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Original Research

Red mombin by-product as a functional ingredient for improving the quality of sliced bread

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Abstract: Background and aims: This study investigated the potential use of red mombin frozen pulp by-product as a functional ingredient in sliced bread. **Methods:** Sliced breads containing 5%, 10%, and 15% red mombin residue flour (RMRF) were produced and subjected to sensory evaluation to assess consumer acceptance, preference, and purchase intention. The most accepted formulation was compared with the control bread regarding chemical composition, water activity, caloric value, microbiological quality, physical properties, texture, and color (CIE Lab*). The functional properties of RMRF, as well as the farinographic and alveographic characteristics of wheat flour with and without RMRF addition, were also evaluated. **Results:** Red mombin residue flour exhibited high contents of dietary fiber (27.5 g/100 g), carbohydrates (53.4 g/100 g), and ash (3.07 g/100 g), along with low lipid content (1.98 g/100 g) and low water activity (0.29), indicating its potential contribution to microbiological stability. Bread containing 10% RMRF showed a fivefold increase in dietary fiber compared with the control formulation, as well as higher carbohydrate and ash contents and lower lipid content. Sensory evaluation indicated that the formulation containing 10% RMRF achieved the highest overall acceptance and purchase intention scores among the enriched breads while maintaining adequate technological and physical characteristics. **Conclusion:** The incorporation of 10% RMRF effectively improved the nutritional and functional quality of sliced bread while maintaining consumer acceptability. Among the formulations tested, bread containing 10% RMRF provided the best balance between fiber enrichment, technological performance, and sensory acceptance, demonstrating the feasibility of valorizing red mombin processing by-products as functional ingredients in bakery products.

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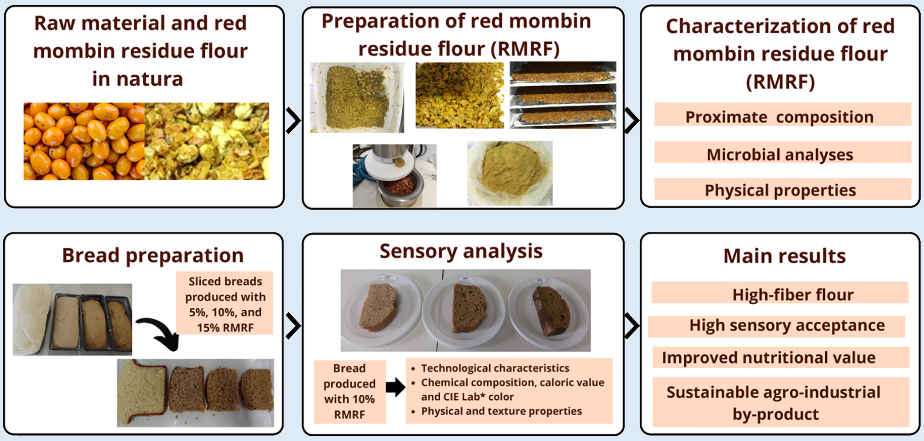
Graphical Abstract:



Keywors: Red mombin residue flour, Sliced bread, Dietary fiber enrichment, Sensory evaluation, Technological quality

1. Introduction

Interest in exotic tropical fruits has increased considerably over the past decade due to their distinctive sensory characteristics, consumer appeal, and nutritional benefits. Fruits such as *Spondias purpurea* L., commonly known as red mombin, have attracted particular attention because of their potential contribution to sustainable food systems and smallholder agriculture [1]. Native to the Americas and widely distributed in the Brazilian Caatinga biome, red mombin has significant economic potential due to its low production costs and adaptability to adverse environmental conditions.

Red mombin fruits are small, round drupes weighing between 5 and 43 g, characterized by a yellow pulp surrounding the seed, a pleasant aroma, and a sweet-acidic flavor. They are rich in carbohydrates, especially glucose, fructose, and sucrose [2], and provide substantial amounts of vitamin C, dietary fiber, minerals (potassium, iron, calcium, magnesium, and phosphorus), and phenolic compounds [3-6]. These fruits also exhibit important antioxidant properties and have been associated with potential protective effects against several chronic conditions, including cardiovascular diseases, diabetes, and oxidative stress-related disorders [6].

Previous studies have demonstrated that red mombin fruits from the Caatinga region contain high concentrations of vitamin C, carotenoids, and phenolic compounds, resulting in strong antioxidant activity [7, 8]. In addition, the peel is particularly rich in phenolic acids and glycosylated compounds, highlighting the nutritional value of processing by-products [9].

Most previous investigations have focused on the characterization of soluble solids and extraction efficiency in fresh red mombin pulp [2], the phytochemical composition of specific fruit fractions such as peel extracts [9], dehydration processes, or the general application of fruit by-products in food systems. However, few studies have evaluated the direct incorporation of red mombin processing residues into staple foods while simultaneously assessing their nutritional, technological, microbiological, and sensory impacts.

Although the bioactive profile of red mombin has been extensively described, limited attention has been given to the technological and functional potential of industrial residues incorporated into widely consumed food products. This knowledge gap is particularly relevant because comprehensive assessments integrating nutritional, technological, microbiological, and sensory aspects in bakery products remain scarce.

Flavonoids, one of the major classes of phenolic compounds found in red mombin residues, are widely recognized for their antioxidant and anti-inflammatory properties [10, 11]. However, the present study focuses on the application of red mombin residue-derived flour as a functional ingredient in bakery products rather than on the characterization of individual bioactive compounds.

The frozen red mombin pulp industry has expanded considerably in recent years due to increased consumer demand for convenient products with extended shelf life. However, this process generates substantial amounts of seeds and peels rich in bioactive compounds that remain largely underutilized despite their high nutritional value [3]. The dehydration of these by-products is an important strategy to extend shelf life, facilitate handling, and broaden their potential applications in food systems.

In this context, the present study advances current knowledge by proposing an integrated valorization strategy for red mombin processing residues, combining chemical, microbiological, physical, and technological characterization with their practical application in sliced bread formulation. Unlike previous studies, this work systematically evaluates the effects of residue-derived flour on sensory acceptance, caloric value, and functional properties, thereby bridging the gap between bioactive compound characterization and the development of innovative food products.

Therefore, this study aimed to produce flour from red mombin residues generated by the frozen pulp industry, characterize its chemical, microbiological, physical, and technological properties, and investigate its potential to improve the nutritional, sensory, caloric, and functional quality of sliced bread.

2. Material and methods

2.1 Materials

Red mombin processing by-products (peels and seeds) were obtained from a frozen fruit pulp processing industry located in Recife, Pernambuco, Brazil. The by-products were collected directly from the production line and immediately transported to the laboratory. The ingredients used for bread production, including white wheat flour (Bunge®), whole UHT milk (Itambé®), sugar (União®), vegetable oil (Soya Bunge®), eggs (Enavis®), instant dry yeast (Fleischmann®), and salt (Lebre®), were purchased from local markets in Recife, Brazil. All reagents and solvents used in the analyses were of analytical grade.

2.2 Methods

2.2.1 Preparation of red mombin residue flour (RMRF)

The seeds were manually separated from the peels, and the peels were dried in a forced-air circulation oven (Model MA 035, Marconi, Brazil) at 50 ± 2 °C until a moisture content of ≤ 10% was reached. The dried peels were ground using a laboratory mill (ET 631/2, Tecnal, Piracicaba, SP, Brazil). The resulting red mombin residue flour (RMRF), with a particle size ranging from approximately 0.8 to 1.0 mm (18-20 mesh), was packaged in high-density polyethylene bags and stored at -22 ± 2 °C until further analyses and bread production (Figure 1). The analyses performed included proximate composition (protein, lipid, ash, total dietary fiber, moisture, and carbohydrate contents), water activity, microbiological counts, water and oil holding capacities, and swelling capacity.

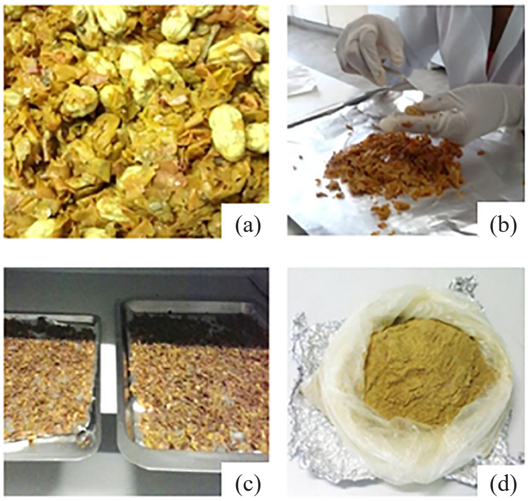


Figure 1. Preparation of the red mombin residue flour
(a) Peel and seed; (b) separation of peel from seed; (c) drying peel; (d) red mombin flour

2.2.2 Proximate composition, water activity, and physical properties of red mombin residue flour (RMRF)

2.2.2.1 Chemical composition and water activity

Proximate composition was determined according to AOAC International methods [12], including moisture content, total nitrogen (Kjeldahl method), lipid content (Soxhlet extraction), ash content (incineration), and total dietary fiber (enzymatic-gravimetric method). Total carbohydrate content was estimated by difference. Water activity was measured using an Aqualab water activity meter (4TE, Decagon Devices, Pullman, WA, USA) at 25 °C. Total caloric value was calculated using Atwater factors.

2.2.2.2 Microbiological analysis

Total and thermotolerant coliforms, total aerobic mesophilic bacteria, and molds and yeasts were analyzed according to AOAC methods [12].

2.2.2.3 Water, oil, and swelling holding capacities

Water holding capacity (WHC), oil holding capacity (OHC), and swelling capacity (SWC) of RMRF were determined according to a standardized method with minor modifications [13]. Briefly, 250 mg of flour was mixed with 25 mL of phosphate buffer (1 M, pH 6.3) or soybean oil. The suspension was stirred and left at room temperature for 1 h. After centrifugation (3,000 × g, 15 min), the supernatant was removed, and the residue was weighed. Results were expressed as grams of water or oil retained per gram of sample. For SWC, 0.2 g of flour was hydrated with 10 mL of distilled water in a graduated cylinder (1.5 cm diameter) at room temperature. After equilibration for 18 h, the final volume was recorded and expressed as mL/g.

2.2.3 Bread preparation

Bread formulations were prepared using wheat flour partially substituted with red mombin residue flour (RMRF) at levels of 5%, 10%, and 15% (w/w). A control formulation containing 100% wheat flour was also prepared. The detailed formulations and ingredient proportions are presented in Table 1.

Table 1. Formulations of sliced bread prepared with different proportions of red mombin residue flour (RMRF)

Ingredient	Control (0% RMRF)	5% RMRF	10% RMRF	15% RMRF
Wheat flour (g)	500	475	450	425
RMRF (g)	0	25	50	75
Whole milk (mL)	300	300	300	300
Soybean oil (mL)	65	65	65	65
Sugar (g)	60	60	60	60
Whole eggs (g)	110	110	110	110
Instant dry yeast (g)	10	10	10	10
Salt (g)	6	6	6	6

Briefly, the control bread formulation consisted of wheat flour, whole milk, soybean oil, sugar, eggs, instant dry yeast, and salt. In the RMRF formulations, wheat flour was partially replaced by red mombin residue flour (RMRF) at proportions of 475 : 25, 450 : 50, and 425 : 75 (wheat flour: RMRF, w/w), corresponding to 5%, 10%, and 15% substitution levels, respectively. All formulations were prepared in triplicate.

The ingredients were mixed using a domestic mixer (Arno Deluxe SX82, São Paulo, Brazil) until a homogeneous and viscoelastic dough was obtained. The dough was transferred to rectangular baking pans (28 × 11 × 9 cm), previously greased with vegetable oil and dusted with wheat flour. Fermentation was carried out for 1 h at 29 °C, followed by baking at 230 °C for 35 min. After cooling to room temperature, the bread was sliced into 25 mm-thick slices for subsequent analyses.

2.2.4 Sensory evaluation and selection of the best formulation

Before participating in the sensory evaluation, all panelists were informed about the objectives of the study, the sensory evaluation procedures, and the characteristics of the bread samples containing different levels of red mombin residue flour (RMRF). They also received information regarding the ingredients used in the formulations and any potential risks associated with consumption, including possible allergic reactions or individual intolerances.

Participation was entirely voluntary, and panelists were informed of their right to decline participation or withdraw from the study at any time without penalty. Prior to the sensory evaluation, all participants provided written informed consent. No personally identifiable information was collected during the study, and all data were anonymized and handled confidentially to ensure participants' privacy.

Sliced breads produced with 5%, 10%, and 15% RMRF (Figure 2) were evaluated by sensory analysis to select the best formulation. Sensory evaluation was conducted with 72 untrained panelists under controlled conditions (25 °C and white light), aged 20-60 years, using acceptance (9-point hedonic scale) and ranking tests, in addition to purchase intention assessment. Samples were prepared one day before analysis, coded with random three-digit numbers, and presented using a randomized complete block design.

The affective method was applied using two tests: acceptance and preference ranking. Acceptance was evaluated using a 9-point hedonic scale (1 = dislike extremely; 9 = like extremely) for appearance, color, aroma, flavor, and texture. Samples were presented monadically in randomized order. For the ranking test, panelists ranked samples from least preferred (1) to most preferred (3). In addition, a questionnaire assessing purchase intention was applied.

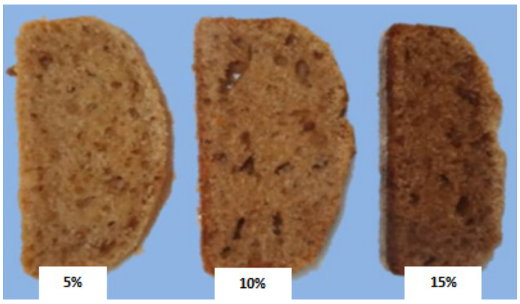


Figure 2. Bread prepared with wheat flour containing different proportions of red mombin residue flour (RMRF)

Based on the results, the most accepted RMRF bread was selected and compared with the control bread. Proximate composition and microbiological analyses were conducted according to standard procedures described by the Association of Official Analytical Chemists (AOAC) [12], while farinographic, alveographic, and texture analyses followed methods recommended by the American Association of Cereal Chemists (AACC) [14]. Detailed methodological procedures for each analysis are provided in the subsections below. The selected bread was compared with the control formulation in terms of chemical composition, caloric value, physical properties, texture, and color parameters (CIE Lab*).

2.2.5 Farinographic and alveographic properties

For farinographic and alveographic analyses, wheat flours containing 0% and 10% RMRF were used. A Brabender Farinograph-E (Duisburg, Germany) was used to determine water absorption (ABS), dough development time (DDT), dough stability time (DST), and mixing tolerance index (MTI), according to method 54-21 [14]. Alveographic analysis was performed using a Chopin Alveograph (Alveolink, Villeneuve-la-Garenne, France) according to method 54-30 [14], measuring tenacity (P), extensibility (L), deformation energy (W), and the P/L ratio.

2.2.6 Physical properties of breads

Physical properties of breads (weight, volume, and dimensions before and after baking) were measured to calculate specific volume, density, and weight loss.

2.2.6.1 Color (CIE Lab*)

Color of crust and crumb (n = 9) was measured using a Chroma Meter CR-400 (Konica Minolta Sensing, Osaka, Japan) according to the CIE Lab* system, under illuminant D65 and 10° observer angle. Lightness (L*), red/green (a*), and yellow/blue (b*) coordinates were recorded, and chroma (C*) was calculated [15].

2.2.6.2 Texture profile analysis

Texture profile analysis was performed on crumb samples standardized at approximately 25 mm thickness and 50 g per slice. Three slices per formulation were analyzed. Hardness, cohesiveness, and springiness were measured 24 h after baking using a Brookfield texture analyzer (CT3, Middleboro, MA, USA). Analyses followed AACC method 74-09.01 [14], using a 25.4 mm cylindrical probe, test speed of 2 mm/s, post-test speed of 10 mm/s, 20% compression, and a 5 g trigger force.

2.2.7 Statistical analysis

All analyses were performed in triplicate, except microbiological analyses, which were performed in duplicate. Data were analyzed using one-way ANOVA. Differences among the three formulations (5%, 10%, and 15%) were assessed by ANOVA. Comparison between the best formulation and the control was performed using Student's t-test at a 95% confidence level. Sensory data were analyzed using Duncan's and Friedman's tests ($p < 0.05$). Statistical analyses were performed using Statistica software (version 7.0, StatSoft Inc., Tulsa, OK, USA).

3. Results and discussion

3.1 Characterization of red mombin residue flour

The chemical composition of red mombin residue flour (RMRF) is presented in Table 2. After dehydration, the moisture content was 7.31 g/100 g, while water activity (a_w) was 0.29. These values are comparable to those reported for other fruit by-product flours, such as apple, orange, mango, and banana residues [16-18]. The low water activity indicates minimal risk of microbial growth and reduced susceptibility to enzymatic activity and non-enzymatic reactions [19]. Water activity reflects the availability of free water in food systems and is a critical parameter for product stability, particularly with respect to microbial safety and physicochemical quality. In this context, the a_w of RMRF is lower than that reported for several fruit by-product flours, highlighting its technological suitability for bakery applications.

RMRF was mainly composed of carbohydrates (53.38 g/100 g), followed by total dietary fiber (27.50 g/100 g) and ash (3.07 g/100 g). The high carbohydrate content influences the chemical and functional properties of the flour, while the elevated fiber content allows RMRF to be classified as a high-fiber ingredient. Notably, its dietary fiber content is higher than values reported for apple (15-20 g/100 g), citrus (18-22 g/100 g), and mango residue flours (20-25 g/100 g), which are commonly used for food enrichment applications [16, 17]. The low lipid content (1.98 g/100 g) is consistent with other fruit by-product flours and is advantageous for the development of bakery products with reduced fat content [20]. Overall, these results indicate that RMRF has promising nutritional and functional potential for application in bakery formulations.

The microbiological counts of red mombin residue flour (RMRF), including coliforms, aerobic mesophilic bacteria, and molds and yeasts, indicated a low microbial load (Table 2). These results demonstrate that adequate hygienic and sanitary conditions were maintained during by-product processing and flour production. This is an important factor for ensuring food safety, particularly for ingredients derived from fruit processing residues.

The physical properties of RMRF are also presented in Table 2. Water holding capacity (WHC), oil holding capacity (OHC), and swelling capacity (SWC) were 2.86 g/g, 3.02 g/g, and 3.40 mL/g, respectively. These functional properties are likely influenced by the high dietary fiber content of the flour. WHC reflects the ability of flour to retain water, which is associated with swelling and gel formation during processing. OHC is an important functional property related to flavor retention, mouthfeel, and textural stability [21].

The OHC value of RMRF (3.02 g/g) was higher than those reported for apple and orange residue flours (0.84 and 1.06 g/g, respectively) [22] and comparable to or higher than values reported for mango peel flour [17]. This higher oil-binding capacity may contribute to improved flavor retention in bakery products containing up to 10% RMRF, compared with formulations containing other fruit by-products, where sensory quality typically decreases at lower substitution levels. High OHC indicates potential suitability for food applications requiring fat-binding properties, such as bakery products and processed meat products.

Overall, the results indicate that RMRF is microbiologically acceptable under the conditions evaluated and exhibits stable physicochemical characteristics. In addition, its high fiber content likely contributes to its WHC, OHC, and SWC, which may positively influence moisture retention, texture, and appearance in bakery products.

Table 2. Proximate composition, water activity, and physical properties of red mombin residue flour (RMRF)

Parameters	
Proximate composition	
Moisture content (g/100 g)	7.31 ± 0.11
Proteins (g/100 g)	6.87 ± 0.19
Lipids (g/100 g)	1.98 ± 0.22
Ash (g/100 g)	3.07 ± 0.07
Total dietary fiber (g/100 g)	27.50 ± 0.91
Carbohydrates (g/100 g)	53.38 ± 0.64
Water activity	0.29 ± 0.01
Microbiological analyses (log CFU/g)	
Aerobic mesophilic	3.02
Total coliforms	1.65
Thermotolerant coliforms	< 1.00
Mold and yeast	4.65
Physical properties	
Water holding capacity (g/g)	2.86 ± 0.16
Oil holding capacity (g/g)	3.02 ± 0.32
Swelling capacity (mL/g)	3.40 ± 0.17

Values are expressed as mean ± standard deviation (*n* = 3). CFU: Colony Forming Unit

3.2 Sensory evaluation of bread containing different proportions of RMRF

Sensory evaluation was conducted with 72 untrained panelists who provided written consent. Most participants were female (79.0%), aged 21-29 years (47.2%), and held a bachelor's degree (48.5%). The acceptance test results (Table 3) showed that mean scores for most attributes were significantly higher ($p < 0.05$) for breads containing 5% and 10% RMRF compared with the 15% formulation.

In addition, breads with 5% and 10% RMRF obtained mean scores above 7 for all evaluated attributes, indicating good acceptance, corresponding to the hedonic descriptor "like very much." The characteristic aroma and flavor of red mombin were still perceptible in the breads, which may have contributed to their higher acceptance. These sensory perceptions may also be associated with functional properties such as oil holding capacity, which may enhance flavor retention, as discussed previously.

Aroma was the only attribute that did not differ significantly among formulations. However, increasing RMRF levels resulted in darker crumb and crust, which negatively affected appearance and texture perception at the 15% substitution level. Similar findings have been reported in previous studies [16, 17], where increased fiber incorporation led to darker color, increased hardness, and reduced acceptability in bread products.

The preference test results indicated that breads containing 5% and 10% RMRF achieved the best overall performance across the evaluated attributes ($p < 0.05$). In contrast, the incorporation of higher levels of RMRF (15%) negatively affected key sensory characteristics from the consumer perspective. Similarly, the purchase intention test (Table 3) showed that consumers expressed willingness to purchase breads formulated with 5% and 10% RMRF ($p < 0.05$). Comparable findings have been reported in breads supplemented with apple residue flour, where the best sensory acceptance was observed at a 5% incorporation level [23]. Heinio et al. [24] reported that dietary fiber fractions can interfere with gluten network formation, reducing gluten strength and elasticity while also decreasing dough extensibility. These effects help explain why substitution levels ≥ 15% may negatively impact the sensory quality of bread formulations.

Table 3. Sensory analysis (acceptance, preference ranking, and purchase intention) of sliced bread formulated with wheat flour containing 5%, 10%, and 15% red mombin residue flour (RMRF)

Attributes		% RMRF		
		5	10	15
Acceptance test[1]	Overall appearance	7.07 ± 1.36^{a}	7.08 ± 1.45^{a}	6.04 ± 1.81^{b}
	Color	7.32 ± 1.17^{a}	7.25 ± 1.35^{a}	6.43 ± 1.69^{b}
	Aroma	7.40 ± 1.47^{a}	7.36 ± 1.43^{a}	6.93 ± 1.57^{a}
	Flavor	7.60 ± 1.31^{a}	7.53 ± 1.35^{a}	6.67 ± 1.86^{b}
	Texture	7.17 ± 1.74^{a}	7.26 ± 1.60^{a}	6.29 ± 1.90^{b}
Preference ranking[2]		170.28 ± 8.43^{a}	160.64 ± 9.96^{a}	122.80 ± 6.05^{b}
Purchase intention (%)		38.4 ± 2.52^{a}	37.2 ± 1.78^{a}	24.4 ± 2.37^{b}

[1] Values are expressed as mean ± standard deviation ($n = 72$). Hedonic scores were obtained using a 9-point scale, where 1 = "dislike extremely" and 9 = "like extremely". Different superscript letters within the same row indicate statistically significant differences according to Duncan's test ($p < 0.05$)
[2] Sum of individual preference rankings ($n = 72$). Different superscript letters in the last row indicate statistically significant differences according to Friedman's test ($p < 0.05$). The minimum significant difference between ranks was 37

Based on the sensory evaluation and purchase intention results, no significant differences were observed between breads containing 5% and 10% RMRF. However, the 10% formulation was selected for further analyses due to its higher dietary fiber content.

3.3 Technological characteristics of wheat flour with 0% (control) and 10% RMRF

The impact of incorporating 10% red mombin residue flour (RMRF) into wheat flour was evaluated using farinographic and alveographic analyses and compared with pure wheat flour (control). The control flour was classified as "very strong" according to standard criteria [14]. The incorporation of 10% RMRF increased water absorption and the mixing tolerance index, while decreasing dough development time and dough stability. These changes are likely associated with the high fiber content of RMRF, which may interact with wheat proteins and affect gluten network formation and dough elasticity [25].

Although dough stability decreased with the addition of RMRF, the observed farinographic changes did not alter the overall strength classification of the flour, which remained suitable for breadmaking according to standard criteria [14]. However, alveographic analysis provides complementary information on dough behavior under biaxial deformation, allowing a more comprehensive evaluation of dough quality [26].

Alveographic results (Table 4) showed that the incorporation of 10% RMRF increased tenacity and reduced extensibility and deformation energy (W) ($p < 0.05$). In addition, changes in the P/L ratio indicated modifications in dough balance. Despite these effects, the technological performance of the flour with 10% RMRF remained adequate for bread production.

Fiber–protein interactions may weaken the gluten network due to the abundance of hydroxyl groups in dietary fiber, which increases water binding through hydrogen bonding and reduces water availability for gluten protein hydration and interactions.

In general, partial substitution of wheat flour with fiber-rich ingredients affects dough formation and rheological behavior, since gluten network development is highly dependent on protein interactions and hydration conditions [26, 27]. In the present study, incorporation of 10% RMRF did not significantly compromise gluten network formation, as the resulting flour was still classified as strong based on rheological parameters. However, the 15% substitution level negatively affected protein interactions, resulting in breads with lower volume and increased firmness.

Table 4. Farinographic and alveographic properties of wheat flour containing 0% (control) and 10% red mombin residue flour (RMRF)

Parameters	% RMRF	
	0	10
Farinographic		
Water absorption (%)	59.20 ± 0.10^{b}	60.20 ± 0.10^{a}
Dough development time (min)	15.74 ± 0.31^{a}	8.90 ± 0.36^{b}
Stability (min)	26.37 ± 5.52^{a}	11.33 ± 0.12^{b}
Mixing tolerance index (UF)	4.34 ± 1.15^{b}	47.67 ± 1.53^{a}
Alveographic		
Tenacity (P)	128.34 ± 7.64^{b}	186.00 ± 3.12^{a}
Extensibility (L)	49.67 ± 4.51^{a}	16.00 ± 2.11^{b}
Deformation energy (W)	258.00 ± 7.94^{a}	111.00 ± 5.57^{b}
Configuration, equilibrium of the curve (P/L)	2.61 ± 0.39^{b}	11.62 ± 0.43^{a}

Values are expressed as mean ± standard deviation ($n = 3$). Different superscript letters within the same row indicate statistically significant differences (t-test, $p < 0.05$)

3.4 Chemical composition, caloric value and CIE Lab* color of breads with 0% and 10% RMRF

The incorporation of 10% red mombin residue flour (RMRF) into wheat flour resulted in breads with similar moisture and protein contents compared with the control, but with increased levels of dietary fiber, carbohydrates, and ash, and reduced lipid content (Table 5). The most pronounced change was observed in dietary fiber content, which was approximately five times higher than that of the control bread (0.88 g/100 g). This increase is directly associated with the high dietary fiber content of RMRF (27.50 g/100 g). Consequently, the fiber content of the bread increased sufficiently to allow its classification as a "source of fiber", exceeding 3 g of dietary fiber per 100 g of product.

There were no significant differences in water activity between breads containing 0% and 10% RMRF. Similarly, total caloric value was not affected by the incorporation of 10% RMRF.

The color characteristics of the crust and crumb of breads with 0% and 10% RMRF are presented in Table 5. Bread containing 10% RMRF showed lower L*, a*, b*, and C* values in the crust. In the crumb, higher b* values were observed in breads with 10% RMRF compared with the control, which may be associated with the presence of carotenoids in added flour.

According to El-Sohaimy et al. [28], bread color, both crust and crumb, is influenced by the chemical composition of the ingredients used in the formulation. Higher protein content and reducing sugars can enhance Maillard reactions and browning development. In addition, natural pigments such as carotenoids may also contribute to bread color.

Table 5. Proximate composition, water activity, total caloric value, and CIE Lab* color characteristics of the crust and crumb of sliced bread made with wheat flour containing 0% (control) and 10% red mombin residue flour (RMRF)

Parameters	% RMRF	
	0	10
Proximate composition (g/100 g)		
Moisture content	35.80 ± 1.13 [a]	33.81 ± 1.35 [a]
Proteins	8.55 ± 0.25[a]	7.92 ± 0.15[a]
Lipids	9.66 ± 0.44[a]	8.12 ± 0.41[b]
Ash	0.45 ± 0.03[b]	1.01 ± 0.08[a]
Total dietary fiber	0.88 ± 0.06[b]	4.75 ± 0.06[a]
Carbohydrate	42.16 ± 0.25[b]	44.39 ± 0.58[a]
Water activity	0.95 ± 0.06[a]	0.94 ± 0.06[a]
Caloric value (kcal/100 g)	287.44 ± 12.40[a]	282.32 ± 10.78[a]
Color characteristics		
Crust		
L*	51.94 ± 0.64[a]	47.94 ± 2.32[b]
a*	12.43 ± 0.36[a]	9.07 ± 0.61[b]
b*	29.61 ± 0.38[a]	18.74 ± 2.35[b]
Chroma	32.12 ± 0.48[a]	20.84 ± 2.18[b]
Crumb		
L*	65.81 ± 0.75[a]	50.59 ± 1.15[b]
a*	2.18 ± 0.16[b]	3.32 ± 0.24[a]
b*	15.56 ± 0.27[b]	18.40 ± 0.85[a]
Chroma	15.71 ± 0.25[b]	18.65 ± 0.95[a]

Values are expressed as mean ± standard deviation (n = 3). Different superscript letters within the same row indicate statistically significant differences (t-test, $p < 0.05$)

3.5 Physical and texture properties of breads containing 0% and 10% RMRF

Bread containing 10% RMRF showed higher density, but lower weight (initial and final), volume, specific volume, and height compared with the control ($p < 0.05$), likely due to its higher dietary fiber content (Table 6). Dietary fiber particles may interfere with gluten network development by disrupting the continuity of the viscoelastic matrix, thereby limiting gas retention and dough expansion during fermentation and baking. Consequently, reduced loaf volume is commonly associated with weakened gluten structure and impaired gas-holding capacity [29].

Texture profile analysis indicated that bread with 10% RMRF was harder and exhibited lower cohesiveness and springiness compared with the control ($p < 0.05$) (Table 6). Despite the significant differences in physical and instrumental texture parameters, these changes did not negatively affect the overall sensory acceptance of the formulation (Table 3).

Table 6. Physical and texture characteristics of sliced bread made with wheat flour containing 0 (control) and 10% red mombin residue flour (RMRF)

Characteristics	% RMRF	
	0	10
Physical		
Initial weight (g)	1038.88 ± 5.00^{a}	1018.73 ± 3.21^{b}
Final weight (g)	964.30 ± 2.76^{a}	952.77 ± 4.80^{b}
Width (cm)	10.50 ± 0.10^{a}	10.30 ± 0.11^{a}
Height (cm)	10.80 ± 0.17^{a}	9.80 ± 0.32^{b}
Length (cm)	27.00 ± 0.00^{a}	27.00 ± 0.00^{a}
Volume (cm³)	3080.00 ± 35.96^{a}	2686.90 ± 90.90^{b}
Specific volume (cm³/g)	3.19 ± 0.05^{a}	2.81 ± 0.08^{b}
Density (g/cm³)	0.32 ± 0.00^{b}	0.35 ± 0.00^{a}
% Weight loss	7.18 ± 0.00^{a}	6.47 ± 0.00^{a}
Texture		
Hardness (g)	83.13 ± 14.59^{a}	123.00 ± 8.23^{b}
Cohesiveness	0.89 ± 0.02^{a}	0.81 ± 0.02^{b}
Springiness (mm)	4.55 ± 0.13^{a}	4.49 ± 0.12^{b}

Values are expressed as mean ± standard deviation (n = 3). Different superscript letters within the same row indicate statistically significant differences (t-test, $p < 0.05$)

4. Conclusions

The flour produced from red mombin frozen pulp by-products is a promising ingredient for breadmaking, contributing to increased dietary fiber content. The flour was easily obtained using a forced-air circulation oven and exhibited high levels of dietary fiber and carbohydrates, low water activity, and satisfactory microbiological quality. It also showed relevant water and oil holding capacities, as well as swelling capacity.

Breads containing 5% and 10% RMRF were well accepted by untrained panelists, and the 10% formulation could be classified as a "source of fiber". The use of dried red mombin pulp by-products in bread formulation represents a viable strategy to improve nutritional and functional properties. In addition to potential health-related benefits, this approach adds value to agro-industrial by-products and contributes to environmental sustainability.

However, it should be noted that farinographic and alveographic analyses were performed only for the control flour and wheat flour containing 10% RMRF. Therefore, rheological results may not fully represent all formulations, and caution is required when extrapolating these findings.

For potential commercialization, factors such as large-scale production of the flour, shelf stability, cost-effectiveness, and consumer acceptance across different markets should be further investigated. Future studies should focus on process optimization to improve dough stability and storage behavior, as well as on evaluating the effects of RMRF incorporation on rheological, technological, and sensory properties at an industrial scale. In addition, the application of RMRF in other bakery products may further expand its industrial potential.

Ethics statement

This study involving human participants was reviewed and approved by the Research Ethics Committee of the Universidade Federal Rural de Pernambuco (UFRPE), under the Comissão Nacional de Ética em Pesquisa (CONEP) system (Protocol number: 00441026.4.0000.9547).

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Author contributions

Helen M. L. Silva: Planned the research and performed chemical and physical analyses. Marcony E. Silva Júnior: Obtained the samples and performed chemical and physical analyses. Michelle M. B. Souza: Performed sensory analysis. Daniele S. Ribeiro: Analyzed technological properties (farinographic and alveographic analyses), analyzed the data, and wrote the manuscript. Maria Beatriz A. Gloria: Analyzed the data and wrote the manuscript. Maria Inês Sucupira Maciel: Supervised the project, planned the methodology, and reviewed the manuscript. All authors have approved the final article.

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Conflict of interest

The authors declare no conflict of interest.

Generative AI statement

The authors declare that no generative artificial intelligence (AI) was used in the creation of this manuscript.

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