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Effect of a mixture of nut residue powder, potato starch and instant dry yeast on the quality of sandwich bread

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ABSTRACT

This study employed a combination of nut residue powders (soy, peanut, and cashew) to partially replace wheat flour in a sandwich bread formulation. In the initial trial, the nut residue mixture (NRM) powders, substituting wheat flour at levels ranging from 10% to 17.5%, were coded as G1 through G4, with a control sample G0 containing 100% wheat flour. Subsequently, potato starch (PS) (6% to 10%) was incorporated as a substitute for wheat flour, and instant dry yeast (0.5% to 0.7%) was added to enhance the physical qualities of the final product. Among the four recipes designed for partial wheat flour replacement, the results indicated that bread from Recipe G2, which contained NRM powder and wheat flour in a ratio of 12.5:87.5%, exhibited high specific volume and volume expansion, along with moderate hardness (727.37 and 277.90 grams-force, respectively) and an appealing color. However, the specific volume and volume expansion of G2 bread remained lower than those of the control G0. The subsequent partial replacement of wheat flour with potato starch and the use of quick-dry yeast compensated for this shortcoming. The formulation, referred to as PI, with a ratio of PS:NRM: wheat flour of 7.79:12.5:79.71% and yeast at 0.56%, produced a product with superior structure and higher contents of protein, fat, fiber, ash, and total polyphenols compared to G0. Notably, the fiber content in the PI sample was approximately 3.3 times higher. Additionally, the estimated glycemic index (eGI) of the PI bread was lower at 51.16 compared to 67.6 for G0, indicating a medium-low glycemic response. This research demonstrates the effective utilization of by-products in food processing and suggests potential for further application in the bakery industry or other food sectors where demand exists for healthier and functional products.

Contribution/Originality: This study explores the use of NRM powder and potato starch as substitutes for wheat flour, along with a small amount of instant dry yeast in sandwich bread production, significantly enhancing quality. Utilizing these by-products not only reduces environmental pollution but also promotes the development of a circular and sustainable economy.

1. INTRODUCTION

Bread is a fermented food composed of four primary ingredients: wheat flour, water, yeast, and salt. It is a popular cuisine among consumers because of its simple preparation, soft texture, delicate flavor, and distinct aroma. As living standards rise, so do consumers' expectations for bread quality. Bread dough fermentation, in particular, has a

significant impact on bread quality (Hu et al., 2023). However, there is concern that consuming bread can cause a sudden spike in blood sugar levels (Asghar et al., 2023). To address the increased consumer demand for stable blood sugar levels, manufacturers are increasingly resorting to fiber-rich meals. Fiber is well-known for its ability to lower blood sugar and low-density lipoprotein levels, which aids in the prevention of cardiovascular disease.

Vegan condensed milk can be made from plants or nuts with high nutritional value. Among the ingredients, soybeans are the most popular. Soybeans are an important legume, providing all the essential amino acids for humans. Soy isoflavones have antioxidant effects, and their role in preventing breast and prostate cancer has also been reported (Pejčić et al., 2023). Soybeans contain approximately 37–42% protein (Murphy, 2008). The fat content of the seeds is approximately 19%, with relatively large amounts of unsaturated fatty acids such as oleic acid and polyunsaturated fatty acids (Kamshybayeva et al., 2017). The antioxidant, antidiabetic, antiproliferative, antiobesity, and anti-inflammatory roles of soybeans have also been discussed (Amol, Bhati, & Bhati, 2021; Dukariya, Shah, Singh, & Kumar, 2020). Therefore, soybean consumption has been shown to provide many potential health benefits and to reduce the risk of numerous chronic diseases (Dukariya et al., 2020).

In addition, peanuts (*Arachis hypogaea* Linn.) are a popular nut known for their delicious flavor and high nutritional value. Peanuts and peanut products are beneficial for health because they contain unsaturated fatty acids and bioactive substances such as phytosterols, phenolic compounds, stilbenes, lignans, and isoflavonoids. These substances have the potential to protect the body from serious illnesses, including cardiovascular disease, type 2 diabetes, and cancer (Çiftçi & Suna, 2022). Peanuts contain both water-soluble and fat-soluble micronutrients (Davis & Dean, 2016) and high levels of B vitamins, vitamin E, and fiber, but no cholesterol. As a result, peanuts are highly nutritious, containing a variety of macro- and micronutrients (Çiftçi & Suna, 2022). However, peanuts contain 32 distinct proteins, 18 of which may cause allergic reactions. These allergenic proteins are resistant to proteases, high temperatures, and chemical denaturation (Toomer, 2018). Cashews are both nutritious and delicious. Cashew nuts include both protein and fat, which have been shown to lower LDL cholesterol and reduce the risk of coronary heart disease (Bes-Rastrollo et al., 2007). The nuts are also rich in unsaturated fatty acids (oleic and linoleic acids), flavonoids, anthocyanins, tannins, fiber, folate, and tocopherols (Cordaro et al., 2020). Cashews and their derivatives also possess antioxidant and antibacterial effects. However, during the production of vegan condensed milk, the residue left (soybean, peanut, cashew) after filtering the milk liquid is usually discarded. Almost all of these residues are utilized as animal feed, fertilizer, and are potential sources of by-products that can be used as human food. Seed by-products contain vitamins, minerals, phytochemicals, bioactive compounds, dietary fiber, lignin, proteins, hydrolyzed proteins, peptides, polysaccharides, prebiotics, and oils, as well as antioxidant and antimicrobial properties, and are considered health-promoting compounds (Alasalvar et al., 2025; Baptista, Gonçalves, Bressan, & Pelúzio, 2018). It has been demonstrated that soybean residue retains fiber, fat, protein, vitamins, and trace minerals. This presents an opportunity to generate value-added food products while also reducing waste. When added to processed foods, the nutritional value improves, primarily by increasing fiber and protein content (Zhao, Xie, Chen, Zheng, & Li, 2025). Vong and Liu (2016) discovered that soybean by-products, which are commonly regarded as waste due to their estimated annual global production of more than 4 million tons, still contain high levels of nutrients such as fiber (14.5-58.1%), protein (24.5-37.5%), fat (9.3-22.3%), and trace amounts of carbohydrates, ash, and bioactive compounds such as isoflavones and soyasaponins (Radočaj & Dimić, 2013). Furthermore, peanut by-products are a resource that can be well utilized, as the rich amino acid composition of peanut meal suggests that it can serve as an ingredient for protein enhancement (Yu, Ahmedna, & Goktepe, 2007). Cashew meal has not been properly processed despite its potential as a processed food ingredient with many benefits. These findings clearly demonstrate that leftovers from the manufacturing process still retain numerous valuable nutritional components such as fiber, protein, fat, and minerals. Consequently, research into their utilization or effective exploitation for subsequent processing is an important area of focus. However, studies on the use of residues, combined with potato starch and instant dry yeast, on the physicochemical properties of baked products are still limited. This study employs

residues (from the process of filtering milk for the production of vegan condensed milk) and potato starch to replace part of the wheat flour, along with instant dry yeast, to create a sandwich bread product rich in fiber and protein, with a good texture, and highly accepted by consumers. However, due to the coarse texture of the fiber in these nut residues, their integration into bread might result in poor texture and impair sensory features. Additionally, fiber addition can slow down the fermentation process, leading to incomplete fermentation and a lower bread volume (Zhao et al., 2025).

As a result, other components must be included in research to offset any potential downsides to the overall quality of the final product. In this context, yeast and potato starch play vital roles. During incubation, yeast catalyzes the breakdown of starch into smaller saccharides, which are then converted by enzymes such as maltase and invertase into carbon dioxide, ethanol, and other nutrients (Bellido, Scanlon, & Page, 2009). This process improves the bread's fluffiness, flavor, and texture. Additionally, potato flour is high in vitamins, minerals, and fiber, and has a balanced amino acid profile, making it a healthier alternative to wheat flour (Singh, Raigond, Dutt, & Kumar, 2020). Replacing wheat flour with gluten-free potato flour can alter the protein content, protein-starch interactions, and overall protein quality, which in turn affects the texture, flexibility, and final qualities of the product.

The use of okara (soybean residue) as a substitute ingredient in bread manufacturing to enhance nutritional value, particularly protein, fiber, and phenolic compounds, has been the primary focus of previous research (Ostermann-Porcel, Quiroga-Panelo, Rinaldoni, & Campderrós, 2017; Pešić et al., 2023; Yaseen, Shouk, & Abousalem, 2009). These studies demonstrate that adding okara to bread increases its functional value and reduces its carbohydrate content, resulting in a healthier and more palatable final product. However, most research has focused solely on okara; other nut residues, such as peanut meal, cashew meal, or combinations of various residues, have not yet been adequately explored for their potential applications in food processing.
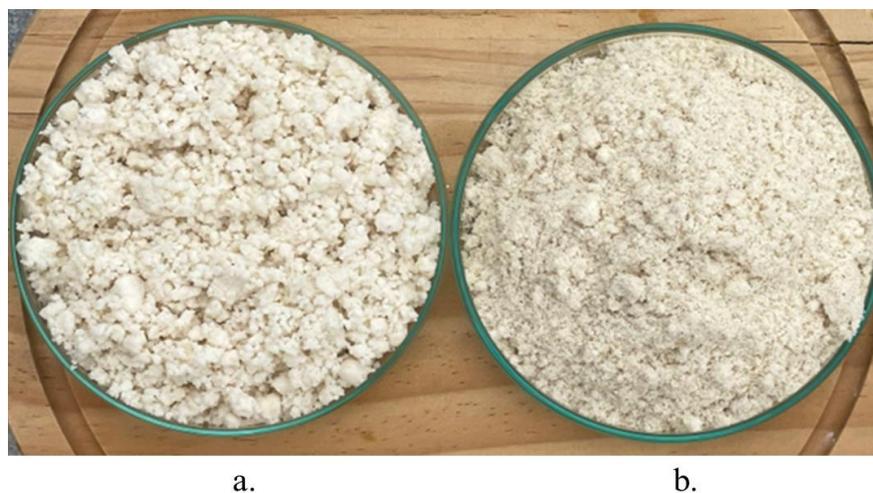
The use of soybean, peanut, and cashew residues in powder form not only makes good use of these by-products but also increases their shelf life. The finished powder can be utilized to produce value-added products. Proper utilization of these by-products contributes to reducing environmental contamination, which is a concern for the entire population. Functional food innovations that align with the goals of sustainable development and the circular economy are relevant stages in this context. However, there is still limited research on the combined use of nut residue mixture (NRM) powder in bread formulations, particularly regarding their effects and interactions with wheat flour or other ingredients. This is despite the growing interest in adding value to agro-industrial wastes. Additionally, the effects of substituting potato starch and instant dry yeast in sandwich breads on their textural characteristics have not been thoroughly studied. Therefore, the objectives of this study were: (i) to improve the quality of sandwich bread by appropriately replacing wheat flour with mixed nut residue powder in the formulation, and (ii) to investigate the influence of potato starch substituting a portion of wheat flour and instant dry yeast on the overall texture of sandwich bread.

2. MATERIALS AND METHODS

2.1. Sample Collection and Powder Preparation

Soybeans (*Glycine max*), peanuts (*Arachis hypogaea* L.), and cashew nuts (*Anacardium occidentale* L.) were purchased from local markets in the country. The raw materials were cleaned of dirt through sieving, and damaged nuts were removed. Peanuts and cashew nuts were roasted, dehusked, and ground separately with water (in specific proportions); meanwhile, soybeans were pre-soaked, dehusked, drained, and ground with water. The filtrate from the three types of nuts was collected for the research process involved in developing vegan condensed milk products (the research was conducted simultaneously). The residues obtained from this process included soy residue, peanut residue, and cashew nut residue, which were combined in equal proportions (by weight) to form a nut residue mixture, used for this study (Figure 1). The NRM was spread on a stainless steel tray lined with wax paper, with a sample thickness of approximately 3 mm. The sample (Figure 1a) was dried in a convection oven (MEMMERT, UN260, Germany) at

60ºC for 3.75 hours (based on preliminary experimental results) until the moisture content reached equilibrium (<6%). The sample was collected and ground into a fine powder using a superfine powder grinding mill (QE-5000, Vietnam). After, the powder was sieved through a sieve size of about 100 μm (Figure 1b).

a.   b.

Figure 1. Mixed nut residue (Soybean, peanut, and cashew nut) after collection (a) And their powder after drying (b).

2.2. Formulation of Sandwich Bread

The mass of some ingredients was weighed at a constant amount, including 23.4 g of margarine (Tuong An, Vietnam), 27 g of sugar, 2.7 g of salt, 117 g of fresh milk (TH True Milk, Vietnam), 2 g of instant dry yeast (Mauripan dry yeast, Vietnam), and 54 g of eggs. The total weight of the recipe was 487.1 g. The contents of wheat flour (Bakers' Choice flour, Vietnam) and NRM powder were prepared using five different formulas, with recipe G0 serving as the control sample (100% wheat flour, 261 g), which contained only wheat flour. The percentage of NRM powder used to replace wheat flour in formulations G1, G2, G3, and G4 were 10%, 12.5%, 15%, and 17.5%, respectively. An automatic bread machine (PETRUS PE9600, China) with a baking temperature of 165°C was used. The total time for mixing, proofing, and baking was approximately 3 hours and 20 minutes. The moisture content, hardness, specific volume, expansion volume, and color of the sandwich bread were analyzed.

2.3. An Experimental Design for the Effects of Potato Starch and Instant Dry Yeast

The data from the previous experiment were utilized to develop a formulation in which NRM powder ratios replaced a portion of wheat flour. The study employed the Central Composite Design (CCD) 2^2+star, using Statgraphic Centurion software version XV.I (USA), with two variables: PS ratio and instant dry yeast concentrations. Prior to conducting the optimization experiment, optimal parameters were determined based on previous exploratory trials. The optimal PS substitution ratio for a portion of wheat flour and the amount of additional instant dry yeast were identified as 8% and 0.6%, respectively. These values were selected as the central points for the experimental design. The lower and higher levels of PS and instant dry yeast were arranged according to the CCD 2^2+star design (see Table 1). The parameters measured included bread loaf hardness (measured in grams-force), volume expansion (percentage), and specific volume (cm³/g). The total number of experimental runs is presented in Table 2.

Table 1. Factors and PS and instant dry yeast concentration levels based on CCD 2^2+star.

Factors	Coded	Levels				
		-α (-1.41)	−1	0	+1	+α (+1.41)
Instant dry yeast (%)	X_1	0.46	0.50	0.60	0.70	0.74
PS (%)	X_2	5.17	6	8	10	10.83

Table 2. Experimental setup by CCD 2^2+star.

Run	Instant dry yeast (%)	PS (%)	Run	Instant dry yeast (%)	PS (%)
1	0.6	8	8	0.7	6
2	0.6	5.17	9	0.6	8
3	0.6	10.83	10	0.6	8
4	0.5	10	11	0.5	6
5	0.74	8	12	0.46	8
6	0.6	8	13	0.7	10
7	0.6	8			

2.4. Determination of Physico-Chemical Properties

The total polyphenol content (TPC) was determined using the Folin-Ciocalteu test method (Fu et al., 2011). The reaction solution containing polyphenolic compounds was extracted from NRM powder, and its absorbance was measured at 738 nm. TPC was then calculated as milligrams of gallic acid equivalent per gram of material (mg GAE/g) using a standard curve established for this purpose.

A Hunter Lab Colorimeter (Color Flex, USA) was used to read the color values (L*, a*, b*). The ΔE (total color difference) is a colorimetric parameter commonly used to characterize the variation of color in foods during processing (Azizpour, Mohebbi, & Khodaparast, 2016), is calculated through Equation 1.

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

Browning index (BI) was calculated based on L*, a*, and b* values (Pathare, Opara, & Al-Said, 2013), and estimated by Equation 2.

$$BI = \frac{100\left[\frac{a^*+1.75L^*}{5.645L^*+(a^*-0.3012b^*)}-0.31\right]}{0.17} \quad (2)$$

Sandwich bread hardness was measured using the TA.XTplusC Texture Analyzer (Stable Micro Systems, England). The bread loaf was sliced into 2 cm thick slices, which were then compressed with a cylindrical probe applying 50% strain.

Loaf volume expansion was calculated as the difference between the dough volume before proofing and the bread volume after baking (for sandwich bread) (Pratama, Hardiyanti, & Hintono, 2024).

The specific volume of sandwich bread was calculated as described by Ding, Peng, Li, and Yang (2019) (Equation 3).

$$\text{Specific volume (cm}^3\text{/g)} = \frac{Volume\ of\ bread}{Mass\ of\ bread} \quad (3)$$

The moisture content and nutrients, including protein, lipids, carbohydrates, ash, and fiber were determined according to the methods established by the Association of Official Agricultural Chemists (AOAC, 2005).

The glycemic index (eGI) was estimated according to Goñi, Garcia-Alonso, and Saura-Calixto (1997).

2.5. Statistical Analysis

All measurements were performed in triplicate, and results were expressed as mean ± standard deviation (STD). Data were analyzed using Statgraphics Centurion XV.I (USA), with statistical significance set at $P < 0.05$. The multiple regression model, combined with Response Surface Methodology (RSM), was used to optimize the process. The effectiveness of the model was assessed by verifying the factor effects through analysis of variance (ANOVA).

3. RESULTS AND DISCUSSION

3.1. Quality of Mixed Nut Residue Powder (Soybean, Peanut, Cashew Nut)

The quality study of NRM powder (shown in Figure 1) revealed that the powder had a low moisture content (4.9%) and other components, including 40.19% fat, 27.27% protein, 24.75% carbohydrate, 4.2% fiber, 2.89% ash, high

polyphenol content (2.68 mgGAE/g), and 67.35% DPPH radical-scavenging activity. NRM powder had a low moisture content (4.9%), which favors shelf stability, consistent with previous findings on nut-based by-products used as functional food ingredients (Sharif et al., 2018). The lipid content (40.19%) was notably high, as expected for nut-derived residues such as peanut and cashew, which retain considerable oil even after defatting (El Idrissi et al., 2024; Suleman et al., 2023). This lipid fraction may enhance the caloric value and contribute to improved texture and mouthfeel in bakery applications. The protein content (27.27%) indicates that NRM powder can serve as a potential plant-based protein source. Comparable protein levels have been reported in okara, the soybean pulp by-product from tofu and soy milk production, which typically contains 24.5–37.5 g/100 g of protein, 14.5–55.4 g/100 g of fiber, and 9.3–22.3 g/100 g of lipids (Jiménez-Escrig, Tenorio, Espinosa-Martos, & Rupérez, 2008; Surel & Couplet, 2005). NRM powder contains moderate amounts of carbohydrates, but it is mostly rich in fiber. These nuts contain high fiber content, particularly insoluble fiber (Gonçalves et al., 2023). Fiber is essential for numerous physiological processes in the human body and helps prevent a variety of disorders. As a result, daily intake of fiber-rich foods is crucial for lowering or controlling plasma cholesterol and triacylglycerol levels, while also promoting overall human health (Redondo-Cuenca, Villanueva-Suárez, & Mateos-Aparicio, 2008).

3.2. Effect of NRM Powder as A Partial Replacement of Wheat Flour on Sandwich Bread Quality

3.2.1. Physical Characteristics of Sandwich Bread Prepared from Different Recipes

The results in Table 3 reveal that the moisture content of sandwich bread decreased as the quantity of NRM powder used increased. Increasing the amount of NRM powder from 10% to 17.5% (recipes G1 to G4) reduced the moisture content of the bread from 33.24% to 29.71%, which was 33.86% lower than the control sample (100% wheat flour - sample G0). Due to the difference between the moisture content of wheat flour (higher) and NRM powder (lower), the moisture content of the bread decreased with the increasing proportion of NRM powder. Dietary fiber reduced the moisture content in sandwich bread ($P < 0.05$), presumably because of its superior water-holding capacity. (Kırbaş, Kumcuoglu, & Tavman, 2019). Generally, fiber has a high water-binding and retention capacity, enabling it to sequester free water from dough, thereby altering the porosity and gas phase structure, which results in a lower moisture content in the finished baked product (Aydogdu, Sumnu, & Sahin, 2018; Verbeke, Debonne, Versele, Van Bockstaele, & Eeckhout, 2024).

Table 3. Physical characteristics of sandwich bread prepared from five recipes.

Formulas	Moisture Content (%)	Hardness (g force)		Specific volume (cm³/g)	Loaf volume expansion (%)
		Crust	Crumb		
G0	33.86±0.13[d]	574.73±28.86[a]	120.57±11.22[a]	4.22±0.04[d]	242.66±9.82[c]
G1	33.24±0.10[c]	636.13±42.00[a]	262.63±13.29[b]	4.14±0.03[d]	196.92±10.85[b]
G2	32.30±0.33[b]	727.37±40.13[b]	277.90±14.07[b]	3.75±0.12[c]	192.44±9.94[b]
G3	31.99±0.10[b]	1193.23±24.04[c]	430.87±13.25[c]	3.44±0.11[b]	191.61±10.22[b]
G4	29.71±0.40[a]	1197.53±43.09[c]	495.17±12.78[d]	2.52±0.09[a]	116.10±9.32[a]

Note: Values are expressed as mean±STD. Values with different superscripts (a, b, c, d) in the same column are significantly different according to LSD test ($P < 0.05$).

Both the crust and the crumb hardened when the NRM powder ratio increased from 10% to 17.5% (recipes G1–G4) (Table 3). The measured crust hardness increased from 574.73 g-force to 1197.53 g-force as the substitution ratio increased from G1 to G4. Simultaneously, crumb hardness increased from 120.57 g-force to 495.17 g-force between the G1 and G4 samples. It is possible that fiber-rich ingredients contributed to the increased firmness of the bread, as supported by studies such as (Ktenioudaki & Gallagher, 2012; Sudha, Baskaran, & Leelavathi, 2007). Kırbaş et al. (2019) observed that adding fiber sources such as orange, carrot, and apple pomace powder to gluten-free rice flour bread significantly increased its hardness. Furthermore, Da Silva et al. (2009) found that replacing wheat flour with 5%, 10%, or 15% soy okara substantially enhanced the toughness of gluten-free bread.

Table 3 discusses how the specific volume of sandwich bread changes with increasing levels of wheat flour substitution by NRM powder. The specific volume decreased from 4.22 cm³/g to 2.52 cm³/g as the proportion of wheat flour replaced with NRM powder increased from 0% (G0) to 17.5% (G4). This reduction could be attributed to gluten dilution or gluten-fiber interactions, as well as fiber weakening or damaging the dough structure, which diminishes its capacity to retain CO_2. According to (Belghith Fendri et al., 2016), these effects are consistent with the observed decrease in bread volume. Additionally, research on okara incorporation in gluten-free cookies indicates that increasing okara content results in a decrease in the specific volume of the cookies. This is supported by findings from (Ostermann-Porcel et al., 2017), who observed similar trends. The interaction of protein and fiber with the structural matrix can limit the dough's ability to trap gas, as noted by (Tridtitanakiat, Hernández-Estrada, & Rayas-Duarte, 2023).

The loaf volume expansion decreased from 242.66% to 116.10% as the ratio of wheat flour substitution with NRM powder increased from formula G0 to G4. However, there were no statistically significant differences between formulas G1, G2, and G3. The reduction in loaf volume expansion can be attributed to the fact that replacing wheat flour with NRM powder may lead to gluten dilution, which hampers the proper development of the gluten matrix during mixing, formulation, and baking processes. Incorporating gluten-free alternative flours into the dough diminishes CO_2 absorption, resulting in bread with a lower rise (Makinde & Akinoso, 2014). Ribotta, Arnulphi, Leon, and Añón (2005) revealed that high levels of soy ingredients negatively impact gluten network development, extensibility, dough gas retention, and overall bread quality.

3.2.2. Color, The Total Color Difference and Browning Index of Sandwich Bread Prepared from Different Formulations

The study found that increasing the NRM replacement ratio from 10% to 17.5% altered the color values (L*, a*, and b*) of the crust (Table 4). The results indicated that as the NRM powder ratio increased, the crust darkened, and the L* value continuously decreased from 66.62 (formula G0) to 63.18 (formula G4). Simultaneously, the b* value decreased from 22.72 to 19.44, indicating a reduction in the intensity of the yellow hue, while the a* value increased from 5.91 to 7.41, suggesting a deeper red color. The darkening was more pronounced, which was reflected in higher browning index (BI) and total color difference (ΔE) values, increasing from 4.77 to 5.79 and from 190.25 to 191.91, respectively. The browning index of bread is primarily determined by its protein and reduced sugar content. Higher levels of protein and reduced sugar promote the Maillard reaction, thereby increasing the bread's browning index (Goesaert, Slade, Levine, & Delcour, 2009). When the crust is directly exposed to high baking temperatures, the Maillard reaction and caramelization processes become more intense compared to the crumb. Various ingredients, processing methods, and their interactions, such as Maillard or caramelization reactions, significantly influence the color of bakery products (Gularte, De la Hera, Gómez, & Rosell, 2012). Bchir, Rabetafika, Paquot, and Blecker (2014) investigated the effect of incorporating flesh fiber concentrate from apple, pear, and date pomaces into bread. Their findings demonstrated that adding fiber notably increased crumb a* values but significantly decreased b* and L* values. Similarly, breads fortified with okara exhibited darker crumb and crust, especially with 20% okara content, resulting in higher a*, b*, BI and ΔE values. The higher protein content in okara-supplemented bread enhanced non-enzymatic browning (Ibadullah et al., 2024).

Table 4. Color, the total color difference, and the browning index of the crust of sandwich bread prepared from five formulations.

Formulas	L*	a*	b*	ΔE	BI
G0	66.62±0.02[e]	5.91±0.01[a]	22.72±0.32[d]	-	190.25±0.04[a]
G1	65.54±0.14[d]	6.45±0.09[b]	21.29±0.17[c]	4.77±0.04[a]	190.77±0.06[b]
G2	64.84±0.02[c]	6.86±0.10[c]	20.89±0.19[b]	5.00±0.01[b]	191.26±0.08[c]
G3	64.05±0.10[b]	7.35±0.03[d]	20.52±0.23[b]	5.41±0.08[c]	191.87±0.09[d]
G4	63.18±0.34[a]	7.41±0.04[d]	19.44±0.05[a]	5.79±0.21[d]	191.91±0.08[d]

Note: Values are expressed as mean±STD. Values with different superscripts (a, b, c, d, e) in the same column are significantly different according to LSD test ($P < 0.05$).

Along with the slight increase in the a* and b* values, the L* value of the sandwich bread crumb color also changed, from 65.67 (recipe G0) to 67.89 (recipe G4) (Table 5), indicating that the bread crumb color gradually lightened as the proportion of NRM powder increased. The tendency of bread crumbs to lighten could be attributed to the natural hue of the flour combination after drying, which ranged from pale yellow to off-white; therefore, when included in the dough, it enhanced overall brightness. The bread crumb was clearly affected by the initial color of the components employed. Gómez, Ronda, Blanco, Caballero, and Apesteguía (2003) demonstrated that bread crumb color is usually similar to the color of the ingredients since the crumb does not reach the same high temperature as the crust. Unlike the exterior crust of bread, which is exposed to high temperatures resulting in crust color, the internal crumb retains moisture, retarding this change in color, and thus there was little change in lightness (Davy, Kirkman, Scarlett, & Vuong, 2022).

Table 5. Color, the total color difference, and browning index of crumb sandwich bread prepared from five formulas.

Formulas	L*	a*	b*	ΔE	BI
G0	65.67±0.06[a]	1.45±0.05[a]	13.08±0.04[a]	-	184.08±0.05[a]
G1	66.80±0.22[b]	2.23±0.02[b]	14.90±0.03[b]	2.28±0.09[a]	185.13±0.03[b]
G2	66.93±0.03[b]	2.57±0.04[c]	15.67±0.14[c]	3.09±0.12[b]	185.60±0.06[c]
G3	67.53±0.10[c]	2.59±0.05[c]	16.52±0.30[d]	4.07±0.24[c]	185.70±0.10[c]
G4	67.89±0.30[d]	2.80±0.07[d]	17.50±0.24[e]	5.14±0.10[d]	186.05±0.13[d]

Note: Values are expressed as mean±STD. Values with different superscripts (a, b, c, d, e) in the same column are significantly different according to LSD test (P < 0.05).

Additionally, ΔE and BI values tend to increase (2.28 to 5.14 and 184.08 to 186.05, respectively). Although L* rises, the evident increase in red (a*) and yellow (b*) colors raises the BI. This suggests that browning is influenced not only by lightness but also by the overall balance of color characteristics (Subhashree, Sunoj, Xue, & Bora, 2017).

3.3. Effect of Potato Starch and Instant Dry Yeast on Sandwich Bread Quality

The overall comparison revealed that the specific volume and volume expansion of the G2 formula sandwich bread were less than those of the control sample G0. As a result, further studies are needed to improve the qualities of bread enriched with grain pulp powder in order to optimize the production process and deliver the highest quality product.

3.3.1. Loaf Volume Expansion and Specific Volume

The results were analyzed using analysis of variance (ANOVA), which aligned with the experimental design. The analytical results revealed that the effects of instant dry yeast (X_1), PS ratio (X_2), and squared interactions (X_1X_1, X_2X_2) had P values less than 0.05, indicating that they were statistically significant at the 95.0% confidence level. However, the interaction between X_1 and X_2 did not show statistical significance (P > 0.05). The lack-of-fit test was performed to determine whether the chosen model could adequately describe the observed data. The P value for the lack-of-fit was greater than 0.05 (0.3188), implying that the model fit the observed data well at the 95.0% confidence level. The R^2 statistic indicated that the fitted model accounted for 92.35% of the variation in loaf volume expansion (%). The standard error indicated that the residuals had a standard deviation of 12.32. The X_1X_2 interaction had no significant effect, so it was dropped from the correlation model, and a new model (Equation 4) was created. With this new model, the high values of R^2 (92.32%) and R^2_{adj} (91.42%), combined with the P value of Lack-of-fit > 0.05 (P = 0.4516), demonstrated that the chosen model was accurate enough to predict the loaf volume expansion from the independent variables.

$$Y_1 = -1121.43 + 2136.91X_1 + 201.34X_2 - 1826.32X_1^2 - 12.90X_2^2 \quad (4)$$

Where Y_1 is loaf volume expansion (%), X_1 is instant dry yeast ratio (%), X_2 is PS ratio (%).

Similarly, the optimization of the specific volume value based on influencing factors was also conducted (data not shown). Instant dry yeast (X_1), PS ratio (X_2), squared interactions (X_1X_1, X_2X_2), and pair interaction (X_1X_2) all significantly affected the specific volume ($P < 0.05$). The model is based on a strong correlation between experimental and predicted data (Equation 5). The R^2 statistic indicates that the model explains 92.21% of the variation in the specific volume. The adjusted R^2 statistic, which is useful for comparing models with different numbers of independent variables, is 91.03%. The lack-of-fit was not significant ($P > 0.05$), and the standard error of estimate was 0.17. All statistical results suggest that the mathematical model is adequate for predicting the experimental data.

$$Y_2 = -10.88 + 26.51X_1 + 2.24X_2 - 27.32X_1^2 + 0.54X_1X_2 - 0.16X_2^2 \quad (5)$$

Where Y_2 is specific volume (cm³/g), X_1 is instant dry yeast ratio (%), X_2 is PS ratio (%).

The Pareto charts (Figure 2) illustrate the effects of X_1 and X_2 on loaf volume expansion and specific volume. The Pareto chart for loaf volume expansion (Figure 2a) shows that the effect bars X_1, X_2, X_1X_1, and X_2X_2 intersect the reference line, indicating they are statistically significant at the 5% level. From this figure, it can be observed that the PS ratio has the most significant impact on specific volume. Similarly, Figure 2b demonstrates that X_1, X_2, X_1X_1, X_2X_2, and X_1X_2 are significant factors for specific volume, with the PS ratio again being the most influential variable.

a. Loaf volume expansion   b. Specific volume
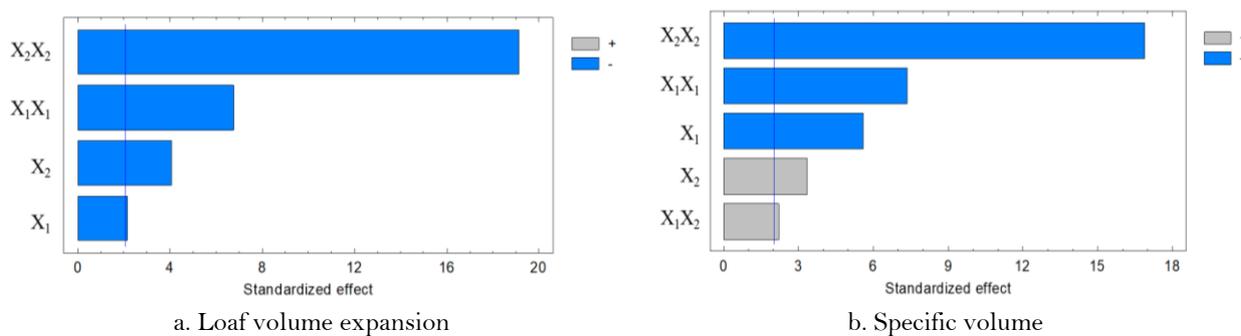
Figure 2. Pareto chart of the effects of instant dry yeast ratio, PS ratio on the following parameters: loaf volume expansion (a) and specific volume (b).

The specific volume of bread is a direct predictor of bread quality, indicating the dough's ability to retain air and expand (Zhang et al., 2018). It was observed that yeast and PS affected the rise and specific volume of sandwich bread. When the instant dry yeast ratio was fixed at 0.4%, increasing the PS ratio from 6% to 10% resulted in a tendency for loaf volume expansion and specific volume to increase, followed by a decrease (Figure 3a and 3b). The findings revealed that at low levels of PS substitution, a small amount of the alternative could improve water absorption or yeast activity, leading to a higher dough rise. In this scenario, it would have no substantial effect on the gluten network but would instead support the structure, thereby increasing the specific volume.

However, larger replacement levels reduced dough formation time and stability, resulting in protein weakening and decreased bread volume (Zeng et al., 2019). Furthermore, adding more potato starch reduced the specific volume of bread. Perhaps the addition of potato starch diluted the gluten content and lowered the dough's gas-holding capacity, preventing carbon dioxide from being properly retained during fermentation. Therefore, insufficient expansion of the gluten network in the dough resulted in a decrease in the bread's specific volume (Ju et al., 2020).

At a fixed PS ratio of 6%, the instant dry yeast ratio was adjusted from 0.5% to 0.7%, resulting in a significant increase in loaf volume expansion and specific volume. As the yeast content increases, so does the overall yeast activity in the dough, which enhances gas production capabilities. This leads to a more stable gluten network structure in the dough and a stronger gas-binding capacity of the starch inside. The bread also exhibited increased viscosity and flexibility, creating a synergistic effect between the starch's gas-binding capacity and the yeast's gas-generating capacity (Feng, Ma, Wang, & Wang, 2022). Consequently, the bread's porosity increased, contributing to a higher specific volume. Zhang and Tan (2021) found that increasing the fermentation level in bread dough also improved its specific volume.
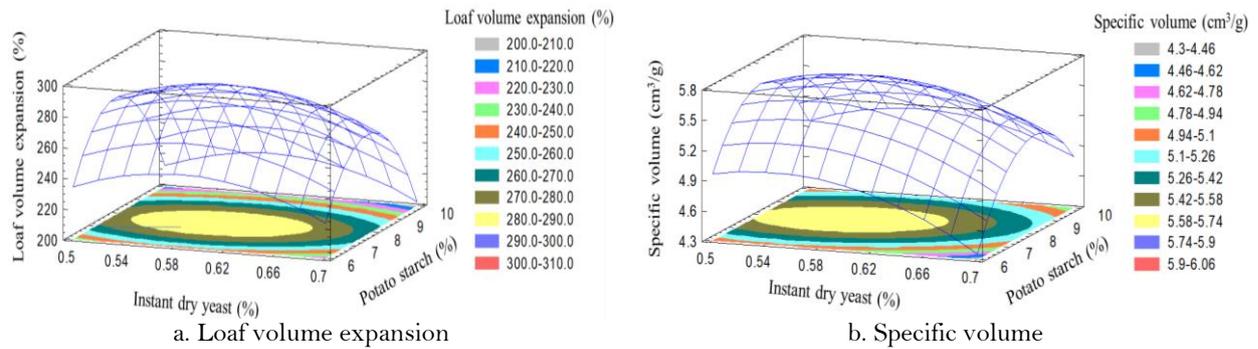
a. Loaf volume expansion   b. Specific volume

Figure 3. Response surface and contour plot for loaf volume expansion (a) and specific volume (b).

Furthermore, Thuy et al. (2023) found that the yeast addition rate had a substantial effect on the rising volume of bread, with the bread increasing in volume from 5.23 to 5.34 times when the yeast concentration was increased from 0.3% to 0.5%.

As previously stated, *Saccharomyces cerevisiae* is responsible for the fermentation process. Yeast absorbs sugars and transforms them into ethanol and carbon dioxide (Ali, Shehzad, Khan, Shabbir, & Amjid, 2012), inflating gas bubbles in the dough and causing it to rise. Under typical conditions, the yeast remains active and begins to grow and multiply rapidly when added to the dough. The rate of gas production is related to the quantity of yeast used. If too much yeast is used, the volume of the loaf decreases, and the product develops a yeasty odor (Sun, Scanlon, Nickerson, & Koksel, 2023).

3.3.2. Hardness

Analysis of variance (ANOVA) was also performed (full results are not presented here). The analysis results show that there were three effects, including instant dry yeast ratio (X_1), PS ratio (X_2), square interaction (X_1X_1, X_2X_2), and pair interaction (X_1X_2), all significantly impacting hardness ($P < 0.05$). The P value for the lack-of-fit was larger than 0.05 (0.1458), indicating that the model fit the observed data well at the 95.0% confidence level. With this model (Equation 6), the high values of R^2 (98.49%) and R^2_{adj} (98.26%) demonstrated that the selected model was sufficiently accurate to predict hardness from the independent variables.

$$Y_3 = 4469.19 - 1555.83X_1 - 975.836X_2 - 1506.62X_1^2 + 526.04X_1X_2 + 48.28X_2^2 \quad (6)$$

Where Y_3 is hardness (g force), X_1 is instant dry yeast ratio (%), X_2 is PS ratio (%).

The results of 13 runs using the CCD 2^2+star model (Figure 4) show that adding instant dry yeast and replacing wheat flour with PS had an impact on product hardness, with hardness values ranging from 665 to 1528.83 g force. The hardness of the product shows a positive relationship with the proportion of PS partially replacing wheat flour. Sandwich bread hardens when the PS content increases. When the instant dry yeast concentration is fixed at 0.5% and the wheat flour replacement ratio with PS is increased from 6% to 10%, the hardness tends to increase.

The high amylopectin and phosphate group content of potato starch contributes to enhanced apparent viscosity and a stronger gel network, which affects the dough's hydration level, consistency, and mixability (Hu, Li, Tan, McClements, & Wang, 2022; Zhou, Zhang, Liu, Liu, & Hu, 2021). Furthermore, during dough formation, potato starch gelatinization competes with gluten for moisture, resulting in the creation of a flocculent gluten network, increased gliadin exposure, and potato starch expansion (Wang et al., 2022). As a result, the addition of potato starch has been demonstrated to have a considerable effect on dough hydration and gas retention, influencing the fermentation and texture of baked items. Increased gelatinization enhances dough gas retention while potentially reducing overall gas volume, resulting in a denser and more uniform crumb structure (Witczak, Ziobro, Juszczak, & Korus, 2021). Similarly, Ju et al. (2020) found that adding potato flour increased the toughness of wheat and potato flour bread crumb substantially. It could be owing to the low density of wheat flour and potato starch, which makes the bread crumb tougher, resulting in high hardness. Furthermore, because potato starch absorbs water more

strongly, the sandwich bread recipe with potato starch contains more water, causing the starch to expand and dissolve completely, increasing the contact surface between starch and gluten and thus increasing the hardness of the bread crumb (Gumul, Krystyjan, Buksa, Ziobro, & Zięba, 2014). When the ratio of wheat flour replacement with PS is fixed at 6%, the ratio of instant dry yeast addition increases from 0.5% to 0.7%. The hardness drops somewhat, from 775.77 to 760.94 g force (at 0.63%), before progressively increasing as the instant dry yeast ratio increases. With the optimum yeast addition rate, CO_2 gas produced during fermentation aids in the formation of a porous structure, reduces crumb density, and reduces product hardness. However, introducing too much yeast reduces the percentage volume of holes, as well as the force required to compress the bread sample and its tenacity.

Furthermore, the high number of small pores results in a harder bread structure. Gas generation occurs too quickly, and the gas bubbles are easily fractured or fused together, making the internal structure of the bread unstable and causing the bread to collapse, while the crumb thickens and becomes harder (Sun et al., 2023). The Pareto chart (Figure 5) demonstrates that all components and their squared interactions have a considerable impact on hardness. X_2 has the largest influence on hardness, as indicated by its longest bar length.
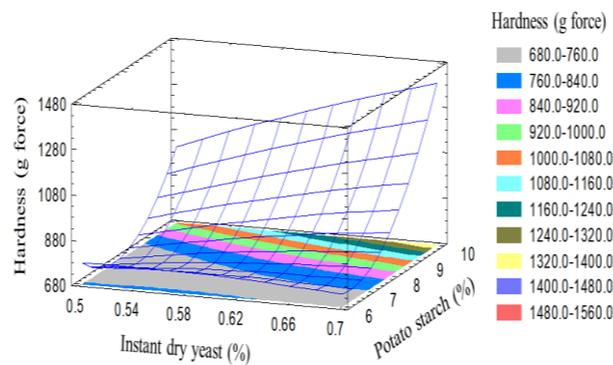

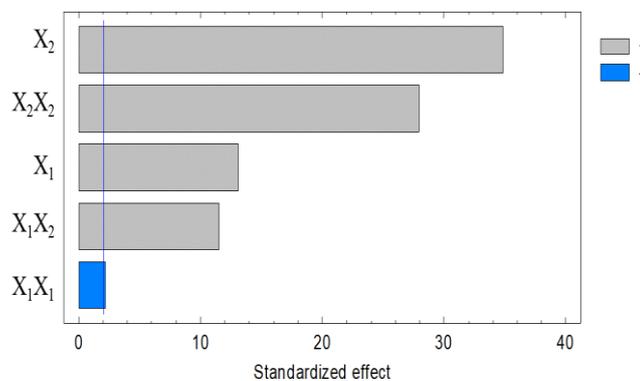**Figure 4**. Response surface and contour plot for hardness.

Figure 5. Standardized Pareto chart for hardness (X_1: instant dry yeast; X_2: PS).

3.3.3. Simultaneous Optimization

Statgraphics software was used to optimize the sandwich bread preparation to produce a product with the highest loaf volume expansion, specific volume, and the desired product hardness (750 g force). By superimposing the contour plots, the simultaneous optimization points of all conditions and the answers are displayed (Figure 6). The results show that the best conditions were achieved with instant dry yeast addition and PS replacement for wheat flour at 0.56% and 7.79%, respectively (shown by asterisks in the figure), using Optimize Desirability (Statgraphics Centurion XV.I). Under these conditions, the maximum expansion and specific volume values were achieved, respectively, at 288.08% and 5.69 cm³/g.
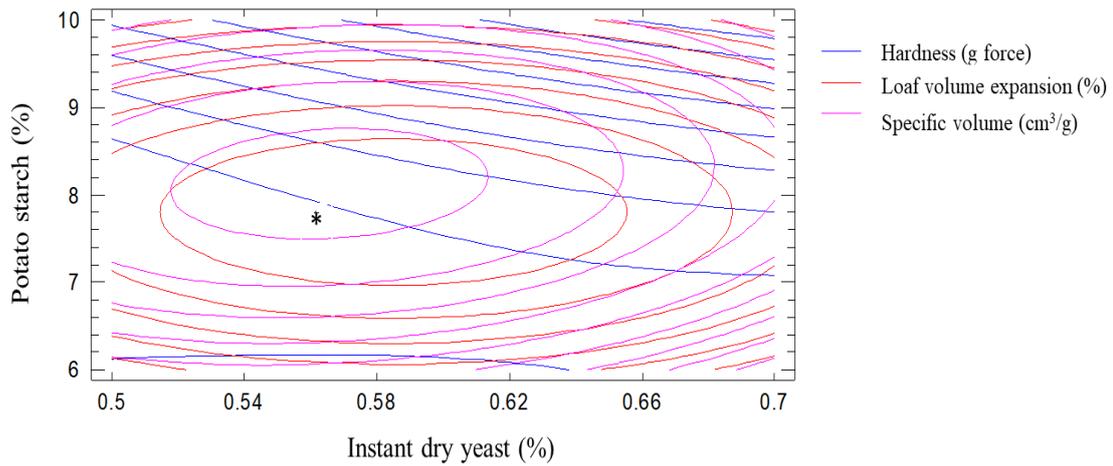
Figure 6. Overlapping plot of hardness, loaf volume expansion, and specific volume, showing optimal values* (with different levels of independent variables).
Note: * denotes the optimal point.

To validate the prediction models, the indicated optimal values for the product's hardness, specific volume, and loaf volume expansion attributes were used: 748.25 g-force, 5.67 cm³/g, and 291.93%, respectively. The measured findings during the test were quite comparable to the projected results from the model, varying by only 0.23%, 0.35%, and 1.3%, respectively, with the hardness, specific volume, and loaf volume expansion. The difference is within the permissible limit (<5%).

3.4. Nutritional Quality of the Control and Selected Sandwich Bread Samples

Partial replacement of wheat flour with NRM powder, combined with optimizing potato starch and instant dry yeast levels, significantly improved the structural characteristics and sandwich bread quality (Figure 7 and Table 6).
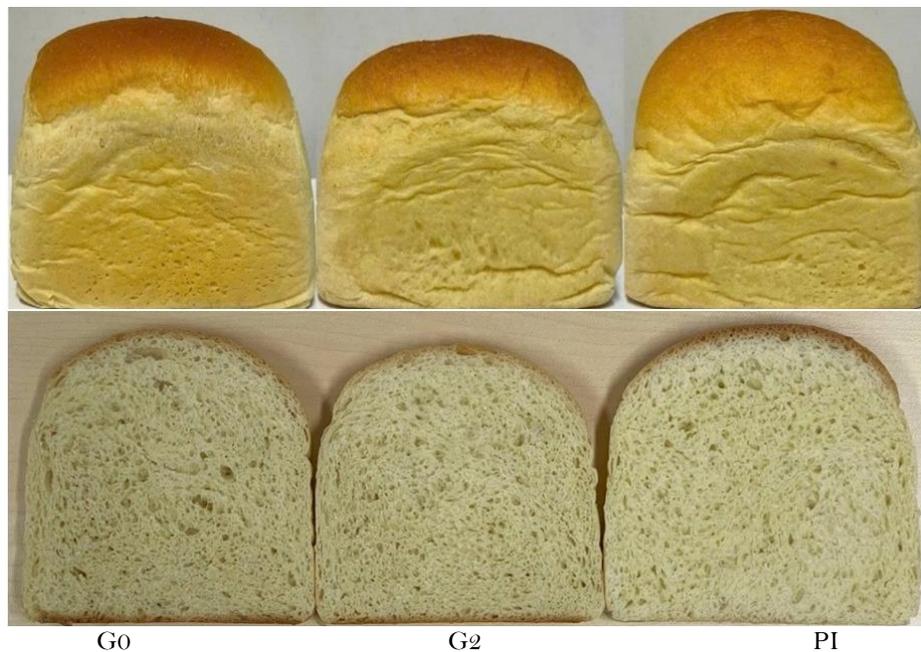
Figure 7. Sandwich breads formulated with different percentages.
Note: G0 as the control sample (100% wheat flour), G2 (NRM powder substituting wheat flour by 12.5%), and PI (With the ratio of PS: NRM powder: wheat flour is 7.79:12.5:79.71%, instant dry yeast supplement 0.56%).

The G2 sample showed higher protein, lipid, and ash contents (9.52%, 10.12%, and 2.08%, respectively) compared to the control sample G0 (8.92%, 4.97%, and 1.47%). Meanwhile, the PI sample exhibited no significant differences in these parameters compared to G2. This could be because a mixture of NRM powder contains a high lipid and protein

content (40.19% and 27.27%, respectively), whereas wheat flour is mostly starch with minimal amounts of protein, fat, and minerals. When compared to wheat flour and dehulled soy flour, moist soybean by-product contained more protein (Davy et al., 2022).

The total fiber of G2 and PI was exceptionally high, 3.3 times that of the control sample. Ostermann-Porcel et al. (2017) investigated how to make bread with increased nutritional quality using okara, soy milk residue, and discovered that the more okara powder used, the greater the protein and fiber content. Cashew pomace flour's high crude fiber content may make it useful for improving cereal diets. Fiber's therapeutic effects on the prevention of heart disease, colon cancer, and diabetes, as well as its role in the treatment of digestive diseases (diverticulosis) and constipation, have been thoroughly explored (Dosumu, Oluwaniyi, Awolola, & Oyedeji, 2012).

The sample PI had a higher moisture content (33.94%) than G2 (32.30%) and the control sample (33.86%). However, G2 and PI had lower carbohydrate contents (45.98% and 46.00%) than the control sample (50.78%). The reduction in carbohydrate content compared to the 100% wheat flour control can be attributed to the compositional differences between wheat flour and NRM powder. Wheat flour is predominantly composed of starch, whereas NRM powder contains higher amounts of protein, dietary fiber, and lipids, but lower levels of available carbohydrates. Similarly, Yaseen et al. (2009) found that adding okra to bread considerably lowered its carbohydrate content, making it suitable for low-calorie and nutritionally enriched diets (Ibadullah et al., 2024).

Table 6. Nutritional composition, estimated GI value, and total polyphenol content of sandwich bread.

Parameters	Formula G0 (Control sample)	Formula G2 (Selected sample)	Formula PI (Selected sample)
Moisture content (%)	33.86±0.13	32.30±0.33	33.94±0.65
Protein (%)	8.92±0.15	9.52±0.12	9.10±0.61
Carbohydrate (%)	50.78±0.12	45.98±0.16	46.00±0.13
Lipid (%)	4.97±0.18	10.12±0.16	8.98±0.18
Ash (%)	1.47±0.08	2.08±0.09	1.98±0.03
Total fiber (%)	0.45±0.06	1.5±0.21	1.47±0.23
eGI	67.6±0.19	54.24±0.25	51.16±0.46
TPC (mgGAE/100 g)	9.57±0.18	28.07±0.20	27.68±0.30

Note: Values are expressed as mean±STD, with G0 as the control sample (100% wheat flour), G2 (NRM powder substituting wheat flour by 12.5%), and PI (with the ratio of PS: NRM powder: wheat flour is 7.79:12.5:79.71%, instant yeast supplement 0.56%).

It is also evident that the TPC of sample G2 and PI has significantly improved (28.07 mg GAE/100 g and 27.68 mg GAE/100 g, respectively) compared to sample G0 (9.57 mg GAE/100 g). Pešić et al. (2023) demonstrated that the addition of okara in gluten-free bread production resulted in a product with a TPC of 133.75 mg GAE/100 g FW. This study also highlighted that incorporating phenolic-rich by-products not only enhances nutritional value and antioxidant capacity but also contributes to effective waste management.

Table 6 also shows that the estimated glycemic index of the PI, G2, and G0 samples were 51.16 (low eGI), 54.24 (low eGI), and 67.6 (medium-high eGI), respectively. Adding flour made from byproducts can improve the glycemic index due to increased fiber and phenolic content (Zuñiga-Martínez et al., 2022). Legume- and nut-enriched bakery products have been reported to exhibit significantly reduced GI values compared to wheat-based controls due to these combined effects (Naveed et al., 2024). Alongi, Melchior, and Anese (2019) reported that partially replacing wheat flour with apple pomace dramatically lowered the glycemic index of cookies. As a result, reusing fiber-rich plant by-products not only helps to reduce food waste, lowering the environmental impact of food production, but it can also be a useful technique for designing dietary strategies to manage type 2 diabetes.

Furthermore, potato starch's high fiber and resistant starch content can help reduce the glycemic index of processed foods (Raatz, Idso, Johnson, Jackson, & Combs Jr, 2016). According to Sajilata, Singhal, and Kulkarni (2006), resistant starch has a hypoglycemic effect because it takes longer for digestive enzymes to hydrolyze and

release glucose. Consuming foods containing resistant starch effectively lowers postprandial blood sugar levels and helps diabetics control insulin resistance.

4. CONCLUSION

The incorporation of nut residue mixture (NRM) powder, potato starch, and instant dry yeast in bread formulation produces a unique and more nutritious product compared to conventional bread, offering a cost-effective partial replacement for wheat flour and promoting the sustainable use of local by-products. These findings highlight the potential for commercial-scale production of affordable, healthy bakery products that can diversify food options and enhance local income sources. However, this study was limited to specific formulation and processing conditions, without extensive evaluation of storage stability or shelf life. Therefore, our future research will focus on optimizing formulation parameters, exploring other local residue sources, assessing long-term product quality, and examining consumer acceptance to support large-scale application and commercialization.

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