a	8.2 ^a	8.2 ^a	8.2 ^a
S1 (20% PMF)	7.2 ^{ab}	8.0 ^a	8.9 ^a	8.2 ^a	8.1 ^a	8.08 ^{ab}
S2 (40% PMF)	6.8 ^{bc}	7.9 ^a	7.9 ^b	7.1 ^b	7.9 ^a	7.52 ^b
S3 (60% PMF)	6.8 ^{bc}	7.9 ^a	7.3 ^c	7.1 ^b	7.3 ^b	7.28 ^b
S4 (80% PMF)	6.8 ^{bc}	7.0 ^b	7.3 ^c	7.2 ^b	8.0 ^{ab}	7.26 ^b

PMF: Pearl Millet flour; Values with different superscript letters differ significantly ($p < 0.05$).

3.2 Proximate Analysis

The proximate composition of the six cookie formulations is summarized in Table 3. Analysis of variance (ANOVA) established significant differences ($p < 0.05$) between treatments regarding moisture, protein, fat, carbohydrate, fiber, and ash content. Moisture content exhibited a linear reduction, decreasing from 13.18 g in the control to 11.21 g in the S5 formulation.

Conversely, crude protein content demonstrated a gradual augmentation, rising from 8.58g to 10.97g across the treatments. Fat content followed an inverse trajectory, decreasing from 10.65 g to 5.14 g across treatments. The carbohydrates level is ranged between 73.4 g and 79.5 g, while crude fiber and ash content increased from 1.73 g to 2.07 g and 1.26 g to 2.05 g, respectively.

3.3 Correlation analysis

Pearson correlation analysis was conducted to elucidate the interrelationships between the physicochemical and nutritional variables across the six formulations (Table 4). Moisture content exhibited a robust inverse correlation with crude protein ($r = -0.96$), ash ($r = -0.96$), calcium ($r = -0.97$),

and phosphorus ($r = -0.95$). Conversely, protein levels in the PMF-substituted treatments demonstrated strong positive associations with mineral content. Lipid concentration showed a statistically significant negative correlation with both protein and mineral parameters. Furthermore, the high positive correlation coefficients—ranging from 0.98 to 1.00—observed among ash, calcium, phosphorus, and fiber underscore a concomitant increase in these nutritional components proportional to the level of PMF incorporation.

3.4 Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was performed on the pooled nutritional dataset to evaluate multivariate interrelationships and identify patterns among proximate and mineral parameters across the six cookie formulations (0–100% PMF substitution). The first two principal components (PC1 and PC2) collectively accounted for 97% of the total variance, with PC1 explaining 89% and PC2 contributing 8%.

Analysis of the factor loadings revealed that PC1 was characterized by high positive loadings for protein, crude fiber, ash, calcium, phosphorus, and iron, whereas moisture and fat content exhibited strong negative loadings. In contrast, PC2 was predominantly influenced by carbohydrate content and iron concentrations. The resulting PCA score plot (Figure 1) demonstrated a distinct segregation of treatments along the PMF substitution gradient. Formulations with higher PMF formulations clustering with higher protein and mineral contents, while the control and low-PMF treatments clustered with higher moisture and fat levels.

Table 3. Nutritional Profile of the Six Treatment Groups of cookies with PMF substitution

Treatment Code	Moisture (g)	Protein (g)	Carbohydrates (g)	Fat (g)	Crude Fibers (g)	Ash (g)	Calcium (mg/100 g)	Phosphorus (mg/100 g)	Iron (mg/100 g)
Control (0% PMF)	13.18±0.02	8.58±0.03	74±0.03	10.65±0.02	1.73±0.05	1.26±0.04	23.3±0.04	121.2±0.02	2.7±0.03
S1 (20% PMF)	13.05±0.01	8.63±0.05	74.2±0.05	10.02±0.02	1.77±0.04	1.31±0.02	24.2±0.02	129.1±0.02	3±0.05
S2 (40% PMF)	12.95±0.02	8.81±0.01	73.4±0.01	9.25±0.01	1.82±0.02	1.51±0.05	27.1±0.04	141.2±0.03	3.1±0.03
S3 (60% PMF)	12.54±0.01	9.22±0.02	75.6±0.02	8.15±0.04	1.89±0.04	1.71±0.02	29.8±0.05	153.3±0.02	5.2±0.02
S4 (80% PMF)	11.95±0.02	9.75±0.03	78.5±0.02	6.12±0.02	1.92±0.05	1.89±0.03	32.8±0.02	175.2±0.01	4.3±0.02
S5 (100% PMF)	11.21±0.05	10.97±0.01	79.5±0.04	5.14±0.03	2.07±0.02	2.05±0.05	37.0±0.05	227.2±0.02	6.53±0.02

Table 4. Correlation Matrix of Key Nutritional Parameters in Pearl Millet Cookies with PMF Substitution

Treatment Code	Moisture	Protein	Carbohydrates	Fat	Crude Fibers	Ash	Calcium	Phosphorus	Iron
Moisture	1	-0.98	-0.77	0.94	-0.95	-0.96	-0.97	-0.95	-0.82
Protein	-0.96	1	0.91	-0.99	0.98	0.98	0.98	0.97	0.89
Carbohydrates	-0.77	0.91	1	-0.93	0.85	0.82	0.83	0.83	0.69
Fat	0.94	-0.99	-0.93	1	-0.97	-0.97	-0.97	-0.96	-0.87
Crude Fibers	-0.95	0.98	0.85	-0.97	1	0.99	0.99	0.98	0.94
Ash	-0.96	0.98	0.82	-0.97	0.99	1	1	0.99	0.95
Calcium	-0.97	0.98	0.83	-0.97	0.99	1	1	0.99	0.95
Phosphorus	-0.95	0.97	0.83	-0.96	0.98	0.99	0.99	1	0.96
Iron	-0.82	0.89	0.69	-0.87	0.94	0.95	0.95	0.96	1

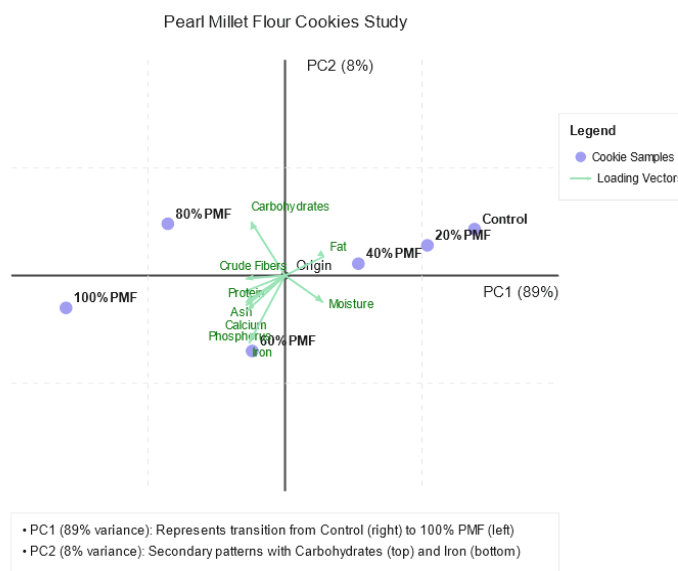


Figure 1: The Principal Component Analysis (PCA) matrix of treatment groups of cookies with PMF substitution

4 DISCUSSION

4.1 Impact of PMF Substitution on Sensory Attributes

The sensory evaluation (Table 2) indicates that incremental increases in PMF substitution significantly modulated the organoleptic profile of the formulations ($p < 0.05$). While scores for appearance, color, and texture exhibited a gradual attenuation as PMF levels rose, cookies containing up to 40% PMF maintained sensory parity with the control. The darkening of the crumb and the mildly coarse mouthfeel observed at higher inclusion levels are attributable to the natural pigmentation (anthocyanins and polyphenols), elevated fiber content, and larger particle size of pearl millet flour. These observations align with prior research on legume-

and millet-enriched baked goods, which suggests that moderate substitution levels preserve consumer acceptability while excessive inclusion adversely impacts visual and textural parameters (Kaur et al., 2015; Saleh et al., 2013). Notably, the relative stability of taste scores indicates that PMF incorporation does not compromise palatability at technologically viable substitution levels.

4.2 Nutritional Amelioration through PMF Incorporation

Proximate and mineral analyses (Table 3) exhibit a robust upward trajectory in nutritional density proportional to PMF substitution. The significant increases in crude protein, ash, fiber, and essential minerals (calcium, phosphorus, and iron) reflect the nutrient-dense profile of pearl millet, a finding

corroborated by studies on composite millet-based bakery systems (Chandrasekara & Shahidi, 2011).

A notable reduction in lipid content was observed as PMF inclusion increased ($p < 0.05$). This decrease may be attributed to a synergistic interplay of factors: the lower intrinsic lipid profile of pearl millet relative to refined wheat (Saleh et al., 2013); the high dietary fiber content which alters dough rheology and reduces fat-binding capacity (Devi et al., 2014); and the dilution of the gluten matrix, which diminishes structural cohesion and facilitates lipid migration during thermal processing (Bala et al., 2014). Furthermore, the increased porosity associated with coarser PMF particles may enhance surface fat transport (Cheng & Bhat, 2016). Collectively, these mechanisms highlight the potential of PMF as a functional ingredient for the formulation of reduced-fat bakery products.

4.3 Nutrient Interrelationships and Multivariate Insights

Correlation analysis (Table 4) revealed robust positive associations between protein, ash, crude fiber, and minerals, confirming that PMF enrichment concurrently enhances multiple nutritional attributes. In addition, the significant inverse correlation between moisture/fat and protein/minerals suggests that increasing nutrient density is associated with reduced lipid and moisture retention. The PCA results strengthen these relationships by clearly segregating PMF-enriched formulations from the control. The multivariate approach demonstrates that PMF substitution induces a systematic nutritional shift rather than isolated variations. By moving beyond univariate analysis, this study addresses a frequent methodological limitation in cereal research, providing a holistic interpretation of the nutritional landscape.

4.4 Safety and Anti-Nutritional Considerations

Pearl millet is a globally recognized staple cereal, characterized by a lack of intrinsic toxicity. While it contains moderate concentrations of anti-nutritional factors (ANFs) such as phytates and tannins, these compounds are substantially degraded during milling and high-temperature baking (Obilana & Manyasa, 2002; Navinraj et al., 2025). Extensive literature confirms the safety, bioavailability, and nutritional suitability of pearl millet-based food systems for human consumption (Meena et al., 2024). Consequently, the PMF-substituted formulations in this study present no toxicological or safety concerns.

4.5 Technological Viability and Sustainable Development

This study establishes the technological viability of incorporating PMF into bakery systems to produce

nutritionally superior cookies without significant sensory compromise at substitution levels of 20 – 40%. The integration of composite flour technology with multivariate evaluation aligns with the development of sustainable food systems utilizing climate-resilient, underutilized cereals. This development is in line with the application of climate-resilient, underutilized cereals, and with sustainable food systems development. Such innovations hold significant promise for functional food development, school feeding initiatives, and commercial bakery sectors targeting health-conscious consumers. Furthermore, the utilization of pearl millet supports the attainment of United Nations Sustainable Development Goals (SDG 2: Zero Hunger; SDG 3: Good Health and Well-being) by leveraging agrobiodiversity for public health interventions.

4.6 Limitation and Prospective Research

Nevertheless, the positive findings, this study is subject to certain limitations. Long-term shelf-life stability, textural evolution during storage, and consumer acceptance across broader demographic cohorts remain to be elucidated. Moreover, the mineral bioavailability and the impact of processing on the glycemic response were beyond the current scope. Future investigations should focus on shelf-life kinetics, glycemic index (GI), profiling, and the optimization of PMF pre-treatments—such as fermentation or hydrothermal processing—to further enhance organoleptic quality at higher substitution levels.

5 CONCLUSIONS

This investigation demonstrates that the partial substitution of wheat flour with pearl millet flour (PMF) significantly enhances the nutritional profile of cookies while preserving acceptable sensory characteristics at moderate inclusion levels. The gradual incorporation of PMF facilitated a substantial increase in crude protein, dietary fiber, and essential minerals—specifically calcium, phosphorus, and iron—concurrent with a reduction in total fat content.

Sensory analysis indicated that formulations with up to 40% PMF substitution were statistically comparable to the control in terms of overall acceptability, suggesting commercial feasibility. Multivariate PCA further corroborated a fundamental nutritional transition from moisture- and lipid-dominant profiles toward protein- and mineral-rich matrices. Given the established safety of pearl millet and the effective reduction of anti-nutritional factors during baking, PMF emerges as a functional, sustainable, and climate-resilient ingredient. These findings offer a pragmatic strategy for the food industry to produce nutrient-dense, low-fat baked goods, contributing to global efforts to mitigate malnutrition and diet-related non-communicable diseases (NCDs).

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