Ciência Rural, Santa Maria, v.56:7, e20250332, 2026

http://doi.org/10.1590/0103-8478cr20250332

ISSNe 1678-4596

FOOD TECHNOLOGY

Valorization of coffee hull through reactive extrusion for application as a functional ingredient in breadmaking

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ABSTRACT: The development of new products from coffee hull, an abundant agroindustrial residue, represents a sustainable strategy for valorizing this residue. This study modified coffee hulls through reactive extrusion with alkaline hydrogen peroxide (3% w/w) and evaluated their application as a functional food ingredient in breadmaking. The modified coffee hull was characterized in terms of its composition, techno-functional properties, and impact on bread quality. Three bread formulations were developed: a control bread (CB) sample and two samples with 5% (B5) and 10% (B10) replacement of wheat flour by the modified coffee hull. Sensory analysis was conducted with 117 untrained panelists using a 9-point hedonic scale. The results showed that B5 obtained a high sensory acceptance score (7.77), while B10 had significantly lower scores in appearance (5.43) and texture (6.90). The bread sample obtained with 5% modified coffee hull (B5) had higher moisture (8.83%), proteins (6.32%), and fibers (3.84%) contents compared to the control bread (CB), which presented values of 8.20%, 5.62%, and 1.31%, respectively. The addition of modified coffee hull (5%) increased bread firmness from 4.07 N (CB) to 10.12 N (B5) and reduced specific volume from 2.84 cm^3/g in CB to 2.17 cm^3/g in B5. These results indicate that incorporating modified coffee hull as a functional food ingredient, replacing 5% of the wheat flour, improved the nutritional profile of the bread while maintaining its desirable sensory properties.

Key words: coffee hull, functional bread, sensory evaluation, dietary fiber.

Valorização da casca de café por extrusão reativa para aplicação como ingrediente funcional na panificação

RESUMO: O desenvolvimento de novos produtos a partir da casca de café, um resíduo agroindustrial abundante, representa uma estratégia sustentável para a valorização desse resíduo. Este estudo teve como objetivo modificar a casca de café por extrusão reativa com peróxido de hidrogênio alcalino (3% m/m) e avaliar sua aplicação como ingrediente alimentar funcional na panificação. Para isso, a casca de café modificada foi caracterizada quanto à sua composição, propriedades técnico-funcionais e impacto na qualidade do pão. Além disso, três formulações de pão foram desenvolvidas: uma amostra de pão controle (CB) e duas amostras com 5% (B5) e 10% (B10) de substituição da farinha de trigo pela casca de café modificada. Ademias, uma análise sensorial foi conduzida com 117 provadores não treinados, utilizando uma escala hedônica de 9 pontos. Os resultados mostraram que a amostra P5 apresentou elevada aceitação sensorial (7,77), enquanto a amostra B10 apresentou escores significativamente menores em aparência (5,43) e textura (6,90). Por outro lado, a amostra de pão obtida com 5% de casca de café modificada (B5) apresentou maiores teores de umidade (8,83%), proteínas (6,32%) e fibras (3,84%) em comparação ao pão controle (CB), que apresentou valores de 8,20%, 5,62% e 1,31%, respectivamente. Adicionalmente, o acréscimo da casca de café modificada (5%) aumentou a firmeza do pão de 4,07 N (CB) para 10,12 N (B5) e reduziu o volume específico de 2,84 cm^3/g no CB para 2,17 cm^3/g no B5. Esses resultados indicaram que a incorporação de casca de café modificada como ingrediente alimentar funcional, substituindo 5% da farinha de trigo, melhorou o perfil nutricional do pão, mantendo suas propriedades sensoriais desejáveis.

Palavras-chave: casca de café, pão funcional, avaliação sensorial, fibra alimentar.

INTRODUCTION

Global coffee production in the 2023 – 2024 harvests reached 171.4 million 60-kg bags, with Arabica coffee accounting for 56.7% of the total output, surpassing Robusta and Conilon coffee (43.3%). The three largest global coffee producers – Brazil, Vietnam, and Colombia – accounted for 57% of the total, underscoring their significant role in the worldwide coffee market (EMBRAPA, 2024). Brazil led with 55.01 million bags, followed by Vietnam (27.5 million) and Colombia (11.5 million), consolidating its prominent role in both coffee grain exports and coffee consumption (CONAB, 2023; EMBRAPA, 2024).

The growth in coffee production results in a proportional increase in agroindustrial

Received 06.25.25 Approved 12.21.25 Returned by the author 03.18.26
CR-2025-0332.R1
Editors: Alessandro Dal'Col Lúcio Melissa Walter

residue generation, which can cause impressive environmental impacts. Coffee husks are often underutilized, primarily employed in compost and low-value agricultural applications, despite their high volume of generation (TAMILSELVAN & SUNDARAJAN, 2024). In this context, Brazil's coffee sector stands out for adopting sustainable practices in compliance with increasingly stringent environmental regulations (GARCÍA JUÁREZ et al., 2025).

Coffee processing methods directly influence the volume and chemical composition of the resulting residues. Dry processing, which predominates in Brazil, is recognized for its sustainability regarding water conservation; however, it generates substantial quantities of coffee hull. This byproduct is notably rich in nutrients and bioactive compounds, including caffeine, tannins, and polyphenols (ICO, 2019; DONG et al., 2020). Conversely, wet processing is typically reserved for specialty coffees, as it induces chemical modifications that refine the final product's flavor profile (NIGLIO & GERMER, 2023).

Beyond their origin, coffee hulls offer diverse high-value applications. They are increasingly utilized as organic fertilizers, in biofuel synthesis, and as a dietary supplement for ruminants – provided caffeine levels are strictly monitored (EMMA et al., 2022; FAUSTINO et al., 2020; SILVA et al., 2020). Furthermore, in the food industry, the incorporation of coffee hulls into fiber-rich formulations has emerged as a strategic approach to developing innovative functional foods (DIFONZO et al., 2022; IRIONDO-DEHOND et al., 2020).

Reactive extrusion has been investigated to enhance nutritional and technological properties of lignocellulosic materials, making it more suitable for food applications. Alkaline hydrogen peroxide and sulfuric acid have been used to modify the lignocellulosic complex, increasing fiber solubility and improving their techno-functional properties (JACINTO et al., 2025; MELLO & MALI, 2022; YOSHIDA & PRUDÊNCIO, 2020). Among the studied applications, the partial replacement of wheat flour with modified coffee hull in breadmaking has shown promise for improving the nutritional profile of the products and contributing to more sustainable diets (RIZKAPRILISA et al., 2023; WADDELL & ORFILA, 2022).

In this study, coffee hulls were modified via reactive extrusion using either sulfuric acid or alkaline hydrogen peroxide to utilize them as fiber-rich functional ingredients in bread formulations.

MATERIALS AND METHODS

Materials

Coffee hulls from *Coffea arabica* were kindly supplied by the Instituto de Desenvolvimento Rural do Paraná – IDR (Londrina, Paraná, Brazil). Hydrogen peroxide and sodium hydroxide were of analytical grade (Synthlab, Brazil)

The in natura coffee hull used in this study presented the following physicochemical characterization: Moisture (6.60%), Ash (5.37%), Proteins (11.24%), Lipids (2.50%), Carbohydrates (74.29%), Cellulose (27.92%), Hemicellulose (9.33%), Lignin (28.72%), Insoluble dietary fibers (65.97%), Density (6.11 g/cm^3) and pH (5.47) (JACINTO et al., 2025).

The ingredients used for bread production included wheat flour (Venturelli, Brazil), with a composition of 71% carbohydrates, 13% proteins, 1% lipids, and 2.5% dietary fiber. Other ingredients were fresh eggs, water, vegetable oil (Cocamar), sugar, dry yeast (Fleischmann), and salt.

Coffee hull modification by reactive extrusion

The residue was dried in an air-circulating oven (Marconi MA035, Brazil) for 12 hours at 45 ºC, followed by grinding and sieving to obtain particles with a diameter between 180 µm and 300 µm. Chemical modification was performed through reactive extrusion using 3% alkaline hydrogen peroxide at 100 ºC (all four heating zones) and 60 rpm using a single screw extruder (AX Plastics, Brazil), with a screw diameter of 1.6 cm and a length/diameter ratio of 40, equipped with four heating zones and a 0.8 cm diameter die, with the moisture content adjusted to 32%.

After extrusion, the sample was washed three times with distilled water to neutralize the pH, which was measured using a digital pH meter. The material was then dried at 60 ºC for 12 to 24 hours and milled to achieve particle sizes ranging from 150 µm to 220 µm. Extrusion parameters were based on a previous study (PEREIRA et al., 2022).

The centesimal composition of the modified coffee hull was determined using the official methods established by AOAC (Official Methods of Analysis of AOAC, 2012), including moisture (925.09), ash (930.30), lipids (920.39), proteins (990.03), and total dietary fiber (985.29). Carbohydrate content was calculated by difference. Cellulose and hemicellulose were determined using the method of VAN SOEST (1965), and lignin according to the Technical Association of the Pulp and Paper Industry (TAPPI, 1999).

Bread formulation

Three bread formulations were developed (Table 1): a control formulation (CB) and two with partial replacement of wheat flour by modified coffee hull. Formulation B5 included 475 g of wheat flour and 25 g of modified coffee hull (5% substitution), while formulation B10 contained 450 g of flour and 50 g of hull (10% substitution). All other ingredient quantities remained constant.

Breadmaking was carried out manually. The dry yeast was first dissolved in water for activation, followed by the addition of vegetable oil. Eggs and sugar were then incorporated to ensure homogenization. Wheat flour was gradually added, and salt was included at the end of mixing to avoid interference with fermentation.

The dough was kneaded mechanically for 5 minutes and left to rest for 30 minutes. A second kneading was performed before shaping the loaves, which were placed in greased baking pans. Fermentation was carried out for 2 hours, followed by baking at 180 ºC for 40 minutes.

Bread characterization

Sensory evaluation

Bread samples underwent sensory evaluation following approval by the Research Ethics Committee of the Universidade Estadual de Londrina (CAAE 65306022.5.0000.5231). Regular bread consumers were recruited among university students and employees. Before the tests began, all participants signed an Informed Consent Form (ICF).

Bread samples (10 g) were served in disposable white plastic dishes (15 cm in diameter), each one coded with three random digits. In all tests, participants were asked to taste the bread samples from left to right and drink water between samples to remove the aftertaste. There was no time limit for participants to complete the evaluation.

A panel of 117 untrained participants assessed three bread formulations (CB, B5, and B10). The participants underwent an acceptance test for the sensory attributes, including appearance, flavor, texture, and overall acceptability, using a nine-point hedonic scale as follows: dislike extremely (1); dislike very much (2); dislike moderately (3); dislike slightly (4); neither like nor dislike (5); like slightly (6); like moderately (7); like very much (8) and like extremely (9) (WICHCHUKIT & O'MAHONY, 2015). Following the acceptance test, the purchase intention test was administered using a five-point scale, from 1 (definitely would not buy this product) to 5 (definitely would buy this product).

Centesimal composition

Centesimal composition analyses of the bread samples were conducted following the official methods established by AOAC (Official Methods of Analysis of AOAC, 2012), including moisture (925.09), ash (930.30), lipids (920.39), proteins (990.03), and total dietary fiber (985.29). Carbohydrate content was calculated by difference.

Acidity and pH

To determine the pH, 10 grams of each sample were homogenized in 90 mL of distilled water. The pH of the suspension was measured using a potentiometer (model 0400, Quimis, São Paulo, Brazil), which had been previously calibrated with pH 4 and 7 buffer solutions. Subsequently, each suspension was titrated with 0.1 mol/L NaOH solution using phenolphthalein as an indicator. Titratable acidity was expressed as the volume (in mL) of 0.1 mol/L NaOH required to neutralize 10 grams of bread (ROBERT et al., 2006).

Color

Color analysis was performed at three distinct points on the crust and three on the crumb of each sample. A CR400 colorimeter (Konica

Table 1 - Composition of bread formulations.

Ingredient	----Control Bread (CB) (g)----	--------Bread 5% (B5) (g)-------	------Bread 10% (B10) (g)------
Wheat flour	500	475	450
Modified coffee hull	0	25	50
Egg	150	150	150
Water	100	100	100
Vegetable oil	85	85	85
Sugar	50	50	50
Dry yeast	10	10	10
Salt	6	6	6

Minolta, Osaka, Japan) was used to determine color parameters: L^* (lightness, where 0 = black and 100 = white), a^* (ranging from -60 = green to +60 = red), and b^* (ranging from -60 = blue to +60 = yellow).

Texture

Texture profile analysis (TPA) was conducted using a TA-XT2i texture analyzer (Stable Micro Systems, Surrey, UK) with a 35 mm cylindrical compression probe. The texture parameters evaluated were firmness (N), springiness, cohesiveness, and chewiness (N). Instrumental texture analysis was performed with the following settings: pre-test, test, and post-test speeds were 2.0 mm/s, 5.0 mm/s, and 5.0 mm/s, respectively, with a probe displacement distance of 20 mm. The trigger force was set at 20 g, and the interval between compressions was programmed at 5 seconds. Bread ends were removed to ensure that the measured texture represented only the crumb structure, avoiding interference from the crust (CARR & TADINI, 2003).

Baking loss, specific volume, and density

Baking loss was determined according to the method described by NI et al. (2020), with the results calculated using equation 1:

$$\text{Baking loss } (\%) = \frac{m_0 - m_f}{m_0} \; x \; 100 \quad (1)$$

where m_0 is the initial dough mass before baking, and m_f is the mass after 90 minutes of bread baking.

The specific volume of the bread was determined using the millet seed displacement method, calculated as the ratio between volume (cm^3) and mass (g), and expressed in cm^3/g (AACC Method 10-11, 2000). Mass was measured using an analytical balance, and volume was measured by the displacement of millet seeds in a graduated 100 mL cylinder. Density was the ratio between mass and volume, expressed in g/cm^3.

Statistical analysis

For comparisons between two groups, Student's t-test was performed. For experiments involving three or more groups, Analysis of Variance (ANOVA) and Tukey's test for mean comparisons ($P \leq 0.05$) were applied. All statistical analyses were conducted using R software (R Foundation for Statistical Computing, Vienna, Austria).

RESULTS AND DISCUSSION

Centesimal composition of modified coffee hull

The modified coffee hull obtained through reactive extrusion with 3% alkaline hydrogen peroxide presented the following centesimal composition: 4.31% moisture, 3.61% ash, 10.53% proteins, 0.89% lipids, and 80.67% carbohydrates. The ingredient showed a high insoluble dietary fiber content (78.20%), composed of 45.17% cellulose, 8.46% hemicellulose, and 24.57% lignin.

Compared with the in natura coffee hull profile reported by JACINTO et al. (2025), the modification process reduced moisture, ash, and lipid contents and markedly altered the lignocellulosic matrix. The treatment promoted partial delignification (from 28.72% to 24.57%) and increased the cellulose fraction (from 27.92% to 45.17%), resulting in a higher total insoluble fiber content (from 65.97% to 78.20%). These compositional changes indicated an improvement in the structural and functional characteristics of the material, enhancing its potential application as a high-fiber ingredient in bread formulations.

Sensory evaluation

Table 2 presents the sensory evaluation results for the three bread formulations (CB, B5, and B10) assessed for appearance, flavor, texture, and overall acceptance using a nine-point hedonic scale (1 = "dislike extremely"; 9 = "like extremely"). Purchase intent was evaluated on a five-point scale (1 = "would definitely not buy"; 5 = "would definitely buy").

The sensory analysis revealed no significant differences ($P > 0.05$) between the

Table 2 - Hedonic scores for appearance, flavor, texture, overall acceptance, and purchase intent.

Sample	-----Appearance-----	--------Flavor--------	--------Texture--------	--Overall acceptance--	---Purchase intent---
CB	8.47 ± 0.81^a	8.43 ± 0.81^a	8.30 ± 1.17^a	8.33 ± 0.75^a	4.50 ± 0.57^a
B5	8.07 ± 1.14^a	7.77 ± 1.33^{ab}	8.03 ± 0.96^a	7.77 ± 1.33^a	4.17 ± 0.83^a
B10	5.43 ± 1.95^b	7.27 ± 1.36^b	6.90 ± 1.68^b	6.77 ± 1.52^b	2.90 ± 1.37^b

Means followed by the same letter in the column do not differ significantly by Tukey's test at a 5% significance level (n = 117).

control bread (CB) and the 5% replacement formulation (B5) for any of the evaluated attributes (Table 2). This indicates that the partial substitution of wheat flour with modified coffee hull did not negatively affect consumer perception regarding appearance, flavor, or texture. In contrast, the B10 formulation received significantly lower scores across all attributes, particularly for appearance and texture, suggesting that a 10% substitution level negatively impacts acceptability. Regarding purchase intention, the significant drop in scores for B10 reinforces that the 5% replacement level is the most viable limit for this formulation. Therefore, based on the sensory analysis, the formulation with 5% replacement (B5) was selected for subsequent characterization analyses.

Centesimal composition

The centesimal composition of the CB and B5 samples showed significant differences in moisture, protein, lipids, carbohydrates, and total dietary fiber, except for ash content (Table 3). B5 exhibited higher moisture and protein levels and lower carbohydrate content compared with CB. Total dietary fiber also increased markedly, from 1.31% in CB to 3.84% in B5.

The higher moisture content in the B5 formulation is likely related to the increased water retention capacity of fiber-rich ingredients. Similar trends have been reported by RIZKAPRILISA et al. (2023), who associated moisture elevation with the incorporation of modified coffee hull and other high-fiber components. Enhanced moisture typically contributes to softer-textured baked products, as described by COLLAR et al. (2006).

The increase in protein content in B5 (5.62% to 6.32%) aligns with findings from RIZKAPRILISA et al. (2023) and NI et al. (2020), who observed protein enrichment in formulations containing alternative or fiber-based ingredients. The corresponding reduction in carbohydrate content is explained by the partial replacement of wheat flour naturally rich in digestible carbohydrates with fibrous material that contributes proportionally fewer available carbohydrates. This inverse relationship between fiber substitution and carbohydrate availability is consistent with results reported by KAHLAOUI et al. (2022).

The substantial increase in total dietary fiber in the B5 sample corroborates previous observations by RIZKAPRILISA et al. (2023). Dietary fiber plays an important role in promoting gastrointestinal health, improving glycemic control, and contributing to the prevention of chronic diseases (SHAIKH et al., 2024; SILVA et al., 2022; SLAVIN et al., 2013). Considering that the recommended daily fiber intake for adults in Brazil is 25-30 g (Brasil, 2008), an 80 g portion of B5 bread may contribute approximately 10-12% of this recommendation.

Overall, the compositional changes suggested that bread formulated with 5% modified coffee hull may offer nutritional advantages over the control sample, particularly due to its higher fiber and protein contents. These attributes support the potential of B5 as a nutritionally improved product aligned with dietary strategies aimed at metabolic and cardiovascular health.

pH and acidity

No significant differences were observed between the CB and B5 samples in terms of pH and acidity, as shown in table 4.

SANTOS et al. (2018) reported that the incorporation of fiber-rich flour from papaya peel and seeds significantly affected pH and acidity in bread formulations. The authors attributed the increased acidity to the naturally low pH of

Table 3 - Centesimal composition of control bread (CB) and 5% replacement bread (B5).

Centesimal composition (%)	--------------------------CB--------------------------	--------------------------B5--------------------------
Moisture	8.20 ± 0.20^{b}	8.83 ± 0.10^{a}
Ashes	1.15 ± 0.10^{a}	1.30 ± 0.08^{a}
Proteins	5.62 ± 0.11^{a}	6.32 ± 0.10^{b}
Lipids	8.54 ± 0.15^{a}	10.45 ± 0.22^{b}
Carbohydrates	74.18 ± 0.15^{a}	69.26 ± 0.18^{b}
Total dietary fibers	1.31 ± 0.06^{a}	3.84 ± 0.04^{b}

Means followed by the same letter in the same line do not differ significantly from each other using Student’s t-test at a 5% significance level.

Table 4 - Acidity and pH of control bread (CB) and 5% replacement bread (B5).

Sample	--------pH--------	----Acidity (mol/L)----
CB	4.89 ± 0.05[a]	0.010 ± 0.001[a]
B5	5.08 ± 0.11[a]	0.007 ± 0.001[a]

Means followed by the same letter in the column do not differ significantly from each other using Student's t-test at a 5% significance level.

the added ingredient. In contrast, the modified coffee hull used in the present study has a pH close to neutrality, which explains the absence of significant changes in the acidity parameters of the B5 bread.

Color analysis

The color parameters L^*, a^*, and b^* indicated that the addition of modified coffee hull darkened both the crust and the crumb of the bread, reducing redness and yellowness in comparison to the control sample (Table 5).

Color is an important attribute influencing bread acceptability and is largely affected by Maillard reactions and sugar caramelization during baking. According to PURLIS (2011), breads with L^* values near 70 tend to be well accepted, whereas values below 60 may indicate excessive browning. Although, baking conditions (220 ºC for 10 minutes or 200 ºC for 20 minutes) can modulate color development, darker breads, particularly whole grain and enriched varieties have gained consumer acceptance due to their association with nutritional benefits.

Crumb color is determined mainly by ingredient composition rather than thermal reactions, as the internal temperature of bread rarely exceeds 100 ºC during baking (ZHAO & FUCHS, 2016). The darkening observed in the B5 sample aligns with findings from NI et al. (2020) and KAHLAOUI et al. (2022), who reported that fiber enrichment typically decreases brightness in both crust and crumb.

RIZKAPRILISA et al. (2023) likewise observed reduced lightness and yellowness in bread formulated with coffee hulls, while the red component remained relatively unchanged. The presence of phenolic compounds and natural pigments in coffee hulls acts as a natural colorant (POURFARZAD et al., 2013), potentially enhancing the perception of richer flavor and nutritional value and contributing positively to consumer appeal.

Texture

The B5 bread formulated with modified coffee hull showed significantly greater firmness compared to the control bread (Table 6). Elasticity and cohesiveness did not differ significantly between the two samples, indicating that the structural integrity of the crumb was maintained. Chewiness; however, increased in the B5 sample, resulting in a more resistant texture during mastication.

The significant increase in firmness observed in B5 (Table 6) can be attributed to the dilution of the gluten network and the high water-holding capacity of the added fibers. While RIZKAPRILISA et al. (2023) reported minimal changes at lower concentrations, our results align more closely with) and KAHLAOUI et al. (2022), who observed that fiber enrichment often leads to a denser and firmer crumb structure. This occurs because the insoluble fibers physically disrupt the gluten matrix, restricting gas expansion and resulting in a more compact texture.

Baking loss, specific volume, and density

The replacement of 5% of wheat flour with modified coffee hull did not significantly affect baking loss. However, the B5 formulation showed a significantly lower specific volume and higher density compared to the control bread (Table 7). These results indicate reduced dough expansion and a denser final product.

The decrease in specific volume suggested that the modified coffee hull negatively affected gas retention during fermentation. This effect is visually confirmed in figure 1, which displays a more compact crumb structure with smaller alveoli in the B5 and B10 samples compared to the open cellular structure of the control bread.

Table 5 - Color analysis of control bread (CB) and 5% replacement bread (B5).

		--------CB--------	--------B5--------
Crust	L^*	50.24 ± 0.33[a]	46.01 ± 0.38[b]
	a^*	15.10 ± 0.25[a]	7.33[b] ± 0.37[b]
	b^*	19.94 ± 0.15[a]	18.16 ± 0.12[b]
Crumb	L^*	70.74 ± 0.47[a]	54.72 ± 0.34[b]
	a^*	-2.16 ± 0.18[a]	0.82 ± 0.20[b]
	b^*	18.56 ± 0.15[a]	12.27 ± 0.12[b]

Means followed by the same letter in the column do not differ significantly from each other using Student's t-test at a 5% significance level.

Table 6 - Texture of control bread (CB) and 5% replacement bread (B5%).

Sample	Firmness (N)	Elasticity	Cohesiveness	Chewiness (N)
CB	4.07 ± 0.10[a]	0.88 ± 0.01[a]	0.59 ± 0.10[a]	2.19 ± 0.28[a]
B5	10.12 ± 0.01[b]	0.84 ± 0.02[b]	0.48 ± 0.05[a]	4.06 ± 0.32[b]

Means followed by the same letter in the column do not differ significantly from each other using Student's t-test at a 5% significance level.

Table 7 - Baking loss, specific volume, and density of the control sample and 5% substitution bread.

Sample	Baking loss (%)	Specific volume (cm^3/g)	Density (g/ml)
CB	20 ± 0.47[a]	2.84 ± 0.07[a]	0.35 ± 0.03[a]
B5	21 ± 0.53[a]	2.17± 0.15[b]	0.46± 0.07[b]

Means followed by the same letter in the column do not differ significantly from each other using Student's t-test at a 5% significance level.

Similar reductions in specific volume have been documented in formulations containing okara flour (SILVA et al., 2009) and almond flour (KAHLAOUI et al., 2022), reinforcing the premise that fiber-rich ingredients typically constrain dough expansion. This reduction is a critical quality concern, as specific volume remains a primary determinant of consumer acceptance; generally, larger and lighter loaves are perceived as more desirable.

The increased density observed in the B5 bread aligns with the findings of SANTOS et al. (2018), who reported a similar trend in bread enriched with papaya byproduct flour. This phenomenon is commonly attributed to the weakening of the gluten network, as the physical presence of fibrous materials disrupts the protein matrix, thereby reducing the dough's capacity for gas retention (MARINHO et al., 2021).

Beyond structural interference, fibers also exhibit a high water-holding capacity, which sequesters water from the gluten-forming proteins and decreases its availability for yeast metabolism, subsequently restricting fermentation. Furthermore, ingredients such as wheat bran can significantly alter dough rheology and impair the formation and stability of gas cells, which are vital for achieving an aerated crumb structure (MATSUSHITA et al., 2017). Consequently, even with formulation adjustments, the excessive incorporation of fiber frequently compromises both loaf volume and crumb texture.

CONCLUSION

The partial replacement of wheat flour with 5% modified coffee hulls in bread formulations proved to be feasible, enhancing the nutritional profile, particularly in terms of increased fiber and protein content, without significantly compromising sensory acceptability. In contrast, the 10% substitution harmed appearance, texture, and density, resulting in lower overall acceptance.

Texture analysis revealed increased firmness and chewiness in bread containing the modified hull, resulting in denser and less expansive

Figure 1 - Cross-section of bread samples. From left to right: Control Bread (CB), Bread with 5% modified coffee hull (B5), and Bread with 10% modified coffee hull (B10).

loaves. Beyond functional and nutritional benefits, the proposed application presents a sustainable strategy for valorizing an abundant agroindustrial by-product, contributing to circular economy principles and minimizing environmental impact.

This study makes an innovative contribution to the use of modified plant fibers in bakery products. However, the higher firmness and density observed suggest that formulation adjustments are needed to optimize sensory quality at higher substitution levels. Future studies may investigate the use of modified coffee hulls in other food matrices to assess their storage stability, rheological behavior, and impact on the digestibility of fortified products.

ACKNOWLEDGMENTS

The authors wish to thank the Instituto de Desenvolvimento Rural do Paraná for the donation of coffee hulls. Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-DS Brazil for Jessika Soares Jacinto grant.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to the conception and writing of the manuscript. All authors critically reviewed the manuscript and approved the final version.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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