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Development and Evaluation of Nutritionally-Enriched Breadsticks Using Sweet Lupin and Pearl Millet Powders as Partial Wheat Flour Substitutes

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ABSTRACT

This study evaluated the influence of partially substituting wheat flour (WF) with lupin seed powder (LSP) and pearl millet powder (PMP) on the nutritional composition, rheological behavior, antioxidant potential, and sensory characteristics of breadsticks. Four substitution blends M10, M20, M30, and M40 were tested alongside a control sample. Proximate analysis revealed that LSP had the highest protein (41.50%), fat (7.20%), and crude fiber (14.90%) contents, while PMP was richest in antioxidants, exhibiting the highest total phenolic content (120mg GAE/g) and flavonoid content (29.44mg QE/g). Amino acid profiling showed that both LSP and PMP significantly improved the essential amino acid composition and chemical scores compared to WF, particularly for lysine, isoleucine, and valine. Farinograph and extensograph analyses indicated that moderate substitution levels especially M20 enhanced dough stability and water absorption. However, higher substitution levels reduced extensibility and dough strength due to gluten dilution. Texture analysis demonstrated that substitution increased hardness, cohesiveness, and chewiness, with M10 and M20 maintaining acceptable mechanical properties. Nutritionally, increasing LSP and PMP levels enhanced protein, crude fiber, ash, and mineral contents, while reducing available carbohydrates and caloric energy values. Sensory evaluation confirmed that breadsticks with up to 20% substitution retained high consumer acceptability, with M10 closely matching the control in taste, texture, and overall appeal. These findings suggest that incorporating LSP and PMP at moderate levels (M10 and M20) can nutritionally enrich breadsticks without compromising their functional and sensory qualities, offering a promising approach to developing health-oriented baked products.

1. Introduction

Vegetable-based ingredients with high nutritional value include pulses, which are notably rich in protein, dietary fiber, vitamins, and minerals (Boukid & Pasqualone, 2022; Mospah et al., 2024). From a nutritional perspective, combining pulses with cereals creates a complementary amino acid profile: pulses are abundant in lysine but lack methionine, whereas cereals are rich in methionine but deficient in lysine (Marinangeli, 2020; Mospah et al., 2024). Lupin is one of the lesser-studied pulses with significant potential as a highly nutritious ingredient to meet the dietary needs of the growing global population in the coming decades (van de Noort, 2024).

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Belonging to the legume family, lupin (*Lupinus* spp.) is notable for its high protein content approximately 35 g per 100 g of dry matter (DM) and substantial crude fiber content of about 40g/100g DM (Nigro et al., 2025). Moreover, lupin proteins are a valuable source of bioactive peptides known for their health-promoting properties, including blood sugar regulation, cholesterol reduction, and antioxidant activity (Boukid & Pasqualone, 2022). Conversely, some compounds naturally present in seedssuch as alkaloids, anti-nutritional factors, and enzyme inhibitors may exert undesirable effects (Boukid & Pasqualone, 2022; Prusinski, 2017). Nonetheless, research has demonstrated that replacing wheat with lupin in bread formulations significantly enhances nutritional value, particularly in terms of protein and mineral content (Prusinski, 2017; Plustea et al., 2022). According to Nigro et al. (2025), incorporating lupin into bread also promotes greater satiety and reduces overall energy intake. However, using lupin flour at substitution levels ranging from 5 to 30g/100g can adversely affect dough rheology and the technological quality of the final bread product (Villarino et al., 2014; Villarino et al., 2015; Guardianelli et al., 2023; Spina et al., 2024). This is primarily due to gluten dilution, which compromises dough stability (Guardianelli et al., 2023; Dervas et al., 1999), resulting in breads with lower specific volume, reduced loaf height, and a firmer crumb texture (Plustea et al., 2022; Dervas et al., 1999). Millet refers to a group of small-seeded grasses that have served as staple foods for both humans and animals for thousands of years. It is predominantly cultivated in Africa and Asia, with smaller production in parts of Europe and the Americas. Common varieties include pearl millet, finger millet, foxtail millet, and proso millet. Millet grains are highly nutritious, providing a rich supply of dietary fiber, protein, essential vitamins, and minerals. They are naturally gluten-free, making them suitable for individuals with celiac disease or gluten sensitivity. Millet is also notable for its high antioxidant content, which contributes to health benefits such as improved digestive health, reduced risk of cardiovascular disease, and better blood sugar regulation. Millet's versatility allows it to be prepared in various forms, including porridge, bread, and pilaf, or ground into flour for baked goods. In certain regions, millet is also fermented to produce alcoholic beverages. Despite its nutritional advantages and diverse culinary applications, millet remains underutilized in many parts of the world. However, interest in millet is growing, particularly as a sustainable and climate-resilient food source in areas affected by environmental change and declining agricultural productivity. Rich in antioxidants such as phenolic acids, avenanthramides, flavonoids, lignans, and phytosterols, millet helps protect the body against oxidative stress and free radical damage, thereby supporting overall health (Dixit & Ravichandran, 2024). Bakery products such as bread, cakes, muffins, and similar items remain widely popular, with wheat flour both whole and refined serving as their primary ingredient. Incorporating millet flour into bakery formulations has been shown to significantly improve their nutritional value by increasing fiber and micronutrient content, while also providing additional health benefits. Ongoing research focuses on partially replacing wheat flour with millet flour to enhance the nutritional profile of traditional baked goods. Varieties such as finger millet and foxtail millet have already been incorporated into muffins, cookies, cakes, and biscuits. Studies confirm that bakery items containing appropriate levels of millet flour maintain consumer acceptability in terms of taste, texture, and appearance (El-Hadidy et al., 2024; Jain et al., 2024; Sharma et al., 2024). Wheat is a major staple cereal crop worldwide and belongs to the *Triticum* genus, with *T. aestivum* subsp. *vulgare* and the hard wheat *T. durum* being the most commercially important species. Wheat dietary fiber intake has been linked to the prevention of several chronic diseases. Wheat's popularity in bread production is attributed to its long shelf life, pleasant flavor, and unique gluten-forming properties (El-Hadidy et al., 2020; El-Hadidy et al., 2024). Breadsticks, characterized by their thin, pencil-like shape, are baked goods known for their crisp texture and long shelf life. They are widely consumed for their palatable taste and convenience, and they serve as an excellent medium for nutritional fortification, as demonstrated in previous research (El-Hadidy et al., 2020; Rainero et al., 2022; Shaban et al., 2023). Based on these findings, the objective of this study was to partially substitute wheat flour in breadsticks with lupin seed powder and pearl millet powder to enhance their nutritional value and sensory properties, ultimately aiming to develop a high quality, health-oriented product.

2. Materials and Methods

Materials

Source of Raw Materials

Sweet lupin seeds were obtained from the Agricultural Research Center in Giza, Egypt, during the 2024 harvest season and stored in a deep freezer at −20°C until further use. Pearl millet seeds were sourced from the Field Crops Department at the Agricultural Research Center, Giza, Egypt, during the same harvest season and similarly stored at −20°C until use. Wheat flour (72% extraction) was purchased from the Delta Middle and West Milling Company, Tanta, Egypt. Table salt, baker's yeast, sugar, shortening, and baking powder were procured from local markets in Kafrelsheikh City, Egypt.

Sample preparation

Sweet lupin seeds and pearl millet seeds were milled using a Willy mill (IKA, model A11 BS000, Germany) until the powders passed through a 60-mesh sieve. The resulting powders were then packed in polyethylene bags for storage (Abdel-Gawad et al., 2016).

Gross Chemical Composition

The moisture, fat, protein, fiber, and ash contents were determined for lupin seed powder, pearl millet powder, wheat flour, and the various rusk formulations. The mineral composition including potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), phosphorus (P), iron (Fe), zinc (Zn), and manganese (Mn) was analyzed in the rusk samples according to the methods described in AOAC (2012).

The available carbohydrate content (dry weight basis) was calculated using the following formula:

Available carbohydrates (%) = 100 – (% protein+ % fat + % ash + % crude fiber)

Energy Value

As described by James (1995), the energy content was calculated using the following formula:

Energy (kcal/100g)= 9.1 × (% fat) + 4.1 × (% available carbohydrates + % protein)

Determination of Total Polyphenols

Total Polyphenolic Content (TPC)

Total polyphenolic content was determined using the Folin Ciocalteu reagent according to the method described by Thaipong et al. (2006). A UV spectrophotometer (Varian, Melbourne, VIC, Australia) was used to measure absorbance at 760nm, with gallic acid as the standard. Results were expressed as milligrams of gallic acid equivalents per gram of dry matter (mg GAE/g DM).

Total Flavonoid Content

Total flavonoid content was measured following the method described by Vuong et al. (2014). Absorbance was recorded at 510nm using a UV spectrophotometer (Varian, Melbourne, VIC, Australia), with quercetin as the standard. Results were expressed as milligrams of quercetin equivalents (mg QE/g DM).

Antioxidant Activity

Antioxidant activity was evaluated using the DPPH free radical scavenging assay, as described by Lee et al. (2004). The percentage of DPPH radical inhibition was calculated according to formula:

$$\text{Inhibition (\%)} = [(A_c - A_s) / A_c] \times 100$$

Where, Ac represents the absorbance of the control, and As represents the absorbance of the sample.

Amino Acid Profiling

The amino acid profiles of wheat flour (72% extraction), lupin seed powder, and pearl millet powder were analyzed at the National Research Center, Giza, Egypt. Samples were subjected to acid hydrolysis using 6N hydrochloric acid (HCl). Following hydrolysis, the acid was removed by evaporation using a rotary evaporator to obtain the hydrolysate. Amino acid content was determined using an amino acid analyzer (LC 3000; LC Biochrome, Eppendorf, Germany). The analysis was performed in accordance with the procedures outlined by AOAC (2012).

Chemical Score of Amino Acids

The chemical scores for essential amino acids were determined according to the FAO/WHO/UNU (1985) method, using the following formula:

$$\text{Chemical score} = \frac{\text{Essential amino acid / 100 g protein in sample}}{\text{Essential amino acid / 100 g protein in FAO / WHO/UNU}} \times 100$$

* The amino acid with the lowest percentage value is referred to as the limiting amino acid, and the calculated ratio represents its chemical score.

Computed Protein Efficiency Ratio (C-PER)

The C-PER was estimated to use the equation developed by Alsmeyer et al. (1974), as formula:

PER= -0.468 + 0.454 × (leucine) - 0.105 × (tyrosine)

Computed Biological Value

The biological value (BV) was calculated according to the method described by Farag et al. (1996), using the following formula:

$$BV = 49.9 + 10.53 \times \text{C-PER}$$

Where, C-PER represents the computed protein efficiency ratio.

Rheological Analyses

Farinograph analysis

Water absorption, arrival time, dough development time, dough stability, and degree of softening were measured using a Farinograph (Brabender, Duisburg, Type 810105001, No. 941026, West Germany), following the procedures described by AACC (2000).

Extensograph Analysis

Dough extensibility, resistance to extension (elasticity), proportional number, and dough energy were determined using an Extensograph (Brabender, Duisburg, Type 860001, No. 946003, West Germany), according to the method specified by AACC (2000).

Breadstick Preparation

Breadsticks were prepared using wheat flour (72% extraction rate) blended with lupin seed powder and pearl millet powder, as outlined in Table A.

Breadstick Preparation

The straight dough method was used for breadstick preparation. Sugar, fat, table salt, and dry yeast were added to each flour blend along with warm water and vegetable oil, and the mixture was kneaded thoroughly by hand. The dough was fermented at room temperature (30±2°C) for 30min, then divided into portions and allowed to rest for 10 min. Each portion was shaped into the final breadstick form and subjected to a second fermentation for 30 min at 30 ° C with 90% relative humidity. The fermented dough pieces were baked at 170°C for 30 min. (Shaban et al., 2023).

Table A. Breadsticks preparation

Ingredients (g)	Control	M10	M20	M30	M40
WF	100	90	80	70	60
LSP	--	5	10	15	20
PMP	--	5	10	15	20
Salt	0.5	0.5	0.5	0.5	0.5
Yeast	0.6	0.6	0.6	0.6	0.6
Sugar	08	08	08	08	08
vegetable oil	10	10	10	10	10

WF=wheat flour of 72% extraction rate LSP= Lupin seeds powder PMP= pearl millet powder

Sensory Evaluation

The sensory evaluation of the prepared breadsticks made from wheat flour (72% extraction rate) and blends of lupin seed powder and pearl millet powder was conducted by a panel of ten trained panelists. Attributes assessed included flavor, texture, color, taste, and overall acceptability. A 10-point hedonic scale was used, where scores of 9–10 indicated excellent, 6–8 very good, 4–5 fair, and 2–3 unacceptable, following the method described by Renzo (1975).

Statistical Analysis

Data were analyzed using SPSS software (version 26). Mean comparisons were performed using Duncan's multiple range test to determine significant differences among treatments.

3. Results and Discussion

The composition of wheat flour, lupin seed powder and pearl millet powder

Table 1 presents a comparative profile of the nutritional, mineral, and phytochemical compositions of three raw materials: wheat flour (72% extraction), lupin seed powder, and pearl millet powder. Wheat flour shows the highest moisture content (14.40%), markedly greater than that of lupin seed powder (6.30%) and pearl millet powder (5.00%), indicating its comparatively lower dry matter concentration. In terms of crude protein, lupin seed powder stands out with 41.50%, far exceeding pearl millet (14.20%) and wheat flour (11.80%), highlighting its potential as a rich plant-based protein source. A similar pattern is observed in fat and crude fiber contents, with lupin again recording the highest values (7.20% fat and 14.90% crude fiber), followed by pearl millet and wheat flour, reflecting lupin's superior nutritional density (Kefale and Yetenayet, 2020). Wheat flour, however, contains the highest percentage of available carbohydrates (85.05%) and total carbohydrates (85.85%), underscoring its primary role as an energy-rich carbohydrate source. Pearl millet has moderately high carbohydrate levels, while lupin shows the lowest, consistent with its higher protein and fiber contents. This trend is also reflected in caloric values: wheat flour provides the highest energy (413.47 kcal/100 g), followed by pearl millet (407.18 kcal/100 g), with lupin contributing the least (369.33 kcal/100 g). Regarding mineral composition, lupin again dominates, with significantly higher potassium (1200 mg/100g), calcium (190.30mg), and magnesium (205.00mg) compared to the other two ingredients. Pearl millet generally ranks second in mineral content but leads in iron (8.00mg), followed by lupin (5.90 mg) and wheat flour (2.55mg). Pearl millet also has the highest manganese content (4.00mg), whereas phosphorus is most abundant in wheat flour (180.45 mg). Sodium content is greatest in wheat flour (23.20 mg), likely due to processing. Phytochemical and antioxidant profiles reveal notable differences. Pearl millet powder contains the highest total phenolic content (TPC, 120mg GAE/g) and total flavonoid content (TFC, 29.44mg QE/g), along with the greatest antioxidant activity (81.20%). Lupin ranks second in these parameters, while wheat flour scores lowest, indicating limited functional or health-promoting compounds. Overall, these findings suggest that lupin seed powder is nutritionally rich in proteins, fats, fibers, and key minerals (Kefale and Yetenayet, 2020), while pearl millet excels in antioxidant and phytochemical properties. Wheat flour, though energy-dense and high in carbohydrates, is comparatively limited in other nutritional and functional components. Incorporating lupin and pearl millet into food formulations could therefore enhance both nutritional value and functional quality (Salem et al., 2023; Sharma et al., 2024; Khattab et al., 2024; Mospah et al., 2024; Abd Rahman et al., 2025; Elbassiony et al., 2025; El-Hadidy et al., 2025).

Amino acids of lupin seed powder, pearl millet powder and wheat flour 72% extraction (g/100g of Protein)

Table 2 presents a comparative analysis of essential and non-essential amino acid compositions (g/100 g protein) for wheat flour (72% extraction), lupin seed powder, and pearl millet powder, alongside the reference amino acid pattern proposed by FAO/WHO/UNU (1985). The table also includes calculated protein quality indices C-PER (Calculated Protein Efficiency Ratio) and BV (Biological Value). Wheat flour contains the lowest total essential amino acids (EAA; 36.15g/100g protein) compared with lupin (40.85) and pearl millet (40.75). Among EAA, lysine commonly the limiting amino acid in cereals is particularly low in wheat (3.20), but markedly higher in lupin (6.70) and pearl millet (4.30), with both approaching or exceeding the FAO/WHO/UNU requirement (5.80). Isoleucine, leucine, and valine contents are also higher in millet and lupin than in wheat, and all exceed the reference pattern. Threonine and tryptophan are present at relatively higher levels in lupin and millet compared to wheat. In contrast, methionine a sulfur-containing amino acid is notably deficient in lupin (0.95), falling well below the recommended 2.20g, which could limit its protein quality despite its high overall EAA content. For non-essential amino acids (NEAA), wheat flour has the highest total (62.35g/100g protein), largely due to its elevated glutamic acid (30.00) and proline (9.95) contents. Lupin and pearl millet have lower total NEAA (52.50 and 53.00, respectively), but show a more balanced distribution, with higher aspartic acid and arginine contents than wheat. Alanine is most abundant in millet (7.90), which may support better energy metabolism (Khattab et al., 2024). Protein quality metrics reveal a similar trend. Wheat flour exhibits the lowest C-PER (2.29) and BV (74.01), indicating relatively poor digestibility and biological utilization. Lupin shows moderate improvement (C-PER: 2.51; BV: 76.30), while pearl millet achieves the highest values (C-PER: 3.35; BV: 85.12), suggesting superior protein quality. These results reinforce the potential of lupin and pearl millet as valuable plant protein sources, particularly when incorporated into blends to complement wheat's amino acid limitations (Salem et al., 2023; Khattab et al., 2024).

Table 1. The analysis composition of wheat flour, lupin seed powder and pearl millet

Raw materials	Wheat flour 72%	Lupin seed powder	pearl Millet powder
Moisture	$14.40^{a}\pm0.05$	$6.30^{b}\pm0.02$	$5.00^{c}\pm0.02$
Crude protein%	$11.80^{c}\pm0.03$	$41.50^{a}\pm0.05$	$14.20^{b}\pm0.06$
Fat%	$1.80^{c}\pm0.03$	$7.20^{a}\pm0.04$	$6.20^{b}\pm0.04$
Crude fiber%	$0.80^{c}\pm0.02$	$14.90^{a}\pm0.05$	$5.00^{b}\pm0.05$
Ash%	$0.55^{c}\pm0.01$	$3.80^{a}\pm0.03$	$3.25^{b}\pm0.04$
Available carbohydrates%	$85.05^{a}\pm0.15$	$32.60^{c}\pm0.15$	$71.35^{b}\pm0.04$
Total carbohydrates%	$85.85^{a}\pm0.10$	$47.50^{c}\pm0.10$	$76.35^{b}\pm0.06$
Energy (K Cal /100g)	$413.47^{a}\pm0.12$	$369.33^{c}\pm0.12$	$407.18^{b}\pm0.09$
Minerals (mg /100g)			
K	$130.60^{c}\pm0.70$	$1200^{a}\pm3.10$	$380.30^{b}\pm4.0$
Ca	$32.21^{b}\pm0.30$	$190.30^{a}\pm0.90$	$22.50^{c}\pm0.60$
Mg	$123.40^{c}\pm0.45$	$205.00^{a}\pm0.50$	$150.35^{b}\pm0.40$
Na	$23.20^{a}\pm0.10$	$20.00^{b}\pm0.05$	$6.20^{c}\pm0.04$
P	$180.45^{a}\pm0.10$	$65.00^{c}\pm0.15$	$160.45^{b}\pm2.0$
Fe	$2.55^{c}\pm0.01$	$5.90^{b}\pm0.02$	$8.00^{a}\pm0.04$
Zn	$3.50^{c}\pm0.01$	$4.95^{a}\pm0.02$	$4.30^{b}\pm0.01$
Mn	$3.80^{c}\pm0.01$	$3.90^{b}\pm0.02$	$4.00^{a}\pm0.01$
Antioxidants			
TPC (mg GAE/g)	$0.75^{c}\pm0.05$	$30.40^{b}\pm0.06$	$120^{a}\pm0.10$
TFC (mg of QE/g)	$0.15^{c}\pm0.02$	$20.20^{b}\pm0.03$	$29.44^{a}\pm0.05$
Antioxidant activity (%)	$50.20^{c}\pm0.06$	$70.00^{b}\pm0.05$	$81.20^{a}\pm0.04$

Means with different letters in the same row are significantly different at LSD at ($p \leq 0.05$).
- Each value was an average of three determinations ± standard deviation.

Indispensable amino acids and chemical scores

Table 3 presents the indispensable amino acid profiles of wheat flour (WF), lupin seed powder (LSP), and pearl millet powder (PMP), along with their chemical scores relative to the FAO/WHO/UNU (1985) reference amino acid pattern. The chemical score, expressed as a percentage, is calculated as the ratio of the amino acid content in the sample to that in the reference pattern. Scores below 100% indicate limiting amino acids, which can constrain protein quality. In WF, lysine is the first limiting amino acid, with a chemical score of 55.17%, indicating a pronounced deficiency relative to the reference value (5.80g/100g protein) a well documented shortcoming of cereal proteins. Threonine and phenylalanine are the second and third limiting amino acids, respectively. In contrast, isoleucine (141.07%), leucine (106.06%), methionine (134.00%), valine (124.29%), and tryptophan (120.00%) exceed the reference values. LSP exhibits a markedly improved amino acid profile. Lysine content (6.70g/100g protein) surpasses the reference value, yielding a chemical score of 115.52%, and thus is not a limiting amino acid. Other EAAs, including isoleucine, histidine, threonine, and tryptophan, also exceed the FAO/WHO/UNU pattern. Methionine remains the lowest-scoring EAA (114.00%) but still exceeds the minimum requirement, indicating no limiting amino acid in LSP. PMP shows a similarly balanced profile. Lysine, although still limiting at 74.14%, is present in higher amounts than in WF, suggesting an improvement in protein quality when used in blends. PMP demonstrates particularly high scores for isoleucine (167.86%), leucine (136.36%), valine (167.14%), methionine (160.00%), and tryptophan (145.00%), with threonine and phenylalanine also surpassing 100%. Overall, both LSP and PMP substantially improve amino acid balance when blended with WF, particularly by compensating for its lysine deficiency. This complementary effect could enhance the protein quality of composite flours for bread-making and other cereal-based products, offering a more complete amino acid profile for populations reliant on wheat as a staple.

Table 2. Amino acids of lupin seed powder pearl millet powder and wheat flour 72% extraction (g/100g of Protein)

Amino acids	Wheat flour 72%	Lupin seed powder	pearl millet powder	FAO/WHO/UNU (1985) pattern
Lysine	3.20	6.70	4.30	5.80
Isoleucine	3.95	4.20	4.70	2.80
Leucine	7.00	6.90	9.00	6.60
Phenylalanine	4.30	5.50	4.95	6.30
Tyrosine	4.00	1.50	2.60	
Histidine	2.10	2.90	2.50	1.90
Valine	4.35	4.60	5.85	3.50
Threonine	2.70	3.90	4.40	3.40
Methionine	1.65	0.95	2.60	2.20
Tryptophan	1.20	1.80	1.45	1.00
Cysteine	1.70	1.90	1.40	
Total (EAA)	36.15	40.85	40.75	
Aspartic acid	5. 00	9.00	9.30	
Glutamic acid	30.00	22.0	19.10	
Serine	5.00	4.00	3.80	
Proline	9.95	3.7	5.10	
Glycine	5.00	3.6	3.40	
Alanine	3.20	3.2	7.90	
Arginine	4.20	7.00	4.40	
Total (NEAA)	62.35	52.50	53.00	
C-PER	02.29	02.51	03.35	
BV	74.01	76.30	85.12	

EAA: Essential amino acids. NEAA: Nonessential amino acids, C-PER = Computed protein efficiency ratio. BV = Biological value

Table 3. Chemical scores of essential amino acids in wheat flour, lupin seed powder, and pearl millet powder compared to FAO/WHO/UNU (1985) reference pattern

Amino acids	WF	Chemical scores	LSP	Chemical scores	PMP	Chemical scores	FAO/WHO/ UNU (1985) pattern
Lysine	3.20	*55.17	6.70	115.52	4.30	*74.14	5.80
Isoleucine	3.95	141.07	4.20	150	4.70	167.86	2.80
Leucine	7.00	***106.06	6.90	104.55	9.00	136.36	6.60
Phenylalanine	4.30	131.75	5.50	*111.11	4.95	**119.84	6.30
Tyrosine	4.00		1.50		2.60		
Histidine	2.10	110.53	2.90	152.63	2.50	131.58	1.90
Valine	4.35	124.29	4.60	131.43	5.85	167.14	3.50
Threonine	2.70	**79.41	3.90	***114.71	4.40	***129.41	3.40
Methionine	1.65	134	0.95	**114	2.60	160	2.50
Cysteine	1.70		1.90		1.40		
Tryptophan	1.20	120	1.80	180	1.45	145	1.00

*First limiting amino acids, **Second limiting amino acids, ***Third limiting amino acids

Farinograph profile

Table 4 presents the farinograph characteristics of wheat flour (WF) partially substituted with lupin seed powder (LSP) and pearl millet powder (PMP) at varying inclusion levels. Water absorption capacity showed slight variation among blends. The control (WF 100%) exhibited a water absorption of 63.2%, with a minor reduction in M10 (62.6%). At higher substitution levels, absorption increased, reaching 66.3% in M40. This trend suggests that blends containing greater proportions of LSP and PMP absorb more water, likely due to their higher crude fiber and protein contents, which enhance water-binding capacity (Plustea et al., 2022; Nigro et al., 2025). Arrival time remained constant at 1.00 min across all formulations, indicating that initial dough formation was not markedly influenced by the addition of LSP and PMP. Dough development time was consistent at 1.5 min. for most samples, except M30, which increased to 2.5min. possibly reflecting delayed gluten development caused by interference from non-gluten proteins and fiber. Dough stability improved markedly with the inclusion of LSP and PMP. The control sample exhibited a stability of 2.5 min. which increased in the substituted samples, peaking at 7.5min. in M20. This suggests enhanced dough strength and resistance to mechanical mixing at moderate substitution levels. However, stability declined in M30 (6.5min.) and M40 (5.0 min), likely due to gluten dilution and excessive fiber disrupting gluten network formation. Dough weakening, reflected by the degree of softening, rose progressively from 70 B.U. in the control to 110 B.U. in M40, indicating that higher LSP and PMP incorporation produced softer dough. This effect is most likely attributable to the high crude fiber content and non-gluten proteins weakening the gluten structure.

Table 4. Farinograph characteristics of wheat flour (WF) substituted with lupin seed powder (LSP) and pearl millet powder (PMP)

Parameters	Water absorption (%)	Arrival time (min.)	Dough development time (min.)	Dough Stability (min.)	Degree of softening (B.U)
Control	63.2	1.00	1.5	2.5	70
M10	62.6	1.00	1.5	3.0	60
M20	63.5	1.00	1.5	7.5	70
M30	63.5	1.00	2.5	6.5	80
M40	66.3	1.00	1.5	5.0	110

Extensograph analysis

Table 5 presents the extensograph parameters of dough samples prepared by partially substituting wheat flour (WF) with lupin seed powder (LSP) and pearl millet powder (PMP) at varying inclusion levels. Parameters evaluated included elasticity, extensibility, the ratio of resistance to extensibility (P/N), and energy, all of which are key indicators of dough rheology and baking performance. Elasticity, which measures the dough's resistance to extension, increased significantly at the 10% substitution level (M10), reaching 480 B.U. compared to 280 B.U. in the control. This suggests a firmer, more elastic dough, likely due to the protein-rich composition of LSP and PMP. However, elasticity decreased progressively with higher substitution levels, reaching 170 B.U. in M40, indicating disruption of the gluten network and reduced dough strength. Extensibility, reflecting how far the dough can stretch before breaking, was highest in the control (130mm) but dropped sharply in M10 (65mm) and reached its lowest value in M30 (50mm). This reduction suggests gluten dilution and interference from crude fiber. Interestingly, M40 showed a modest recovery in extensibility (70mm), possibly due to altered hydration dynamics at higher fiber content. The P/N ratio, representing the balance between strength and extensibility, was markedly higher in M10 (7.39) than in the control (2.15), indicating a strong but less extensible dough that may be more difficult to handle. More moderate ratios in M20 (2.10) and M40 (2.43) suggest a better balance, though still distinct from the control (Plustea et al., 2022). Energy, which quantifies the total work required to stretch the dough, was highest in the control (67cm²) and declined steadily with higher substitution levels, reaching a minimum in M40 (21 cm²). This decline reflects weakened gluten structure and reduced gas retention capacity, which may impair loaf volume and crumb texture. Overall, low substitution levels (notably M10) enhanced elasticity but reduced extensibility, while higher levels diminished both extensibility and energy. Moderate substitution (around M20) may provide the most favorable compromise between improved nutritional profile and acceptable dough handling properties.

Table 5. Extensograph characteristics of wheat flour (WF) substituted with lupin seed powder (LSP) and pearl millet powder (PMP)

Parameters	Elasticity (B.U)	Dough Extensibility (mm)	P/ N ratio	Energy (cm^2)
Control	280	130	2.15	67
M10	480	65	7.39	46
M20	210	100	2.10	35
M30	220	50	4.40	32
M40	170	70	2.43	21

Sensory attributes of breadsticks enriched with sweet lupin and pearl millet powders

Table 6 presents the sensory characteristics of breadsticks prepared by replacing wheat flour (WF) with varying levels (10–40%) of lupin seed powder (LSP) and pearl millet powder (PMP). Attributes evaluated included color, taste, flavor, texture, and overall acceptability, using a 10-point hedonic scale.

The control sample (WF 100%) achieved the highest scores across all attributes color (9.50), taste (9.30), flavor (9.80), texture (9.50), and overall acceptability (9.60) indicating excellent sensory quality and confirming WF as the most preferred base for breadstick production. At 10% substitution (M10: WF:LSP:PMP = 90:5:5), scores remained close to the control, with only slight reductions color and taste (9.00), flavor (9.30), texture (9.10), and overall acceptability (9.00) suggesting that minimal incorporation of LSP and PMP does not compromise, and may slightly enhance, sensory appeal. Increasing substitution to 20% (M20) led to moderate reductions, with color decreasing to 8.00 and overall acceptability to 8.50, though the product remained generally well accepted. At 30% (M30), scores for color (7.50), taste (8.10), and overall acceptability (8.00) showed further decline, reflecting reduced consumer preference. The most pronounced drop occurred in M40, with color (7.00) and overall acceptability (7.50) indicating noticeable impacts on appearance and taste at higher substitution levels. Overall, substitution with LSP and PMP up to 10–20% maintained acceptable sensory quality, whereas higher levels (≥30%) significantly reduced consumer preference, likely due to changes in color, taste, and texture arising from the functional properties of LSP and PMP (Kefale & Yetenayet, 2020; Plustea et al., 2022).

Table 6. Sensory scores of breadsticks formulated with different substitution levels of lupine seeds powder (LSP) and pearl millet powder (PMP)

Blends	Color (10)	Taste (10)	Flavor (10)	Texture (10)	overall acceptability (10)
Control	$9.50^{a}\pm0.15$	$9.30^{a}\pm0.15$	$9.80^{a}\pm0.30$	$9.50^{a}\pm0.20$	$9.60^{a}\pm0.30$
M10	$9.00^{b}\pm0.10$	$9.00^{b}\pm0.13$	$9.30^{b}\pm0.25$	$9.10^{b}\pm0.12$	$9.00^{b}\pm0.25$
M20	$8.00^{c}\pm0.20$	$8.50^{c}\pm0.20$	$8.70^{c}\pm0.15$	$8.80^{c}\pm0.17$	$8.50^{c}\pm0.20$
M30	$7.50^{d}\pm0.25$	$8.10^{d}\pm0.14$	$8.20^{d}\pm0.20$	$8.30^{d}\pm0.20$	$8.00^{d}\pm0.15$
M40	$7.00^{e}\pm0.13$	$7.60^{e}\pm0.30$	$7.90^{e}\pm0.35$	$8.00^{e}\pm0.10$	$7.50^{e}\pm0.22$

Each value was an average of ten determination ± standard deviation
Different letters indicate to significant differences between blends in the same column($p\leq0.05$)

Texture properties of breadsticks with LSP and PMP substitution

Table 7 presents the texture properties of breadsticks prepared by replacing wheat flour (WF) with lupin seed powder (LSP) and pearl millet powder (PMP) at substitution levels of 10–40%. The evaluated parameters included hardness (N), cohesiveness, adhesiveness (MJ), and chewiness (MJ), all of which are key indicators of mechanical performance and consumer perception.

The control breadsticks (WF 100%) recorded the lowest values across all parameters: hardness (37.50N), cohesiveness (2.50), adhesiveness (0.55MJ), and chewiness (105MJ) indicating a soft, light, and easy-to-chew product consistent with typical consumer expectations for crisp breadsticks. With 10% substitution (M10:WF:LSP:PMP = 90:5:5), hardness increased to 42.50N and chewiness to 115MJ, while cohesiveness (2.90) and adhesiveness (0.60MJ) also rose slightly, suggesting a firmer structure and marginally stickier mouthfeel. At 20% substitution (M20), further increases were observed hardness (48.33N), chewiness (120MJ), cohesiveness (3.20), and adhesiveness (0.70MJ) reflecting greater resistance to deformation and improved structural integrity. The highest values were recorded in M30 and M40, with M40 (WF:LSP:PMP = 60:20:20) reaching hardness (54.60N), chewiness (130MJ), cohesiveness (3.80), and adhesiveness (0.80MJ). These substantial increases are likely due to the high protein and crude fiber content of LSP and PMP, which enhance water absorption and dough density (Mospah et al., 2023; Shaban et al., 2023). Overall, moderate substitution levels (10–20%) improved textural properties without substantially compromising consumer preference. In contrast, higher substitution levels (≥30%) produced breadsticks with markedly firmer, denser textures that may reduce acceptability for consumers who prefer light, crisp products (Nigro et al., 2025).

Table 7. Texture profile analysis of breadsticks containing lupin and millet flour blends

Blends	Hardness (N)	Cohesiveness	Adhesiveness (MJ)	Chewiness (MJ)
Control	37.50^{e}±0.30	2.50^{e}±0.01	0.55^{e}±0.01	105^{e}±0.55
M10	42.50^{d}±0.20	2.90^{d}±0.02	0.60^{d}±0.02	115^{d}±0.60
M20	48.33^{c}±0.40	3.20^{c}±0.03	0.70^{c}±0.01	120^{c}±0.45
M30	51.90^{b}±0.45	3.40^{b}±0.04	0.75^{b}±0.02	126^{b}±0.25
M40	54.60^{a}±0.55	3.80^{a}±0.02	0.80^{a}±0.01	130^{a}±0.70

Each value was an average of three determination ± standard deviation
Different letters indicate to significant differences between raw materials in the same column($p \leq 0.05$)

Chemical composition of breadsticks (g/100 g on dry weight basis)

Table 8 presents the nutritional composition of breadsticks prepared with varying substitution levels of wheat flour (WF) by lupin seed powder (LSP) and pearl millet powder (PMP), compared to a control sample. Progressive inclusion of LSP and PMP from 10% (M10) to 40% (M40) resulted in significant increases in protein, fat, crude fiber, and ash content, while available carbohydrates and energy values decreased correspondingly. Protein content rose markedly from 9.92% in the control to 15.30% in M40, confirming the protein-enriching potential of LSP and PMP. Fat content also increased from 9.92% to 11.56%, reflecting the contribution of healthy lipids present in these ingredients. Crude fiber content showed a substantial increase from 0.67% (control) to 3.75% (M40), indicating improved dietary fiber levels that may support digestive health. Ash content, representing total mineral content, rose steadily from 0.46% to 1.46%, suggesting an enhanced mineral profile. In contrast, available carbohydrate content decreased from 79.03% in the control to 67.93% in M40, likely due to the replacement of carbohydrate-rich WF with protein- and fat-rich LSP and PMP. This compositional shift contributed to a modest reduction in energy values, from 454.97kcal/100g in the control to 446.44kcal/100g in M40. Overall, these results indicate that partial substitution of WF with LSP and PMP significantly improves the nutritional quality of breadsticks, particularly in terms of protein, dietary fiber, and mineral content, while slightly lowering caloric value making them a nutritionally enhanced alternative to conventional breadsticks (Kefale and Yetenayet, 2020; Plustea et al., 2022; Salem et al., 2023; Sharma et al., 2024).

Table 8. The chemical composition of breadsticks (g/100g on a dry weight basis)

Components	Protein %	Fat %	Crude fiber, %	Ash %	Available carbohydrates %	Energy (KCal /100g)
Control	9.92^e±0.02	9.92^e±0.01	0.67^e±0.01	0.46^e±0.05	79.03^a±0.03	454.97^a±0.02
M10	11.27^d±0.03	10.69^d±0.03	1.44^d±0.01	0.71^d±0.01	75.89^b±0.04	454.64^b±0.01
M20	12.60^c±0.05	11.11^c±0.01	2.21^c±0.03	0.96^c±0.02	73.12^c±0.06	452.55^c±0.03
M30	13.96^b±0.04	11.15^b±0.03	2.98^b±0.02	1.21^b±0.01	70.70^d±0.03	448.57^d±0.05
M40	15.30^a±0.06	11.56^a±0.01	3.75^a±0.03	1.46^a±0.02	67.93^e±0.05	446.44^e±0.06

Each value was an average of three determination ± standard deviation
Different letters indicate to significant differences between raw materials in the same column($p \leq 0.05$)

Minerals in blends of breadsticks

Table 9 shows the mineral composition of breadsticks formulated with varying substitution levels of wheat flour (WF) by lupin seed powder (LSP) and pearl millet powder (PMP), compared to the control. Across all substitution levels (M10 to M40), there was a consistent and significant increase in calcium (Ca), potassium (K), magnesium (Mg), iron (Fe), and zinc (Zn) content as the proportion of LSP and PMP increased. Calcium content rose from 27.00mg/100 g in the control to 51.12mg/100g in M40, while potassium increased substantially from 109.75mg/100g to 323.83 mg/100g, highlighting the mineral-rich nature of the added seed powders. Magnesium showed a similar trend, rising from 103.70mg/100g to 121.95 mg/100g. Iron content increased from 2.14mg/100g in the control to 3.63mg/100g in M40, and zinc from 3.04mg/100g to 3.31mg/100g, collectively enhancing the micronutrient profile of the breadsticks. In contrast, manganese (Mn) content remained relatively stable, ranging narrowly between 3.19mg/100g and 3.24mg/100g, with no statistically significant differences, indicating minimal influence from the substituted ingredients. Notably, phosphorus (P) content decreased from 151.64mg/100g in the control to 128.87mg/100g in M40. This reduction may be due to dilution by the added components or alterations in mineral bioavailability within the modified dough matrix. Overall, substituting WF with LSP and PMP significantly improved the levels of Ca, K, Mg, Fe, and Zn in breadsticks, potentially enhancing their functional and nutritional value. Such mineral-enriched formulations may be particularly beneficial for consumers seeking bakery products with improved micronutrient profiles (Kefale and Yetenayet, 2020; Khattab et al., 2024; Salem et al., 2023; Sharma et al., 2024).

Table 9. Mineral content of breadsticks formulated with different levels of lupin and millet flour

Minerals	Ca (mg/100g)	K (mg/100g)	P (mg/100g)	Mg (mg/100g)	Fe (mg/100g)	Zn (mg/100g)	Mn (mg/100g)
Control	27.00^e±0.30	109.75^e±0.35	151.64^a±0.20	103.70^e±0.10	2.14^e±0.01	3.04^e±0.01	3.19^a±0.02
M10	33.29^d±0.15	165.16^d±0.45	146.10^b±0.15	108.26^d±0.15	2.52^d±0.01	3.07^d±0.02	3.20^a±0.03
M20	39.51^c±0.10	220.57^c±0.50	140.22^c±0.25	112.82^c±0.20	2.88^c±0.02	3.13^c±0.01	3.22^a±0.03
M30	45.32^b±0.25	275.98^b±0.55	134.57^d±0.20	117.39^b±0.10	3.26^b±0.01	3.22^b±0.02	3.23^a±0.04
M40	51.12^a±0.15	323.83^a±0.60	128.87^e±0.15	121.95^a±0.20	3.63^a±0.02	3.31^a±0.01	3.24^a±0.02

Each value was an average of three determination ± standard deviation
Different letters indicate to significant differences between raw materials in the same column($p \leq 0.05$).

4. Conclusion

This study demonstrated that partially substituting wheat flour with lupin seed powder (LSP) and pearl millet powder (PMP) significantly improved the nutritional and functional qualities of breadsticks. Substitution enhanced protein, crude fiber, and mineral content, while reducing carbohydrates and caloric value. LSP improved the essential amino acid profile, particularly lysine, whereas PMP contributed antioxidant activity and minerals such as iron and potassium. Rheological data showed that moderate substitution levels, especially 20% (M20), improved dough properties without negatively affecting processability. Sensory evaluation confirmed that breadsticks with up to 20% substitution retained consumer acceptability. Therefore, using LSP and PMP at moderate levels offers a practical approach for developing healthier, nutritionally enriched bakery products targeted at health-conscious consumers.

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