



Research article

Influence of cereal bran type on rheological, physicochemical and sensory properties of fiber-enriched steamed buns

Thunnop Laokuldilok^{a,c,*}, Pirom Phromthan^a, Phakchuda Promkeaw^a, Nattapong Kanha^{a,b}

^a Faculty of Agro-Industry, Chiang Mai University, Chiang Mai 50100, Thailand

^b Office of Research Administration, Chiang Mai University, Chiang Mai 50200, Thailand

^c Cluster of High Value Products from Thai Rice and Plants for Health, Chiang Mai University, Chiang Mai 50200, Thailand

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Abstract

Importance of the work: Bran type is an important factor influencing the steamed-bun dough structure, nutrition and consumer acceptability.

Objectives: To compare the effects of black rice, wheat and oat brans on the rheological, nutritional and sensory properties of steamed buns.

Materials and Methods: Black rice, wheat and oat brans (5% and 10%) replaced wheat flour in steamed-bun formulations. Dough rheology, specific volume and sensory attributes were analyzed using standard Association of Official Analytical Chemists methods, rheometry and a 9-point hedonic scale. Data were evaluated using analysis of variance ($p < 0.05$).

Results: The black rice bran had the highest values for the moisture (10.42%), water activity (0.55), lipid (17.90%), crude fiber (19.16%) and total phenolic (853.10 mg gallic acid equivalents/100 g) content. Wheat bran had the highest values for the protein content (13.36%) and yellowness ($b^* = 25.46$), while oat bran had the greatest value for lightness ($L^* = 80.81$). All doughs had weak-gel behavior (storage modulus > loss modulus) with $\tan \delta = 0.386\text{--}0.417$, indicating elastic dominance. Fiber fortification increased the phenolic and crude fiber contents but reduced the specific volume. The oat-bran buns were the lightest and smoothest, whereas the black rice-bran buns appeared the darkest. Sensory evaluation at 10% fortification indicated the highest texture (7.27) and overall liking (7.23) for the oat-bran buns, confirming their superior balance of texture, color and acceptability among the tested fiber-enriched steamed buns.

Main finding: Oat bran, rich in soluble β -glucans, improved the texture and acceptability of steamed buns. This comparative analysis clarified how fiber type and composition influenced the dough structure and should help to guide the formulation of nutritionally enhanced, consumer-acceptable steamed foods.

* Corresponding author.

E-mail address: thunnop.l@cmu.ac.th (T. Laokuldilok)

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Introduction

Dietary fiber is a complex carbohydrate polymer from plants that is resistant to digestion and absorption in the human small intestine but is partially or completely fermented by gut microbiota in the colon (Das et al., 2026). It is classified into two primary types: soluble dietary fiber, which dissolves in water to form viscous gels and insoluble dietary fiber, which does not dissolve in water and provides bulk to the diet (Dhingra et al., 2012). These fibers are sourced primarily from fruits, vegetables, legumes and cereal grains (Khorasaniha et al., 2023). Among its sources, cereal fibers are important due to their balanced composition of soluble and insoluble dietary fiber, which contribute differently to nutritional and functional properties in food systems (Nirmala Prasadi and Joye, 2020). Consistently, epidemiological evidence has suggested that higher dietary fiber intake improves bowel regularity, lowers serum cholesterol, enhances glycemic regulation and reduces the risk of cardiovascular disease, type 2 diabetes and several cancers (Reynolds et al., 2019). For example, a study by Wei et al. (2018) highlighted that increasing dietary fiber intake by 10 g per day was associated with an 11% reduction in the risk of developing metabolic syndrome, emphasizing the importance of dietary fiber, particularly cereal fibers, in disease prevention. These findings highlight the importance of increasing dietary fiber intake through the reformulation of staple foods for consumer health benefits.

Steamed buns are a major staple food in China and many Asian countries, where typically, these buns are prepared using refined wheat flour, from which the bran and germ layers are removed during the milling process, resulting in a product low in fiber and micronutrients (Yang and Wang, 2023). Given the high consumption of refined cereal products in Asia, fortifying steamed buns with dietary fiber offers a promising strategy to enhance their nutritional value. However often, fiber incorporation alters the dough matrix by affecting gluten network formation, water distribution and starch-protein interactions, thereby influencing the textural and sensory quality (Liu et al., 2017). Insoluble fibers, such as cellulose and arabinoxylan, can physically disrupt gluten development and reduce gas retention, while soluble fibers, such as β -glucans, increase dough viscosity and moisture-holding capacity, resulting in stiffer doughs and denser crumb structures (Rosell et al., 2001; Wang et al., 2021a).

Different cereal brans vary markedly in their composition and functionality. For example, cereal brans, including wheat, oat and black rice, are rich in dietary fiber and bioactive compounds, which have been shown to exhibit antioxidant, cholesterol-lowering and anti-inflammatory properties (Anderson et al., 2009; Alahmari, 2024). Wheat bran is rich in arabinoxylans, cellulose and lignin, representing a major source of insoluble dietary fiber (Molina et al., 2021). Oat bran contains β -glucans, which are recognized for their viscosity-modifying effect and ability to reduce glycemic and insulinemic responses (Zurbau et al., 2021). Black rice bran provides both dietary fiber and phenolic antioxidants, such as anthocyanins, γ -oryzanol and ferulic acid, contributing to health-promoting and color-enhancing functions (Das et al., 2023). While the effects of cereal fibers on the dough structure and bread quality have been investigated widely in baked systems, there has been only poor characterization of their behavior under steamed dough conditions. The thermal moisture environment of steamed buns alters starch gelatinization and gluten denaturation compared with baking, which may modify fiber-protein-starch interactions in ways not yet systematically understood. In addition, there have been limited comparative studies considering the markedly different soluble-to-insoluble fiber ratios of cereal brans. Consequently, there has been insufficient elucidation of the mechanisms by which insoluble fiber-rich brans (such as wheat and black rice) and soluble fiber-rich brans (such as oats) differentially influence gluten development, water redistribution and starch-protein interactions during steaming. This lack of understanding constrains the rational selection of fiber sources for steamed-bun fortification and the development of fiber-enriched products with acceptable structural and sensory quality.

Accordingly, the current study investigated the effects of fortifying steamed buns with different cereal fiber sources, (brans from black rice, wheat, oats) on their physicochemical and sensory properties. The parameters of dough rheology, specific volume, total phenolics and consumer acceptability were investigated to establish a scientific basis for developing fiber-enriched steamed buns that combined improved nutritional quality with desirable sensory attributes and contributed to the formulation of health-oriented staple foods.

Materials and Methods

Materials

Black rice bran (cultivar Kum Doi Saket) obtained from a local rice miller in Chiang Mai, Thailand, roasted wheat bran (Leing Nok Tha Organic Community Enterprise; Yasothon, Thailand) and coarse oat bran (McGarrett; Australia) were used as the cereal fiber sources. The ingredients used in the formula for steamed buns were all-purpose wheat flour, yeast, soybean oil, hydrogenated oil, double baking powder, salt and sugar; all were purchased from a local supermarket in Chiang Mai, Thailand.

Analysis of physicochemical properties of cereal brans

Proximate analysis

The proximate composition analysis was performed according to Association of Official Analytical Chemists (2000) methods. The moisture content of the samples was analyzed based on drying in a hot-air dryer (UN110; Memmert GmbH + Co. KG; Bavaria, Germany) at 105°C. Total lipids (fat) were evaluated using a Soxtec unit (Soxtec™ 8000; Foss; Hillerød, Denmark). The protein content was determined using the combustion method in a Leco unit (Leco; Hazel Grove, UK), with nitrogen-to-protein conversion factors of 5.95 for black rice bran, 6.31 for wheat bran, 5.83 for oat bran and 5.70 for the control wheat flour. Crude fiber was measured using a Fibertec instrument (Fibertec™ 8000 Auto analysis system; Foss; Hillerød, Denmark).

Water activity

The water activity (a_w) of the cereal brans was analyzed at 25°C using an Aqualab instrument (AquaLab Series 3TE; Decagon Devices Inc.; Pullman, WA, USA).

Color

The color of the cereal brans was quantified using a colorimeter and the CIELAB system (ColorQuest XE; Hunter Lab; Leicester, UK). In this system, L^* values range from 0 (representing total darkness) to 100 (indicating maximum lightness), a $-a^*$ value signifies greenness, while a $+a^*$ value indicates redness. Additionally, a $-b^*$ value represents blueness and a $+b^*$ value corresponds to yellowness.

Total phenolic content

The total phenolic contents (TPCs) of the black rice, wheat and oat brans were quantified using a modified version of the method by Aguilar-Garcia et al. (2007). A sample (1 g) of each bran was extracted with 10 mL of 80% methanol by shaking at room temperature for 60 min. The resulting mixture was passed through No. 4 filter paper and 60 μ L of the clear filtrate was collected for further analysis. To this aliquot were added 2.5 mL of 10% Folin-Ciocalteu reagent, followed by thorough mixing. After incubation in the dark for 2 min, 2.5 mL of 7.5% sodium carbonate solution was introduced and the mixture was shaken thoroughly. Next each sample was incubated at 50°C for 15 min and then cooled immediately. Absorbance was measured at 760 nm using an ultraviolet-visible spectrophotometer (Genesys 10; Thermo Scientific; Madison, WI, USA) against a blank. The TPC was expressed as milligrams of gallic acid equivalent (GAE) per dry weight (DW) that was calculated using a standard curve of gallic acid with a linear range of 50–1,000 μ g/mL (coefficient of determination > 0.99).

Steamed buns formulation and preparation

For the sponge dough preparation, sugar (3%) and yeast (2%) were dissolved in warm water (Mixture 1) and allowed to rest for 5 min to activate the yeast. Wheat flour (37%) was sifted and gradually incorporated into Mixture 1. The dough was mixed in a planetary mixer (KitchenAid; St. Joseph, MI, USA) at low speed for 5 min until homogeneous. Then, the dough was left to rest in a warm place for about 60 min or until the dough volume had approximately doubled.

For the final dough preparation, water (4%), sugar (10%) and salt (1%) were dissolved to form Mixture 2. Wheat flour (15%) and double baking powder (1%) were premixed and gradually combined with Mixture 2. The mixing continued for 10 min or until a uniform dough resulted. Mixtures 1 and 2 were combined with hydrogenated vegetable oil (2%) and soybean oil (5%) and kneaded for 20 min. Next, this dough was proofed for 30–60 min, until it had doubled in size. After degassing, the dough was divided into 50 g portions and steamed at 100 °C for 20 min. For cereal fiber fortification, wheat flour was substituted with 5% or 10% of the different cereal brans. The basic formulations of the steamed bun dough samples are presented in [Table 1](#)

Table 1 Basic formulation of steamed bun dough.

Ingredient	Mixture 1 (% w/w)	Mixture 2 (% w/w)
Water	20	4
Wheat flour	37	15
Sugar	3	10
Yeast	2	–
Double baking powder	–	1
Hydrogenated vegetable oil	–	2
Soybean oil	–	5
Salt	–	1

Analysis of fortified steamed buns

Dough rheological properties

The rheological properties of the doughs were analyzed using a rheometer (TA AR 2000; TA instruments; New Castle, DE, USA), following the method outlined by Upadhyay et al. (2012). Briefly, each dough sample was placed between parallel plates and a thin layer of silicone oil was applied to the plate surfaces to prevent moisture loss during testing. A probe with a diameter of 25 mm and a gap setting of 3.5 mm was utilized for the measurements. The temperature was maintained at 25°C throughout the analysis. The rheological parameters obtained were expressed in terms of the storage modulus (G'), loss modulus (G'') and loss tangent ($\tan \delta = G''/G'$), which provided insights into the dough's viscoelastic behavior.

Specific volume

The specific volume of the steamed bun samples was measured using the sesame seed displacement procedure in a volume-measurement apparatus at 1 hr after steaming (Wang et al., 2021b).

Sensory evaluation

Sensory evaluation was carried out according to the international standard 11136:2014 (International Organization for Standardization, 2014) using a 9-point hedonic scale. Testing was carried out using 30 untrained consumers (10 men and 20 women, aged 18–50 yr) from Chiang Mai University, Thailand. All these participants provided informed consent, with prospective individuals with known food allergies being excluded. The evaluation was conducted as a preliminary consumer test to obtain an initial indication of product acceptability. Steamed bun samples (approximately 15 g) were coded with random three-digit numbers and presented in a randomized and counterbalanced order. Participants

rinsed their mouths with warm water between samples. Appearance, color, odor, taste, texture and overall liking were rated on a 9-point hedonic scale (1 = dislike extremely, 9 = like extremely).

Statistical analysis

All measurements were performed in three independent batches (biological replicates) and results were reported as mean $\pm$ SD values. Statistical analyses were conducted using the SPSS software (version 24; SPSS Inc., IBM Corp.; Armonk, NY, USA). Differences were considered significant at $p < 0.05$.

For TPC, crude fiber content, and specific volume, the six bran-fortified treatments were analyzed using two-way analysis of variance (ANOVA) based on a 3×2 factorial design, with cereal bran type (black rice, wheat, oat) and fortification level (5% and 10%) as fixed factors, according to Equation 1:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \quad (1)$$

where μ is the overall mean, α_i is the effect of cereal bran type, β_j is the effect of fortification level (5% and 10%), $(\alpha\beta)_{ij}$ is the interaction effect and ε_{ijk} is the random error.

To compare all seven treatments, including the control, one-way ANOVA was additionally performed for each variable, followed by Tukey's honestly significant difference test for pairwise mean comparisons when significant differences were detected.

Normality and homogeneity of variance were assessed using the Shapiro-Wilk and Levene tests, respectively. Effect sizes were reported as partial eta squared values (η^2).

The rheological properties (G' , G'' , $\tan \delta$) obtained from the dynamic oscillatory frequency sweep tests were analyzed descriptively to examine viscoelastic trends across the continuous frequency range (0.1–10 Hz).

Sensory evaluation was conducted only at the 10% fortification level; therefore, these differences among samples were analyzed using one-way ANOVA.

When significant differences were observed, Tukey's honestly significant difference test was applied for mean comparison.

Results and Discussion

Physicochemical properties of cereal fiber sources

The proximate composition and physical attributes of the three cereal fiber sources (black rice bran, wheat bran, oat bran) are presented in Table 2. The black rice bran had the highest values for the moisture content and a_w (10.42%; 0.55, respectively), followed by the oat bran (8.30%; 0.47, respectively) and the wheat bran (1.88%; a_w 0.18, respectively). The different moisture content and a_w values may have resulted from the different pre-processing steps; for example, the wheat bran that was roasted before grinding may have had a lower moisture content and a_w than that of the other brans. However, the moisture content (<10–12%) and a_w (<0.6) values of all three brans were within the safe range for the growth of microorganisms (Jay et al., 2005). Significant differences were observed in the color parameters among the three fiber sources. The oat bran had the highest L^* value (80.81), indicating its light cream appearance, whereas the black rice bran had a considerably lower L^* value (42.31), reflecting the presence of concentrated anthocyanin pigments (Laokuldilok et al., 2011). The wheat bran had intermediate lightness (69.07) but the highest b^* (yellowness) value (25.46) due to its carotenoid content (Paznocht et al., 2019). The redness (a^*) did not differ significantly between the black rice and wheat brans but was markedly lower in the oat bran. The dark color of the black rice bran could have contributed to the darker dough and steamed bun color, which may have reduced consumer acceptance. Conversely, the pale tone of the oat bran suggests its greater suitability for producing fiber-enriched steamed buns, with minimal visual deviation from the conventional product.

The wheat bran contained the highest protein content (13.36%), followed by the oat and black rice brans (10.23% and 8.83%, respectively). In terms of fat content, the black rice

bran contained the highest lipid content (17.90%). The oil in rice bran has been reported to be rich in unsaturated fatty acids and tocopherols (Tian et al., 2025). The high lipid content may have contributed to the improved softness and shelf-life of the steamed buns through a lipid-starch complex formation, though excessive fat could inhibit gluten development and gas retention (Kang et al., 2021). The black rice bran had the highest crude fiber content (19.16%), followed by the wheat (12.47%) and oat (11.95%) brans. These results were consistent with Budijanto et al. (2023), who reported that rice bran contained approximately 21.2–30.2% dietary fiber. The crude fiber of the commercial wheat bran used in the current study was lower than literature values (Onipe et al., 2015). This could be attributed to the wheat bran (fine bran) in the current study being contaminated with some visible endosperm fraction, (as suggested by its higher protein content compared to typical wheat bran) which diluted the insoluble pericarp and seed coat fractions. The crude fiber content in the oat bran was the lowest (11.95%), being close to the fiber content oat bran range of 5.3–8.4% reported by Marlett et al. (1994). Considering the type of fiber, oat bran is rich in soluble fiber, which is helpful in lowering blood cholesterol levels, while rice and wheat bran are rich in insoluble fiber, which helps prevent constipation (Bernstein et al., 2013).

The TPC (or in the case of cereals, instead of “total”, it refers to the “free” phenolic content) differed significantly among the samples. The black rice bran contained the highest extractable phenolic concentration (853.10 mg GAE/100g DW), followed by the wheat bran (47.56 mg GAE/100g) and the oat bran (44.17 mg GAE/100g). The high TPC in the black rice bran was mainly derived from anthocyanins and ferulic acid and its esters (Laokuldilok et al., 2011), while wheat bran phenolics are primarily ferulic acid (Kim et al., 2006). The free phenolics in oat bran have been reported to include hydroxycinnamic acids, such as ferulic, p-coumaric and caffeic acids, along with small amounts of avenanthramides (Multari et al., 2018).

Table 2 Physicochemical properties of cereal brans.

Physicochemical properties	Cereal brans		
	Black rice bran	Wheat bran	Oat bran
Moisture content (% wet basis)	10.42±0.27 ^a	1.88±0.21 ^c	8.30±0.13 ^b
Water activity (a_w)	0.55±0.01 ^a	0.18±0.02 ^c	0.47±0.001 ^b
L^* (lightness)	42.31±0.26 ^c	69.07±0.25 ^b	80.81±0.14 ^a
a^* (redness)	7.57±0.22 ^a	7.85±0.43 ^a	3.84±0.08 ^b
b^* (yellowness)	6.50±0.03 ^c	25.46±0.30 ^a	17.96±0.34 ^b
Protein content (% dry basis)	8.83±0.18 ^c	13.36±0.49 ^a	10.23±0.32 ^b
Fat content (% dry basis)	17.90±1.08 ^a	6.35±0.64 ^c	9.10±0.48 ^b
Crude fiber content (% dry basis)	19.16±1.33 ^a	12.47±0.18 ^b	11.95±0.48 ^b
Total phenolics content (mg GAE/100g dry weight)	853.10±13.30 ^a	47.56±3.64 ^b	44.17±3.21 ^b

Mean±SD (n = 3) within the same row followed by different lowercase superscript letters are significantly different ($p < 0.05$).

These bioactive compounds not only enhance the antioxidant potential of fortified steamed buns but may also influence color and flavor attributes.

Rheological behavior of cereal fiber-fortified doughs

Dynamic oscillatory measurements were used to characterize the viscoelastic properties of the doughs. The results were presented descriptively to illustrate the comparative trends in network development across the frequency range (Fig. 1–Fig. 3). All samples exhibited typical weak-gel behavior, with both G' and G'' increasing with frequency. Because G' consistently exceeded G'' throughout the test, the doughs were identified as predominantly elastic. Cereal fiber fortification influenced the viscoelastic matrix; however, the magnitude of this effect depended on the fiber source and fortification level. The 10% oat-bran dough had the highest G' and G'' values, followed by the 10% wheat-bran and 10% black rice-bran doughs, indicating that fiber addition at 10% may have increased dough rigidity. Similar results were reported by Sudha et al. (2007), who observed decreased extensibility of wheat dough with increasing defatted rice-bran addition. Soluble β -glucans from oat bran are capable of gel-formation and substantial water binding, which may favor the development of a more cohesive hydrocolloid-protein phase in wheat dough (Wang et al., 2017; Renzetti et al., 2021). In the current study, the oat bran appeared to moderately increase both G' and G'' through reinforcement by arabinoxylan and cellulose, whereas the black rice bran, rich in lipids, proteins and insoluble fibers, altered the dough structure through multiple mechanisms. Lipids act as plasticizers that reduce G' and G'' (Fu et al., 1997), while insoluble fibers disrupt the starch-gluten matrix and

influence water distribution (Gan et al., 1992). In addition, rice glutelin may interact with glutenin, affecting network integrity (Oszvald et al., 2009). A concentration-dependent trend was observed; at 5% fortification, all brans lowered G' and G'' due to gluten dilution and water competition, whereas at 10%, both these moduli increased, likely from a percolated hydrocolloid network of soluble fibers and additional interactions among polyphenols, proteins and native lipids that strengthened the viscoelastic matrix (Noort et al., 2010).

In all the tested doughs, the $\tan \delta$ values remained below 1.0, confirming elastic-dominant behavior (Fig. 3). At 2 Hz, the control dough had the highest $\tan \delta$ (0.417), whereas the fiber-fortified doughs had lower values (0.386–0.410), indicating a shift toward more elastic-dominant viscoelastic structure. While $\tan \delta$ values below 0.4 are often associated with reduced extensibility and limited expansion (Edwards et al., 1999), the functional implications depend strongly on the nature of the reinforcing components. In the case of the oat-bran fortified dough, the reduction in $\tan \delta$ was accompanied by a concurrent increase in both G' and G'' , indicating an elastic-dominant yet cohesive viscoelastic system rather than a brittle or overly rigid structure. Soluble β -glucans likely form a hydrated, viscous phase that enhanced water retention and polymer entanglement within the gluten-starch matrix. Nevertheless, all the fiber-fortified formulations had lower specific volume values than the control, indicating that gluten dilution and water redistribution still limited gas expansion. In contrast, the doughs fortified with the insoluble-fiber-rich wheat and black rice brans had similarly low $\tan \delta$ values but lower viscous damping and greater physical disruption of the gluten network, which likely restricted expansion and contributed to their denser steamed bun structures (Wang et al., 2022; Fan et al., 2024).

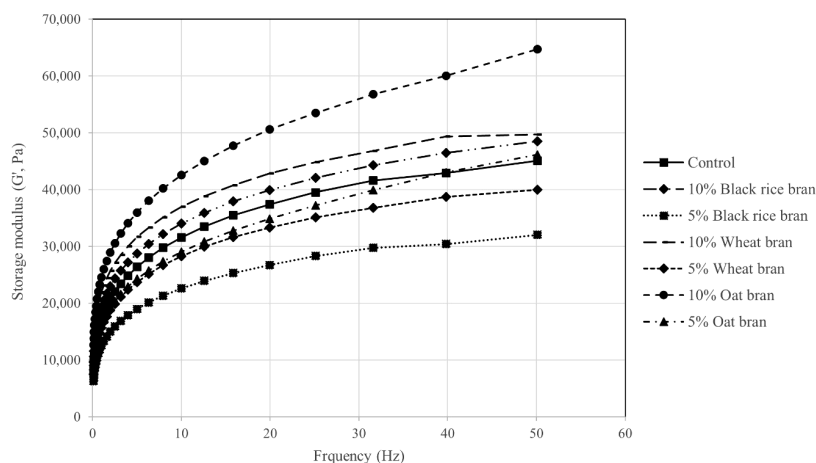


Fig. 1 Storage modulus of dough samples fortified with different cereal brans

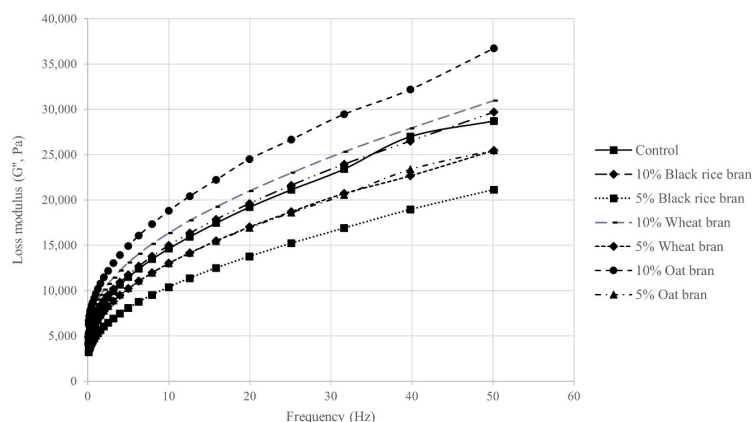


Fig. 2 Loss modulus of dough samples fortified with different cereal brans

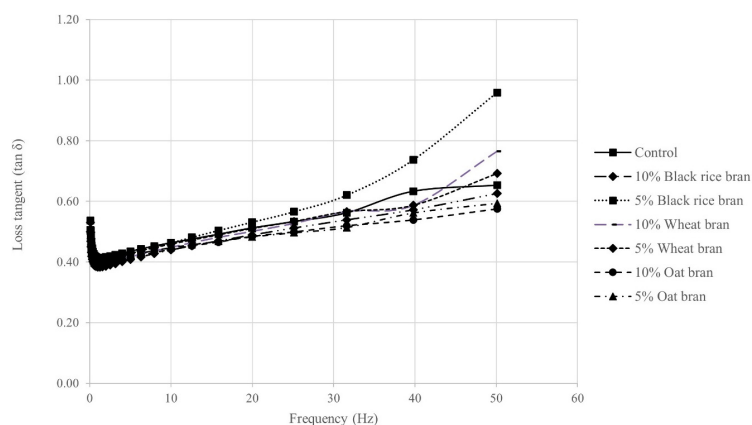


Fig. 3 Loss tangent of dough samples fortified with different cereal brans

Total phenolic content of fortified steamed buns

The TPC of the fortified steamed buns is shown in Fig. 4. All the bran-enriched samples had significantly higher TPC values than the control. The two-way ANOVA revealed significant main effects of cereal bran type and fortification level, as well as a significant interaction between the two factors (Table 3). Cereal bran type showed the largest effect on TPC ($\eta^2 = 0.92$), followed by the interaction between bran type and fortification level ($\eta^2 = 0.50$), while fortification level showed a smaller effect ($\eta^2 = 0.40$). These results indicated that the TPC was determined primarily by differences among bran types, while the response to fortification level also depended on the type of bran used. The addition of black rice bran resulted in the highest TPC, followed by the wheat and oat brans, consistent with their intrinsic phenolic composition (Table 2). The black rice bran provided the greatest increase due to its abundant anthocyanins, γ -oryzanol and ferulic acid, concentrated in the pigmented pericarp (Laokuldilok et al., 2011). Despite its high phenolic content, black rice bran also contained a high lipid content, which may affect the product's

shelf life. The wheat and oat brans had moderate TPC values. Wheat bran's phenolic content is largely bound (esterified to arabinoxylans); however, thermal processing (such as moist heating) can partially release these compounds and increase the measurable TPC (Zhang et al., 2023). Steaming, although milder than baking, still induces oxidative and polymerization reactions that affect phenolic stability and the phenolic retention in buns may arise from non-covalent polyphenol-protein and polyphenol-starch association, which reduces leaching and thermal degradation during heating (Zhang et al., 2019; Yang et al., 2024; Zhang et al., 2024). Such interactions may contribute to the slightly higher G' values observed in rheological analyses, since phenolic-protein bonding can lead to protein aggregation and densification of the gluten network, thereby enhancing dough rigidity (Li et al., 2024). However, in addition to their health benefits, phenolic compounds may affect the taste, color and acceptability of a product. Therefore, optimizing the fiber type and fortification level is crucial to achieving both functional benefits and consumer-preferred attributes in fiber-fortified steamed buns.

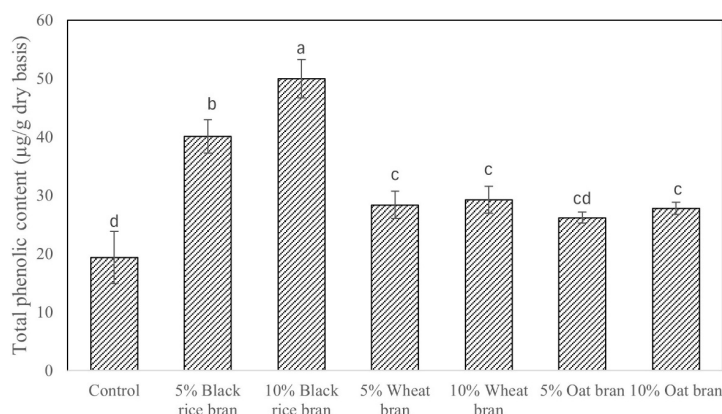


Fig. 4 Total phenolic content of steamed buns fortified with different cereal brans. Bars represent mean and error bars indicate $\pm$ SD. Different lowercase letters above bars indicate significant differences among all treatments based on one-way ANOVA with Tukey's test ($p < 0.05$).

Table 3 Two-way analysis of variance (ANOVA) evaluating the effects of cereal bran type (Factor A), fortification level (Factor B), and their interaction ($A \times B$) on total phenolic content, crude fiber content, and specific volume of fortified steamed buns

Source of variation	df	Total phenolic content	Crude fiber content	Specific volume
Cereal bran type (A)	2	73.77** (0.92)	105.59** (0.95)	16.18** (0.73)
Fortification level (B)	1	8.14* (0.40)	28.75** (0.70)	2.75 ^{ns} (0.19)
A $\times$ B	2	6.06* (0.50)	0.80 ^{ns} (0.12)	0.17 ^{ns} (0.03)
Error	12			

Values are presented as F-statistics, with partial eta squared (η^2) shown in parentheses from factorial analysis. Statistical significance was defined as $p < 0.05$ (*), $p < 0.01$ (**), and ns = non-significant.

Crude fiber content of fortified steamed buns

The crude fiber content of the fortified steamed buns is presented in Fig. 5. The two-way ANOVA showed significant main effects of cereal bran type and fortification level, while no significant interaction effect was observed (Table 3). The larger effect size for cereal bran type ($\eta^2 = 0.95$) than for fortification level ($\eta^2 = 0.70$) indicated that the fiber content depended more on the bran source than on the increase in the fortification level. All the fortified samples contained significantly higher crude fiber contents than the control, confirming the effective incorporation of dietary fiber into

the steamed-bun matrix. The crude fiber content increased in the order: black rice bran > wheat bran $\approx$ oat bran > control, consistent with the intrinsic fiber composition of the raw materials (Table 2). The markedly higher crude fiber content in the black rice-bran bun reflected the abundance of insoluble polymers, such as cellulose and lignin, which remained structurally stable under the mild steaming conditions (< 100 °C). The wheat-and oat-bran buns had moderate crude fiber enrichment, associated with their moderate dietary fiber contents. Thus, cereal bran fortification effectively increased the crude fiber content of the steamed buns, with the greatest increase observed in the black rice-bran samples.

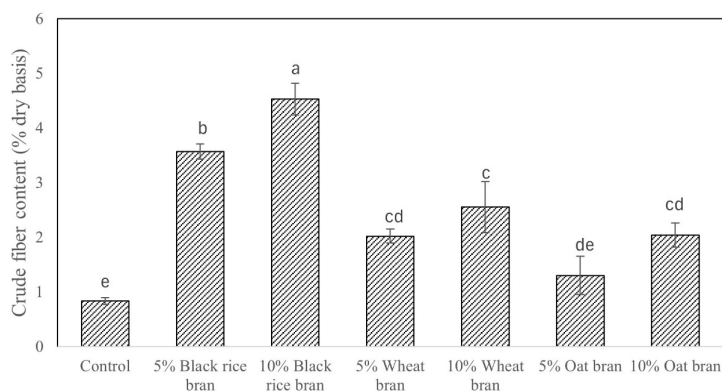


Fig. 5 Crude fiber content of steamed buns fortified with different cereal brans. Bars represent mean and error bars indicate $\pm$ SD. Different lowercase letters above bars indicate significant differences among all treatments based on one-way ANOVA with Tukey's test ($p < 0.05$).

Specific volume of fortified steamed buns

The specific volume of the fortified steamed buns is shown in Fig. 6. All the bran-enriched samples had significantly lower volumes than the control, indicating reduced gas retention following fiber incorporation. The two-way ANOVA showed a significant main effect of cereal bran type, while fortification level and the interaction term were not significant (Table 3). The effect size analysis showed the strong influence of cereal bran type ($\eta^2 = 0.73$) and a minimal effect of fortification level ($\eta^2 = 0.19$). This indicated that the gluten network disruption was driven mainly by the physicochemical properties of the fiber (such as particle morphology and water-binding capacity), rather than the difference between the 5% and 10% fortification levels. The reduction followed the order: black rice bran $\approx$ wheat bran $>$ oat bran $>$ control, reflecting the characteristics of each fiber source. The pronounced decrease in the black rice- and wheat-bran samples may be attributed to their high insoluble fiber contents, which competed with gluten proteins for water, hindering proper gluten hydration and network formation (Rosell et al., 2001). In addition, the coarse, rigid bran particles act as physical discontinuities within the gluten-starch matrix of dough, weakening the gas-cell walls and accelerating collapse (Han et al., 2018). In contrast, oat bran fortification led to only a slight reduction in volume relative to the other cereal brans evaluated in the current study, likely reflecting the presence of soluble β -glucans. These polysaccharides bind substantial amounts of water and form a viscous, hydrated phase within the dough matrix, increasing dough viscosity while preserving gluten network continuity (Wel-Stanowska et al., 2023; Zhou et al., 2025). Unlike insoluble fiber components, β -glucans do not directly fracture gluten strands but instead regulate gas cell expansion primarily through water redistribution and physical entanglement within the gluten–starch matrix, thereby preventing excessive structural collapse (Hu et al., 2022;

Astiz et al., 2023). The reduction in the specific volume may have resulted in the firmer texture of the steamed buns, which may subsequently affect consumer acceptance.

Appearance of fortified steamed buns

The visual appearance of the steamed buns fortified with different cereal fibers is illustrated in Fig. 7. Fiber incorporation markedly altered surface brightness, color and smoothness relative to the control. The control sample had a light cream, glossy surface, characteristic of refined wheat flour, whereas the fiber fortification caused progressive darkening and rougher textures, depending on cereal bran type and level. Among the fortified samples, the oat-bran buns appeared the lightest, followed by the wheat-bran buns with a light brown tone, while the black rice-bran buns had the darkest (brownish-purple) color. These differences corresponded to the pigment composition of each bran, with the oat bran containing few chromophores and abundant soluble β -glucans, while the wheat bran was rich in carotenoids and phenolic acids bound to arabinoxylans (Paznocht et al., 2019) and the black rice bran had a high anthocyanin concentration (Laokuldilok et al., 2011). Although these pigments contribute to the antioxidant value, they produce a darker hue that deviates from the bright, traditional appearance preferred for steamed buns. The control buns maintained a smooth, uniform surface, indicating complete gluten film development during steaming, whereas the fiber-fortified buns became increasingly rough and matte, particularly at 10% substitution. The incorporation of the wheat and black rice brans (both high in insoluble dietary fiber) markedly disrupted the integrity of the starch-gluten matrix, resulting in surface cracking of the steamed buns. In contrast, the oat-bran-fortified buns had a more uniform and compact surface, consistent with the high water-binding capacity of β -glucans, which promotes homogeneous hydration and minimizes shrinkage during steaming.

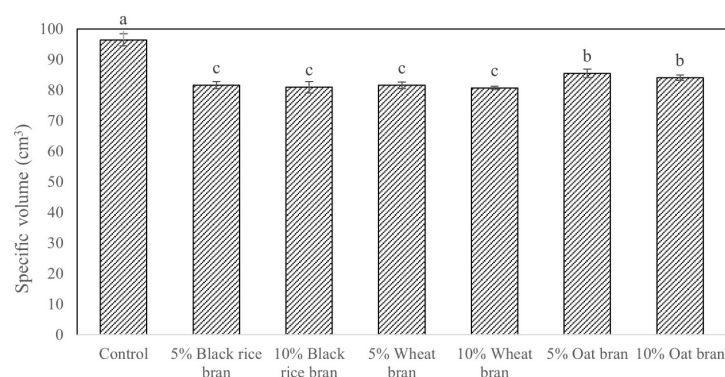


Fig. 6 Specific volume of steamed buns fortified with different cereal brans. Bars represent mean and error bars indicate $\pm$ SD. Different lowercase letters above bars indicate significant differences among all treatments based on one-way ANOVA with Tukey's test ($p < 0.05$).

Sensory characteristics of fortified steamed buns

Because fortification level did not significantly affect specific volume within the 5%–10% range (Fig. 6), and the 10% level provided significantly higher fiber content, only the 10% fortified samples were selected for sensory evaluation. The 9-point hedonic scores for the steamed buns fortified with 10% cereal brans are summarized in Table 4. Fortification significantly decreased the appearance, color, texture and overall liking relative to the control, whereas the odor and taste did not differ significantly among the samples. The addition of the pigmented brans resulted in lower appearance and color scores, consistent with the darker hue and increased particulate heterogeneity observed in the fortified buns (Fig. 7). Although darker coloration reduced the hedonic scores, it may also serve as a visual cue of higher fiber and antioxidant content for health-oriented consumers. Odor and taste scores were statistically comparable across all formulations, indicating that fiber incorporation did not markedly alter aroma or flavor perceptions; although the oat-bran buns had a slightly higher odor score, this difference was not significant.

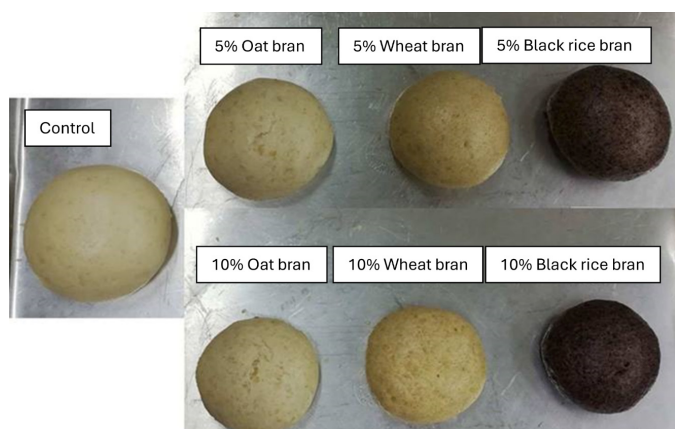


Fig. 7 Physical appearance of steamed buns fortified with different cereal brans. Note: Images are intended for visual appearance and color comparison only; apparent sizes may vary due to camera-to-sample distance. For quantitative expansion data, please refer to the specific volume results in Figure 6.

Texturally, all the fiber-fortified buns were perceived as firmer and less elastic than the control, reflecting the reduced gas retention and increased dough rigidity associated with fiber incorporation. Among the fiber-fortified samples, the buns containing 10% oat bran achieved the highest texture score (7.27) and the highest overall liking score (7.23), despite these values remaining significantly lower than the control. This relatively favorable acceptance could be attributed to the milder impact of the oat bran on the texture and sensory attributes than with the wheat and black rice brans. The water-binding capacity of β -glucans likely contributed to a less rigid crumb structure and improved mouthfeel, while the absence of strong pigmentation and off-flavor compounds minimized any negative effects on color, odor and taste (Lante et al., 2023). Consequently, the oat bran provided the most balanced sensory profile among the fortified formulations, highlighting its suitability for fiber enrichment of steamed buns when consumer acceptance is a key consideration.

Notably, this preliminary sensory evaluation, involving 30 untrained panelists, only provided an initial insight into consumer preference rather than a definitive market assessment. Additionally, panelist effects were not accounted for in the current statistical model. To build on these findings, future studies should involve a larger, trained descriptive panel to further clarify the sensory trade-offs of cereal fiber fortification.

Conclusions

Fortifying steamed buns with cereal fibers (black rice bran, wheat bran, oat bran) significantly altered their physicochemical, rheological, nutritional and sensory characteristics in a source-dependent manner. The distinct composition of each fiber source determined its functionality during dough formation and steaming. The black rice bran, rich in insoluble fiber, lipids and phenolics, produced doughs with higher rigidity and buns with the greatest crude fiber and phenolic enrichment but reduced specific volume, with a darker color and lower sensory scores due to their denser crumb and less favorable appearance, color and texture.

Table 4 Sensory characteristics (9-point hedonic scale) of steamed buns fortified with different cereal brans

Samples	Sensory attributes					
	Appearance	Color	Odor ^{ns}	Taste ^{ns}	Texture	Overall liking
Control	8.30±0.70 ^a	7.57±1.33 ^a	7.50±1.59	7.07±1.68	8.07±1.20 ^a	8.17±1.09 ^a
10% Black rice bran	6.50±1.70 ^c	6.17±2.02 ^b	7.33±1.69	6.63±1.81	6.60±1.63 ^c	6.47±1.85 ^c
10% Wheat bran	6.33±1.75 ^c	5.90±1.32 ^b	7.07±1.76	6.70±1.56	6.67±1.12 ^c	6.37±1.33 ^c
10% Oat bran	7.47±1.14 ^b	7.07±1.33 ^a	7.63±1.67	6.90±1.79	7.27±1.51 ^b	7.23±1.52 ^b

Mean±SD (n = 30) within the same column followed by different lowercase superscript letters are significantly different ($p < 0.05$). ns = non-significant.

The wheat bran provided moderate nutritional improvement and structural reinforcement but limited sensory scores due to its negative effects on the appearance, color and texture of the steamed bun. In contrast, the oat bran, dominated by soluble β -glucans, produced a dough with balanced elasticity and smoother surfaces, resulting in the most favorable sensory preference among the tested formulations under the preliminary consumer evaluation conditions. The results highlight that the technological and sensory outcomes of fiber fortification depended primarily on type, while fortification level influenced some responses. Soluble fibers enhanced texture and overall acceptability, while insoluble, phenolic-rich fibers increased the functional value but required formulation optimization to preserve the volume and color. Fortification at 10% effectively increased the dietary fiber and bioactive compound levels, while maintaining acceptable product quality, especially with the oat bran, supporting its use in developing health-oriented, functional steamed buns aligned with modern nutrition.

However, this study was limited by the absence of quantitative particle size analysis and microstructural imaging, which would provide deeper insight into any fiber-gluten interactions. In addition, the sensory evaluation was conducted as a preliminary consumer test with a relatively small number of untrained panelists, which may limit the generalizability of the sensory findings. Future work should incorporate bran particle size characterization, microstructural analysis using scanning electron microscopy and larger consumer panels, as well as explore combinations of soluble and insoluble fibers to optimize both nutritional value and textural quality.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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