Received: 6 November 2023 | Revised: 26 November 2023 | Accepted: 30 November 2023

DOI: 10.1111/jfpe.14517

ORIGINAL ARTICLE

Journal of Food Process Engineering

WILEY

Innovative use of hazelnut skin and starch modifications in sourdough bread formulation

Yusuf Durmus[1] | Munir Anil[2] | Senay Simsek[3]

[1]Department of Gastronomy and Culinary Arts, Artvin Coruh University, School of Applied Sciences, Artvin, Turkey

[2]Department of Food Engineering, Ondokuzmayis University, Samsun, Turkey

[3]Whistler Center for Carbohydrate Research, Department of Food Science, Purdue University, West Lafayette, Indiana, USA

Correspondence
Senay Simsek, Whistler Center for Carbohydrate Research, Department of Food Science, Purdue University, West Lafayette, IN 47907, USA.
Email: ssimsek@purdue.edu

Abstract

The objective of this study was to explore the use of hazelnut skin and modified starches as functional additives in sourdough bread to valorize food byproducts and maintain product quality. We examined the incorporation of 5% and 10% hazelnut skin in tandem with 3% and 5% cross-linked and oxidized starches into the bread matrix. Our methods included quantitative analysis of nutritional composition changes, and end product quality. Adding 5% hazelnut skin enhanced loaf volume and resulted in a softer crumb structure. Hazelnut skin at 5% significantly ($p < 0.05$) increased bread volume. Hardness values ranged from 2.21 to 11.3 N. In conclusion, sourdough bread formulated with 5% hazelnut skin optimizes quality in terms of volume and softness. Modified starches can be strategically employed to adjust textural challenges presented by the inclusion of dietary fibers. This study demonstrates that strategic ingredient additions can lead to improved utilization of food byproducts while enhancing bread characteristics.

Practical applications

This study presents a novel approach to enhancing sourdough bread quality by incorporating hazelnut skin, a sustainable and underutilized byproduct of the nut industry. The successful addition of 5% hazelnut skin improves loaf volume and softness, which could significantly benefit the bakery sector by providing a means to produce a superior product with added nutritional value. Moreover, the use of modified starches helps mitigate the textural challenges often associated with fiber enrichment in bread, thus allowing bakeries to offer products that cater to health-conscious consumers without compromising on sensory qualities. The industrial adoption of this method can lead to reduced food waste, as hazelnut byproducts are valorized, and may resonate with eco-friendly branding strategies. Our findings support the potential for food industries to create breads with enhanced consumer appeal while contributing to environmental sustainability.

KEYWORDS

bread quality, cross-linked starch, hazelnut skin, oxidized starch, sourdough bread, textural properties

1 | INTRODUCTION

Sourdough is a mixture of flour and water, fermented by lactic acid bacteria and yeasts through either spontaneous fermentation or fermentation initiated by a sourdough starter culture (Anil, 2007; De Vuyst et al., 2009). The use of sourdough in breadmaking contributes to bread properties such as flavor, extended shelf-life, texture, nutritional value, and resistance to microbial spoilage. These benefits are due to the lactic acid bacteria and yeasts naturally found in sourdough (Aplevicz et al., 2013; Durmus, Whitney, et al., 2023; Różyło et al., 2015).

Dietary fiber is essential for a well-balanced diet as it provides health benefits to consumers, but many bread products lack dietary fiber. The addition of wheat bran can improve the nutritional properties of bread products because of the dietary fiber content and antioxidant compounds but results in low bread quality (Boita et al., 2016; Durmus et al., 2021). Hazelnut skin, a byproduct of the hazelnut roasting procedure (perisperm from *Corylus avellana L.*), can also be used in breadmaking to improve the nutritional value of bread due to its high dietary fiber and phenolic content. Many studies show that hazelnut skin is a rich and low-cost source of natural phenolic antioxidants (Contini et al., 2008; Durmus, Anil, & Simsek, 2023; Shahidi et al., 2007). Some researchers produced bread with hazelnut skin and found that the crust and crumb darkness of bread increased and obtained similar or slightly low loaf volumes and sensory properties (Anil, 2007; Velioglu et al., 2017). Anil (2007) reported that the addition of 5% hazelnut skin significantly increased the specific volume of bread. However, Anil (2007) stated that as the hazelnut skin ratio increased, the breads were preferred less by the panelists in the sensory analysis. Velioglu et al. (2017), on the other hand, reported that the general acceptability of the breads they produced by adding hazelnut skin in the proportions of 0, 4%, 6%, and 10% were similar. Nevertheless, there is insufficient research on the interactions of phenolic compounds with sourdough bread components regarding bread quality. In general, the use of dietary fibers in bread production causes low loaf volume, insufficient textural properties, and less favored products, according to consumers.

In order to lessen the undesirable effects of dietary fiber, modified starches that have the capability to interact with dietary fiber and phenolic compounds can be used in breadmaking. Gómez et al. (2003) found that the use of dietary fibers in bread reduced crumb firmness due to the water-binding capacity of dietary fiber and possible interaction between starch and dietary fiber, resulting in the delay of starch retrogradation. Cross-linked starch, a type of modified starch, has a high resistance starch content and, therefore, has similar properties to dietary fiber. Cross-linking the starch can stabilize the granules, make them resistant to low pH, cause higher viscosity, and have less tendency to breakdown compared to natural starch. Several researchers used cross-linked starches in breadmaking and reported changes in loaf volume, bread texture, and crumb structure (Akram et al., 2017; Lee Yeo & Seib, 2009). Toufeili et al. (1999) also found that the addition of cross-linked barley starch resulted in a lower rate of bread staling. Oxidized starch is another type of modified starch, which is produced by reacting starch with a specified amount of an oxidizing reagent under controlled pH and temperature (Kuakpetoon & Wang, 2001). Oxidized starches are used in the food industry for their low viscosity, emulsifying properties, high stability, clarity, and good bonding properties, and are particularly common in food coatings and confectionery products (Chattopadhyay et al., 1997). Oxidized starch can reduce the hardness of the bread with a high specific volume (Akram et al., 2017; Sandhu et al., 2011). The aim of this study was to investigate the effects of hazelnut skin, cross-linked starch, and oxidized starch on sourdough bread quality, utilizing hazelnut skin as a bread component and producing a new valuable product.

2 | MATERIALS AND METHODS

2.1 | Materials

Commercial hard red spring wheat flour without oxidizing agents or other additives was obtained from North Dakota State Mill (Grand Forks, ND, USA.). Hazelnut skin (perisperm from *Corylus avellana L.*) was obtained from a hazelnut processing plant in Ordu, Turkey. Hazelnut skin was milled with a laboratory grinder and sifted through 0.50–0.85 mm. Sodium trimetaphosphate ($Na_3P_3O_9$) modified corn flour cross-linked starch, and sodium hypochlorite (NaClO) modified corn flour oxidized starch were obtained from Pendik Nisasta (Istanbul, Turkey). *Lactobacillus helveticus* + *Lactobacillus delbrueckii subsp. lactis* (LH 100) was obtained from Danisco (Copenhagen, Denmark), and *Lactobacillus plantarum* (SM 199) was obtained from Chr. Hansen (Hoersholm, Denmark).

2.2 | Breadmaking

Lactic acid bacteria (LAB) strains were inoculated at 1% in M.R.S. broth and incubated at 30°C for 16 h. The cells obtained by centrifugation at 4500 rpm for 10 min were washed twice and resuspended in sterile saline water. Subsequently, dough consisting of 1500 g of flour, 30 g of sugar, and 900 mL of distilled sterile water was inoculated from the LAB suspension prepared at 10^7 cfu/g. Sourdough obtained by fermentation at 30°C for 16 h was used by adding 30% with the replacement of flour in bread dough production. The basic breadmaking formula consisted of 70 g of flour (14% moisture basis), sourdough (30 g), salt (1.5 g), sugar (1.0 g), instant yeast (0.5 g), shortening (1.0 g), and water up to 500 BU consistency by the farinograph. Modified starches (cross-linked and oxidized starch) were added on a 3% and 5% flour basis, and wheat flour was substituted with hazelnut skin by 5% and 10%. The dough samples were kneaded (Model C-100, Hobart, Ohio, USA) until the optimum dough development was obtained, considering the farinograph development time. Dough samples were allowed to ferment at 30°C for 50 min. Subsequently, each dough was divided into 160 g pieces and underwent a second fermentation at 30°C for 10 min. After fermentation, the samples were molded and, sheeted, and placed into greased tin pans. Doughs were proofed for 150 min at 30°C and 90% relative humidity and baked at 210°C for 25 min. The loaves were removed from the pans, cooled for 1 h at room temperature, and then sealed in polyethylene bags to monitor changes in bread quality parameters upon storage.

2.3 | Proximate analysis

AACC International Approved Methods 44-15.02, 08-01.01, 02-52.01, 02-31.01, and 46-30.01 were used to determine moisture content, ash content, pH, total acidity, and protein content, respectively (AACC, 2010). Lipid content was determined with a 16-hour Soxhlet extraction with hexane according to the AOCS method Ba 3–38 (AOCS, 1998). Analyses were carried out in triplicate.

2.4 | Color

Colorimetric properties were measured using a colorimeter (Minolta, Chromameter CR-410, Japan). The values were expressed according to the C.I.E. scale, where L*, a*, and b* correspond to brightness, redness, and yellowness, respectively. Browning index (BI) value was calculated using the following equations (Mohapatra et al., 2010).

$$x = \frac{a* + 1.75L*}{5.645L* + a* - 3.012b*} \text{ and } BI = \frac{100\,(x - 0.31)}{0.17}$$

2.5 | Bread texture

Texture profile analysis (TPA) of the sourdough bread was determined on the 1st, 3rd, and 5th days of storage by using a texture analyzer (Stable Micro System, TA-XT2I, Surrey, UK). Two slices of 1.25 cm thick bread overlapped were pressed twice from the midpoint at 40% penetration depth. With a 35 mm diameter cylindrical probe (SMS P/36), 5 kg load cell, 5 mm/s compression rate and 30 s gap between compressions were used in the analysis. Pre-test and test speeds were both 1.7 mm/s, and the post-test speed was 10 mm/s. Hardness (N), resilience (%), cohesion, springiness (%), gumminess, and chewiness properties were determined with the TPA analysis (Coda et al., 2017).

2.6 | Volume and specific volume

Loaf volumes of the sourdough breads were measured by the rapeseed displacement method as described in AACC International Approved Method 10-05.13 (AACC, 2010). The specific loaf volume of sourdough bread was calculated by dividing the volume by the weight of the loaf (AACC, 2010).

2.7 | C-Cell

A C-Cell digital imaging system (Caliber Control Intl. Ltd., UK) was used to analyze bread crumb structure and quality. Image analysis of crumb grain of baked loaves was performed 1 day after baking. Slice area, number of cells, wrapper length, cell wall thickness, and slice brightness were the parameters used to evaluate the bread crumb structure.

2.8 | Sensory evaluation

Sensory evaluation was carried out for bread samples which were sliced (1.5 cm thick) and coded with three-digit random numbers. The panel consisted of 21 panelists (24–45 years old) who evaluated the bread's crumb appearance, aroma, flavor, and general acceptability. A 10-point hedonic scale was used to determine the degree of overall liking or disliking of different types of bread (1: dislike extremely, 10: like extremely). Plain water was used for mouth rinsing before and after each sample testing.

2.9 | Statistical analysis

Statistical analysis software (SAS v.9.4) was used to conduct analysis of variance (ANOVA). Least significant difference (LSD) was used for mean separation.

3 | RESULTS AND DISCUSSION

3.1 | Sourdough bread composition

To provide a comprehensive understanding of the modifications in bread composition due to the addition of hazelnut skin and modified starches, detailed analytical results are presented. In examining sourdough bread's nutritional and physicochemical attributes, we sought to determine the impacts of these additives on moisture, pH, total acidity, ash, protein, and fat content. The bread composition results are represented in Table 1. Moisture content, pH, and total acidity of the breads were not significant ($p > 0.05$), indicating that the fundamental bread matrix was preserved across all samples. However, ash, protein, and fat content showed significant ($p < 0.05$) differences between samples (Table 1), which underscores the influence of the additives on the bread's nutritional profile. The ash content of the breads ranged between 2.12% and 2.35%, with the 10% hazelnut skin bread sample at the high end of the range (Table 1). The high ash content of hazelnut skin led to an increase in ash content in the breads. Bread samples with oxidized starch had slightly higher pH values than the other breads (Table 1). Oxidized starches are anionic due to their structure and, therefore, may cause an increase in pH (Bemiller & Whistler, 2009). The 10% hazelnut skin substitution resulted in significantly ($p < 0.05$) lower protein (12.84%) than the 5%

TABLE 1 Proximate composition of sourdough bread samples produced with modified starches and hazelnut skin.

	Modified starch ratio (%)	Hazelnut skin ratio (%)	% Moisture	%DWB Ash	%DWB Protein	%DWB Fat	pH	%TA Acidity
Refined flour	0	0	8.06a	2.16bc	13.83a	4.79def	4.39a	1.73a
Refined flour	0	5	8.25a	2.29abc	13.48bc	6.24abc	4.38a	1.58a
Refined flour	0	10	8.07a	2.35a	13.19d	6.22abc	4.37a	1.67a
Cross-linked	3	0	8.06a	2.14bc	13.51b	5.22cde	4.40a	1.59a
Cross-linked	3	5	8.06a	2.18abc	13.16d	5.44bcd	4.40a	1.63a
Cross-linked	3	10	7.77a	2.21abc	12.77e	6.77a	4.37a	1.74a
Cross-linked	5	0	7.74a	2.12c	13.19d	4.34ef	4.41a	1.70a
Cross-linked	5	5	7.82a	2.19abc	12.93e	4.93def	4.38a	1.67a
Cross-linked	5	10	7.82a	2.29abc	12.54f	6.50a	4.37a	1.63a
Oxidized	3	0	7.83a	2.21abc	13.37bc	3.99f	4.42a	1.55a
Oxidized	3	5	7.88a	2.28abc	13.17d	6.68a	4.40a	1.64a
Oxidized	3	10	7.80a	2.30abc	12.87e	6.91a	4.39a	1.60a
Oxidized	5	0	7.83a	2.19abc	13.26 cd	4.29ef	4.43a	1.55a
Oxidized	5	5	7.85a	2.22abc	12.87e	6.37ab	4.37a	1.65a
Oxidized	5	10	7.81a	2.32ab	12.53f	6.98a	4.39a	1.67a

Note: Values in the same column with the same letter are not significantly ($p < 0.05$) different.
Abbreviations: DWB, dry weight basis; TA, total acidity.

hazelnut skin substitution (13.15%) and the breads without hazelnut skin (13.52%) (Table 1). Hazelnut skin contains a very low amount of protein compared to wheat flour; therefore, it was expected to reduce protein content when utilized in breadmaking. Similarly, modified starches are considered a poor source of protein and low in protein content in comparison to refined wheat flour. Shukri et al. (2017) found that the addition of cross-linked rice starch to flour resulted in low protein content. Breads containing 10% hazelnut skin had a very high fat content, and the breads containing 5% hazelnut skin had a mid-range fat content (Table 1). This may be the result of the roasting process applied to the hazelnuts. Hazelnut skin is separated from the hazelnut with a high amount of transferred fat. Since the modified starches have a very low-fat content, the results indicate that modified starch application affected bread fat content adversely.

3.2 | Sourdough bread color

Color is consequential for the assessment of bread quality and is a powerful determining factor that plays a critical role in consumer acceptance. Factors such as Maillard reaction, baking temperature and time, milling of wheat, and pigment degradation all affect bread color (Ibrahim, 2016). L*, a*, and b* color values of bread crust varied from 40.97 to 47.96, 9.36 to 15.15, and 18.42 to 26.68, respectively (Table 2). L*, a*, and b* values differed significantly ($p < 0.05$) among the sourdough bread samples for both crust and crumb (Table 2). Bread samples without hazelnut skin had the brightest color, while there was a significant ($p < 0.05$) reduction in the brightness of samples with hazelnut skin (Table 2). Anil (2007) also reported a decrease in brightness (L*) when hazelnut skin content increased from 0 to 5 and to 10%. The brightness of bread samples slightly increased with modified starch addition; however, there was no significant ($p > 0.05$) difference between cross-linked and oxidized starch (Table 2). The crumb L* value was highest in the 0% hazelnut skin samples, followed by the 5% and 10% hazelnut skin breads, respectively (Table 2). Lower L* values in hazelnut skin containing breads was also observed in other research studies (Anil, 2007; Velioglu et al., 2017). No significant ($p > 0.05$) differences in L* values were observed with the cross-linked and oxidized starch bread samples (Table 2). Rodriguez-Sandoval et al. (2017) found that there was no considerable difference in L* values when using a mixture of cross-linked starch and oxidized starch (1:1) at 5% in bread production, but there was a significant increase at 7% and 10%.

The a* value of the bread samples with 0% hazelnut skin were the highest, while the lowest values were obtained in the 10% hazelnut skin samples (Table 2). A similar trend was also observed by Velioglu et al. (2017), where the a* value decreased with the addition of hazelnut skin in flour. Crust a* values of bread made from cross-linked and oxidized starches were similar to each other and showed no significant ($p > 0.05$) differences (Table 2). The hazelnut skin bread samples appeared to have more redness, which is indicated by their higher a* values compared to other samples with low a* values (Table 2).

Similar to the a* values, b* values decreased gradually with the addition of hazelnut skin, and the differences between the ratios were statistically significant ($p < 0.05$) (Table 2). The use of both modified starches slightly increased the yellowness but was not statistically ($p > 0.05$) different (Table 2). This is in agreement with a previous

TABLE 2 Crust and crumb color properties of sourdough bread samples produced with modified starches and hazelnut skin.

	Modified starch ratio (%)	Hazelnut skin ratio (%)	Crust				Crumb			
			L*	a*	b*	BI	L*	a*	b*	BI
Refined flour	0	0	46.95ab	15.02a	25.04ab	96.80ab	73.30a	−0.01c	17.16a	26.01b
Refined flour	0	5	42.88bcd	11.60b	20.88c–g	84.76e	53.25b	3.77b	9.18b	23.78a
Refined flour	0	10	41.98cd	9.81c	18.46g	73.84d	44.59c	5.25a	8.11b	28.35def
Cross-linked	3	0	47.96a	15.15a	26.68a	101.25a	73.80a	0.00c	17.07a	25.65bc
Cross-linked	3	5	44.56a–d	11.63b	21.81b–g	84.58e	54.18b	3.79b	9.16b	23.29a
Cross-linked	3	10	43.53a–d	9.88c	19.58efg	75.12d	45.12c	5.20a	8.12b	27.92f
Cross-linked	5	0	46.27abc	14.69a	24.46ab	96.03ab	74.02a	−0.05c	17.10a	25.57bcd
Cross-linked	5	5	45.52a–d	11.60b	22.90b–e	86.62e	52.97b	3.82b	9.06b	23.70a
Cross-linked	5	10	45.21a–d	9.36c	20.45d–g	73.83d	44.76c	5.29a	8.16b	28.40ef
Oxidized	3	0	47.08ab	14.77a	24.32abc	93.62bc	73.84a	−0.03c	17.00a	25.47b–e
Oxidized	3	5	45.35a–d	11.58b	22.88b–e	86.98e	54.05b	3.74b	9.11b	23.19a
Oxidized	3	10	42.44bcd	9.64c	18.89fg	74.34cd	45.21c	5.19a	8.16b	27.93f
Oxidized	5	0	46.77ab	14.60a	23.64a–d	91.52bcd	73.62a	−0.04c	16.52a	24.74b–f
Oxidized	5	5	45.00a–d	11.17b	22.39b–f	85.18e	52.20b	3.82b	9.04b	24.04a
Oxidized	5	10	40.97d	10.07c	18.42g	76.41d	44.57c	5.22a	8.13b	28.35c–f

Note: Values in the same column with the same letter are not significantly ($p < 0.05$) different.
Abbreviation: BI, browning index.

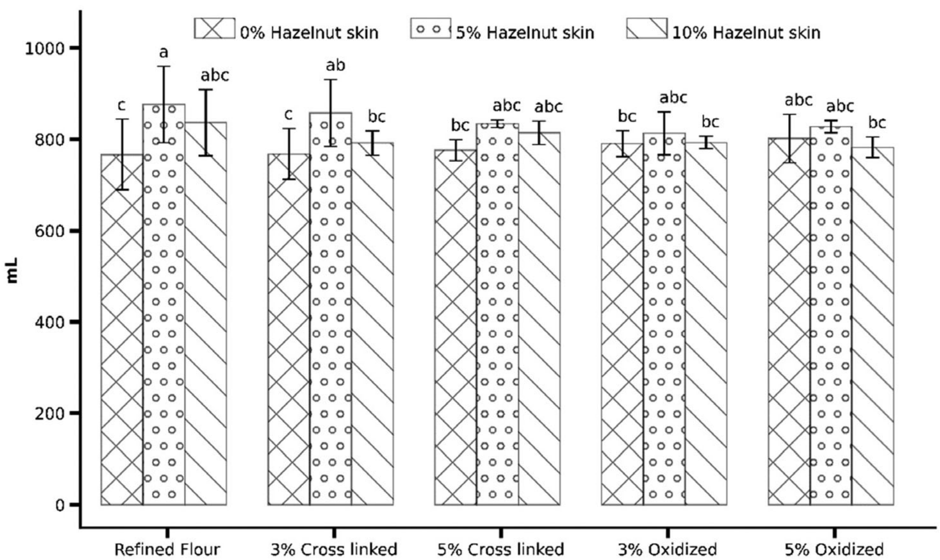

FIGURE 1 Loaf volume of sourdough bread samples produced with modified starches and hazelnut skin. Columns with the same letter are not significantly different ($p < 0.05$). Error bars represent standard deviation.

report stating that there was no significant difference with the addition of cross-linked starch in terms of b* value (Shukri et al., 2017). Additionally, there was a significant ($p < 0.05$) difference in the b* value of the samples, with 0% hazelnut skin having the highest value, while the lowest value was found in the 10% hazelnut skin samples (Table 2).

The browning index (BI) was also calculated to more precisely assess the overall color changes in sourdough bread samples. BI represents the purity of brown color and is reported as an important parameter in processes in which enzymatic and nonenzymatic browning occur. The 10% hazelnut skin samples had significantly ($p < 0.05$) lower BI value than the 0 and 5% hazelnut skin samples, indicating that 10% hazelnut skin bread was lighter in color (Table 2). This is most likely due to a high Maillard reaction in bread samples without hazelnut skin. Additionally, there was no significant ($p > 0.05$) difference in the BI value of the bread samples containing modified starches (Table 2). Contrary to the BI trend for crust values, the crumb of 10% hazelnut skin containing samples showed an increase in the BI values.

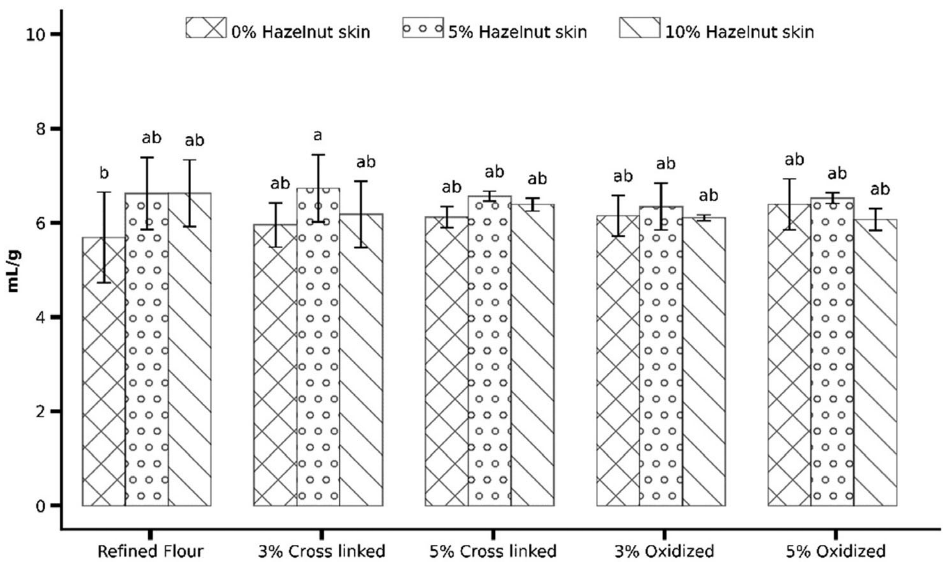

FIGURE 2 The specific volume of sourdough bread samples produced with modified starches and hazelnut skin. Columns with the same letter are not significantly different ($p < 0.05$). Error bars represent standard deviation.

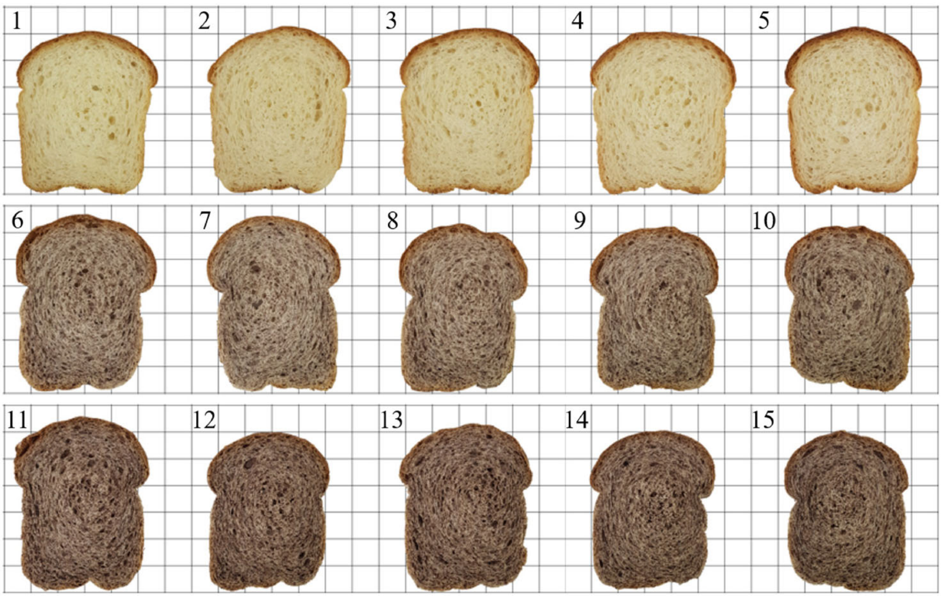

FIGURE 3 Appearance of the sourdough bread slices. *HS, hazelnut skin, (1) Refined flour, (2) 3% Cross-linked starch, (3) 5% Cross-linked starch, (4) 3% Oxidized starch, (5) 5% Oxidized starch, (6) Refined flour +5% HS, (7) 3% Cross-linked starch +5% HS, (8) 5% Cross-linked starch +5% HS, (9) 3% Oxidized starch +5% HS, (10) 5% Oxidized starch +5% HS, (11) Refined flour +10% HS, (12) 3% Cross-linked starch +10% HS, (13) 5% Cross-linked starch +10% HS, (14) 3% Oxidized starch +10% HS, (15) %5 Oxidized starch +10% HS.

3.3 | Volume and specific volume

The bread loaf volume results are illustrated in Figure 1, and the appearance of the sourdough bread slices is shown in Figure 3. The loaf volumes of the sourdough breads ranged between 766.67 and 876.30 cc (Figure 1). The 5% hazelnut skin breads had high loaf volumes, and the 10% hazelnut skin breads had mid-range loaf volumes (Figure 1). The use of hazelnut skin had a positive effect on loaf volume, but the amount of gluten decreased considerably when increasing the ratio from 5% to 10%. This may be caused by phenolic compounds in the hazelnut skin, which form disulfide bonds due to their oxidant properties and contribute to loaf volume by strengthening gluten. Subsequently, increasing the level of hazelnut skin negatively affected the loaf volume. Research studies have reported the adverse effect of dietary fiber on bread loaf volume, which is largely due to the reduction in the amount of gluten present (Júnior et al., 2008; Turfani et al., 2017). Dough with a high dietary fiber content may cause insufficient gluten network formation and gluten aggregation resulting in a low loaf volume (Noort et al., 2010). In the absence of hazelnut skin, cross-linked and oxidized starch showed a slight increase in loaf volume. In contrast, the 5% and 10% hazelnut skin supplemented breads showed an insignificant decrease for both types of modified starches (Figure 1). Breads with oxidized starch showed higher loaf volumes than cross-linked starch when used without hazelnut skin. Lee Yeo and Seib (2009) reported that 10% of cross-linked wheat starch supplementation to flour reduced loaf volume. However, Kang et al. (2018) used 10% oxidized corn starch in breadmaking and found that the loaf volume was the same as the bread without oxidized starch. Specific loaf volume results are represented in Figure 2. Specific loaf volume increased with 5% hazelnut

TABLE 3 Texture profile analysis results of sourdough bread samples produced with modified starches and hazelnut skin.

	Modified starch ratio (%)	Hazelnut skin ratio (%)	Hardness (N)			Resilience (%)			Cohesion		
			Day 1	Day 3	Day 5	Day 1	Day 3	Day 5	Day 1	Day 3	Day 5
Refined flour	0	0	3.69aC	6.29abB	10.40aA	37.63aA	22.69aB	22.91aB	0.749aA	0.540aB	0.523aB
Refined flour	0	5	2.21aC	5.35bB	8.80bA	38.10aA	22.39aB	19.74abB	0.784aA	0.552aB	0.492aB
Refined flour	0	10	2.64aC	5.89abB	8.26bA	36.47aA	23.58bB	18.89abB	0.783aA	0.567aB	0.475aC
Cross-linked	3	0	3.24aC	5.92abB	8.89abA	36.93aA	21.66aB	18.33abB	0.737aA	0.527aB	0.475aB
Cross-linked	3	5	2.73aC	5.28abB	9.24abA	36.96aA	22.43aB	22.27abB	0.776Aa	0.539aB	0.516aB
Cross-linked	3	10	3.04aC	5.41abB	8.95abA	35.63aA	24.87aB	21.43abB	0.755aA	0.571aB	0.517aB
Cross-linked	5	0	3.43aC	7.36aB	10.64aA	36.88aA	22.38aB	20.00abB	0.740aA	0.535aB	0.487aB
Cross-linked	5	5	2.59aC	5.21abB	8.15bA	36.40aA	26.03aB	19.84abB	0.771aA	0.571aB	0.495aC
Cross-linked	5	10	2.88aC	6.03abB	9.26abA	36.72aA	22.31aB	19.52abB	0.763aA	0.539aB	0.482aB
Oxidized	3	0	3.18aC	6.03abB	8.70bA	36.93aA	23.38aB	20.15abB	0.745aA	0.542aB	0.483aB
Oxidized	3	5	2.68aC	5.20abB	8.40bA	37.52aA	23.80aB	19.05abB	0.774aA	0.561aB	0.484aC
Oxidized	3	10	2.91aC	6.33abB	9.98abA	36.29aA	22.31aB	20.50abB	0.760aA	0.548aB	0.495aB
Oxidized	5	0	3.31aC	6.58aB	11.13aA	35.47aA	20.99aB	22.14abB	0.738aA	0.515aB	0.517aB
Oxidized	5	5	2.95aC	4.91bB	7.58bA	37.47aA	22.31aB	17.74bB	0.757aA	0.529aB	0.467aC
Oxidized	5	10	3.66aC	5.70abB	8.87abA	33.24aA	23.75aB	20.40abB	0.727aA	0.563aB	0.493aC

Note: Values in the same column (separately for springiness or gumminess or chewiness) with the same lower-case letters are not significantly ($p < 0.05$) different. Values in the same row (separately for springiness or gumminess or chewiness) with the same upper-case letters are not significantly ($p < 0.05$) different.

skin substitution; however, specific loaf volume declined when hazelnut skin was added to flour at 10% (Figure 2). No significant ($p > 0.05$) differences in specific volume were observed with the addition of modified starches (Figure 2).

3.4 | Sourdough bread texture

The textural parameters of the sourdough breads from the TPA test are presented in Tables 3 and Table 4. The hardness of the sourdough breads ranged between 2.21 and 3.69 N on the 1st day of storage, 4.91 and 7.36 N on the 3rd day of storage, and 7.58 and 11.13 N on the 5th day of storage (Table 3). The increasing level of hardness during storage was expected as the day-old bread had the lowest moisture content. It was determined that hardness significantly ($p < 0.05$) decreased with the addition of hazelnut skin and the 5% hazelnut skin bread had the lowest hardness value (Table 3). This result appears to be related to the specific volume findings observed with the 5% hazelnut skin bread. Weight to volume ratio in bread has been reported as the most important factor in the development of bread's physical properties (Scanlon & Zghal, 2001). Lebesi and Tzia (2011) stated that the use of dietary fiber reduces moisture loss, decreases hardness, and increases shelf life; therefore, large amounts of dietary fiber should not be used in bread formulations. This supports the results shown in Table 3, as well as those of Cikrikci et al. (2016), who reported that hardness decreased with the addition of 10% hazelnut skin in cake, while hazelnut skin at 15% and 20% caused an increase in hardness. Another reason for the decrease in hardness may result from the interactions between fiber and starch. Demirkesen et al. (2013) indicated that the formation of hydrogen bonds between dietary fiber and starch prevents starch-starch interactions, which causes a decrease in starch availability for crystallization. The observed decrease in hardness values of bread samples with the addition of hazelnut skin may be due to the dietary fiber affecting the structure of starch fractions. The specific volume appears to be negatively related to hardness, which was demonstrated in this study since the hazelnut skin bread samples with high specific volume showed low hardness values. There was no significant ($p > 0.05$) difference between cross-linked and oxidized starch in terms of bread hardness (Table 3). The hardness of the breads with 5% modified starch was slightly higher than that of bread containing 0 and 3% modified starch; however, modified starch had no significant ($p > 0.05$) influence on bread hardness (Table 3).

Resilience demonstrates how well a product returns to its original position after a certain force is applied. Resilience is largely related to the gluten network, which imparts viscoelastic structure to the dough. A high reduction of resilience was observed at the end of the third day of storage (Table 3). In addition, hazelnut skin, modified starch type, and modified starch ratio factors did not have a significant ($p > 0.05$) effect on resilience (Table 3). Breads susceptible to crumbling and fracture have low cohesiveness (Onyango et al., 2011). Therefore, bread with a relatively high cohesiveness is desirable. The cohesiveness results in this study were similar to the resilience results, with a significant ($p < 0.05$) reduction over the storage period (Table 3). The addition of hazelnut skin slightly increased the

TABLE 4 Texture profile analysis results of sourdough bread samples produced with modified starches and hazelnut skin.

	Modified starch ratio (%)	Hazelnut skin ratio (%)	Springiness (%)			Gumminess			Chewiness		
			Day 1	Day 3	Day 5	Day 1	Day 3	Day 5	Day 1	Day 3	Day 5
Refined flour	0	0	100.72bA	100.24abA	99.29aA	280.10aB	342.89abB	549.02abA	281.45abC	343.74abcB	545.33abA
Refined flour	0	5	99.70bA	100.16abA	99.68aA	176.00bC	301.24bB	440.52cdA	211.07bC	301.85bcB	439.11cdefA
Refined flour	0	10	101.50abA	100.12abAB	98.30aB	209.73abB	341.10abA	400.33deA	237.83abB	341.61abcA	393.75efA
Cross-linked	3	0	100.29bA	100.85aA	99.28aA	240.69abB	317.36bB	427.67cdA	240.65abB	320.55bcB	423.53cdefA
Cross-linked	3	5	103.03ababA	99.32abd-jB	99.05ae-jB	216.57abB	289.99bB	486.88bcA	222.84abB	288.34cB	482.40bcdA
Cross-linked	3	10	99.92bA	98.64abA	98.28aA	233.31abB	312.75bB	469.13cdA	233.11abC	372.70abB	462.23bcdeA
Cross-linked	5	0	101.59abA	100.24aA	99.64aA	255.07abC	404.23aB	528.27abA	304.73aC	405.12aB	526.34abA
Cross-linked	5	5	101.79abA	100.68aA	99.53aA	201.43abC	303.14bB	410.34cdA	258.81abB	305.06bcB	408.45defA
Cross-linked	5	10	103.06abA	99.17abB	96.12bC	222.72abC	331.05abB	455.94cdA	228.27abC	328.34abcB	438.32cdefA
Oxidized	3	0	101.99abA	100.36aAB	98.85aAB	237.63abC	332.72abB	426.06cdA	246.48abC	334.51abcB	421.28cdefA
Oxidized	3	5	100.76bA	100.48aA	97.60abB	211.09abC	297.36bB	414.67cdA	212.45bC	298.90bcB	404.73defA
Oxidized	3	10	103.55aA	98.14abB	98.60abB	224.70abC	353.74aB	504.64abA	232.15abC	347.10abcB	497.31abcA
Oxidized	5	0	99.64bA	100.84aA	99.00aA	245.63abC	343.48aB	581.19aA	285.66abB	346.41abcB	576.06aA
Oxidized	5	5	100.18bA	100.76aA	98.26abA	227.25abB	263.99bB	361.30eA	269.69abB	265.22cB	355.60fA
Oxidized	5	10	100.00bA	97.61bA	98.03abA	271.30aB	323.88bB	445.14cdA	268.12abB	315.52bcB	436.78cdefA

Note: Values in the same column (separately for springiness or gumminess or chewiness) with the same lower-case letters are not significantly ($p < 0.05$) different. Values in the same row (separately for springiness or gumminess or chewiness) with the same upper-case letters are not significantly ($p < 0.05$) different.

cohesiveness of the bread, whereas both cross-linked and oxidized starches slightly reduced the cohesiveness (Table 3).

The TPA springiness parameter reveals product elasticity. As expected, springiness values significantly ($p < 0.05$) decreased during storage (Table 4). On the first day of observations, samples with hazelnut skin had slightly higher springiness on average; however, 10% hazelnut skin bread had significantly ($p < 0.05$) lower springiness compared to 0 and 5% hazelnut skin samples on the 3rd and fifth days of storage (Table 4). Similar results were obtained for cross-linked and oxidized starch in terms of springiness (Table 4). Gumminess, another TPA parameter, is determined by hardness multiplied by cohesiveness and is defined as the energy required to get a semi-solid food ready to swallow. Gumminess gradually increased during storage, and the differences between the storage days were found to be significant ($p < 0.05$) (Table 4). Breads with hazelnut skin had significantly ($p < 0.05$) lower gumminess for each day of storage compared to the samples without hazelnut skin (Table 4). The addition of modified starch did not significantly ($p > 0.05$) affect the gumminess of the bread samples (Table 4).

Chewiness represents the amount of energy needed to disintegrate food for swallowing and is derived from the product of springiness, hardness, and cohesiveness. The chewiness of bread is quite low when it is first taken out of the oven and develops during storage due to starch recrystallization. The findings from Table 4 display a significant ($p < 0.05$) increase in chewiness during the overall bread storage period. Bread chewiness was highest in the 0% hazelnut skin samples, followed by 10% hazelnut skin and 5% hazelnut skin containing samples, respectively (Table 4). Bourekoua et al. (2017) also reported that chewiness was reduced by using different rates of moringa leaf powder as a dietary fiber source in bread production. However, there were no significant ($p > 0.05$) differences between the cross-linked and oxidized starch samples (Table 4). Therefore, dietary fiber, such as hazelnut skin, has a greater effect on bread chewiness compared to modified starch.

3.5 | C-Cell

The C-Cell analysis was used on the bread slices, and the results are listed in Table 5. Crumb structure analysis revealed changes in cellular parameters. Slice area increased in breads supplemented with hazelnut skin, but a significant ($p < 0.05$) increase was only observed in the 5% hazelnut skin containing breads (Table 5). This may be due to an antioxidant capacity increase with the addition of hazelnut skin, which strengthens the structure of gluten. However, with further hazelnut skin addition, dough structure negatively affected the slice area as a result of the dilution of the gluten network. The slice area of the samples in this study showed a strong relationship to loaf volume and the specific volume of the bread samples. While the addition of modified starches to breads without hazelnut skin showed a positive effect on the slice area, this was not observed in hazelnut skin supplemented breads. Similar to the slice area results, breads with 5% hazelnut skin had the highest cell number; however, further addition of hazelnut skin at 10% significantly ($p < 0.05$) decreased the cell number in the bread crumb (Table 5). Ning et al. (2017) reported that cell number decreased with increasing levels of green tea powder due to the high cellulose content. Accordingly, less water was available for optimal gluten development with high levels of green tea powder, which caused the gas molecules to coalesce, resulting in large-diameter cells and fewer cells in the crumb (Ning et al., 2017). As shown in Table 5, the addition of oxidized starch reduced the cell number in the breads containing hazelnut skin and was significant ($p < 0.05$) with 5% oxidized starch.

Wrapper length results showed no significant ($p > 0.05$) differences among the bread samples (Table 5). Bread crumb cell wall thickness is another parameter measured during C-Cell analysis and has an effect on both eating quality and appearance. Cell wall thickness gradually decreased with the addition of hazelnut skin (Table 5). Although both types of modified starches slightly increased the cell wall thickness, the effect of oxidized starch was found to be more pronounced than cross-linked starch (Table 5). The slice brightness values dramatically decreased with the hazelnut skin substitution (Table 5). Since hazelnut skin is darker in color compared to refined flour, this would be expected, and the skin particles would result in a darker crumb color. There were no significant ($p > 0.05$) differences among modified starch bread samples for slice brightness, which indicates similarity in the fineness and homogeneity of the crumb grain between breads with cross-linked and oxidized starch (Table 5). Although the use of hazelnut skin can have a negative effect on bread crumb structure, the 5% hazelnut skin addition appeared to result in the best crumb structure among all the sourdough bread samples.

3.6 | Sensory evaluation

Sensory evaluation is a valuable instrument for quality maintenance, new product development, and product improvement. The loaves were evaluated for crumb appearance, aroma, flavor, and general acceptability characteristics. Sensory evaluation for sourdough breads, as shown in Figure 4, revealed that increasing the level of hazelnut skin significantly ($p < 0.05$) decreased the crumb appearance, while cross-linked and oxidized starch slightly decreased aroma, flavor, and general acceptability. Velioglu et al. (2017) also found the addition of hazelnut skin at 10% to cause a reduction in crumb appearance scores. Although the use of 5 and 10% hazelnut skin reduced bread crumb appearance scores, this negative effect was lessened with the addition of modified starch. Moreover, no significant ($p > 0.05$) differences were seen in the degree of liking for hazelnut skin and breads containing modified starch in terms of aroma evaluation (Figure 4). Thus, suggesting that the use of hazelnut skin and modified starch did not negatively influence consumers' acceptance of sourdough bread. Despite the undesirable sensory characteristics of bread produced with high dietary fiber substitution, results suggest that the addition of hazelnut skin did not significantly ($p > 0.05$) alter the flavor of sourdough bread (Figure 4). Furthermore, refined flour without hazelnut skin bread had the highest scores among other sourdough breads for flavor attributes, while the 10% hazelnut skin with 5% oxidized starch bread had the lowest score (Figure 4). General acceptability scores

TABLE 5 C-Cell analysis results of sourdough bread samples produced with modified starches and hazelnut skin.

	Modified starch ratio (%)	Hazelnut skin ratio (%)	Slice area (mm^2)	Number of cells	Wrapper length (mm)	Cell wall thickness (mm)	Slice brightness
Refined flour	0	0	5682.67b	2485.00abc	283.75a	0.51a–d	104.15a
Refined flour	0	5	5507.33a	2613.83a	276.33a	0.50bcd	95.23b
Refined flour	0	10	5535.67ab	2475.83abc	278.57a	0.52cd	96.43c
Cross-linked	3	0	5272.33b	2431.17bc	270.92a	0.49abc	106.42a
Cross-linked	3	5	5254.83ab	2583.17ab	269.05a	0.49bcd	106.73b
Cross-linked	3	10	5536.17ab	2526.50abc	278.63a	0.51d	103.20c
Cross-linked	5	0	5618.00ab	2507.33abc	282.47a	0.51a–d	104.57a
Cross-linked	5	5	5672.17ab	2521.50abc	282.55a	0.52a–d	103.70b
Cross-linked	5	10	5678.17ab	2419.67bc	282.10a	0.50bcd	76.58c
Oxidized	3	0	5304.83ab	2453.17abc	269.67a	0.49a	99.27a
Oxidized	3	5	5727.67ab	2453.50abc	283.37a	0.49a–d	69.05b
Oxidized	3	10	5446.17ab	2421.67bc	276.68a	0.49a–d	57.83c
Oxidized	5	0	5565.33ab	2529.50abc	278.48a	0.49ab	96.05a
Oxidized	5	5	5684.33ab	2392.33c	285.03a	0.50a–d	59.03b
Oxidized	5	10	5583.00ab	2368.83c	280.37a	0.49a–d	69.18c

Note: Values in the same column with the same letter are not significantly (p < 0.05) different.

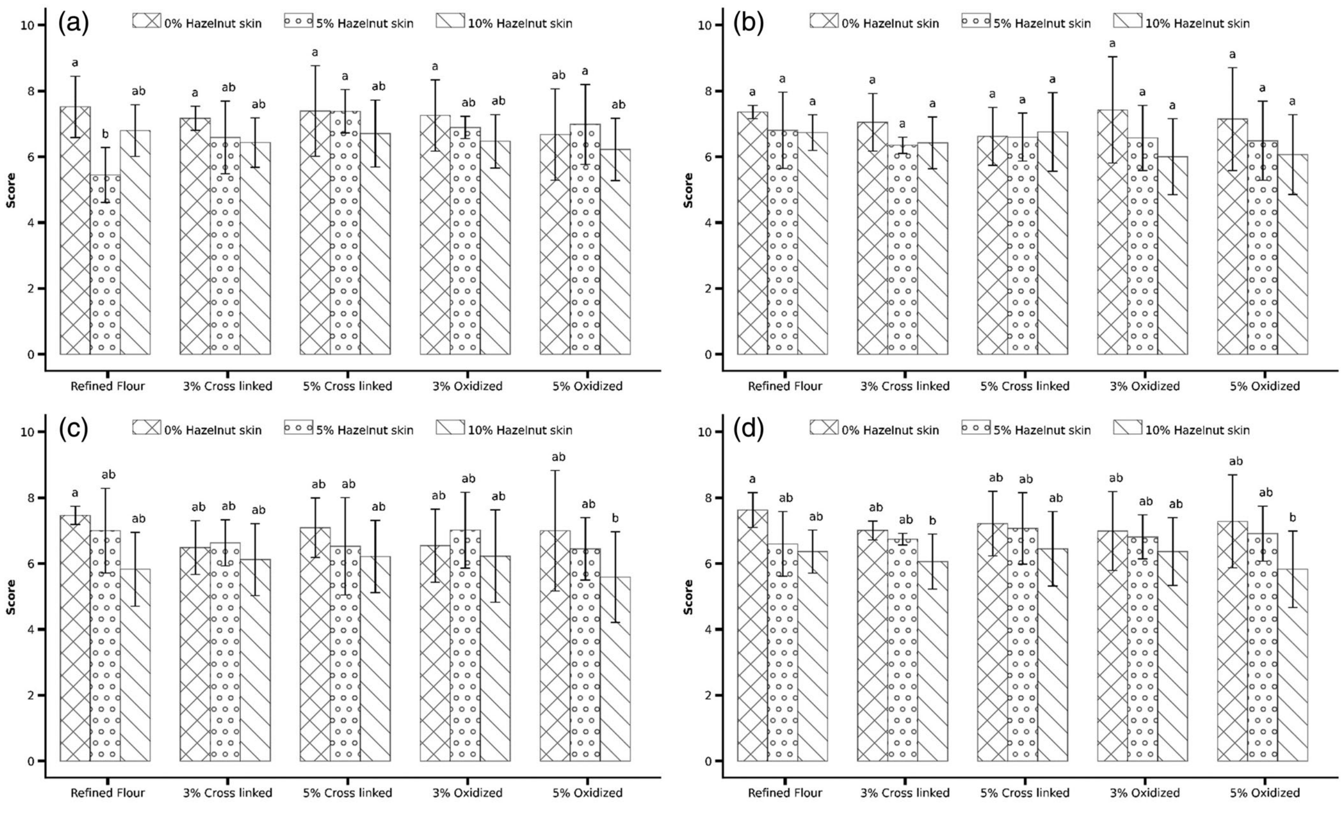

FIGURE 4 Sensory results of bread samples produced with modified starches and hazelnut skin. (a) Crumb appearance, (b) Aroma, (c) Flavor, and (d) General acceptability. Columns with the same letter are not significantly different (p < 0.05). Error bars represent standard deviation.

were not negatively affected by hazelnut skin and modified starch additions. However, general acceptability scores decreased with the combined use of 10% hazelnut skin and modified starches. Scores were noticeably lower, which may be due to the differences in aroma and flavor of these breads as a result of the original properties of the hazelnut skin and modified starches.

4 | CONCLUSION

This study focused on the physical, chemical, textural, and sensory differences between various levels of hazelnut skin and modified starch used in sourdough breads. The addition of hazelnut skin to sourdough bread increased ash content, fat content, crumb darkness, loaf volume, and slice area. The use of hazelnut skin also decreases the bread's hardness, gumminess, chewiness, and crumb appearance with no significant influence on wrapper length, cell wall thickness, and resilience. The color values, loaf volumes, textural properties, and crumb structure of bread made with cross-link and oxidized starches were similar to the control bread. Although the use of modified starches alone did not cause significant differences, the interactions between hazelnut skin and modified starches did cause some significant differences when used together. Even though the loaf volume partially increased with the use of modified starches in hazelnut skin-free breads, the use of modified starches, especially oxidized starch, with hazelnut skin had a decreasing effect on loaf volume. Accordingly, some of the phenolic compounds present in hazelnut skin that oxidize sulfhydryl bonds can form a complex with modified starches, resulting in a weak gluten network. Bread samples with both hazelnut skin and modified starch showed higher hardness values compared to samples containing hazelnut skin.

Similarly, the modified starches appeared to interact with hazelnut skin, improving chewiness. Higher concentrations of hazelnut skin resulted in slightly low sensory properties; however, the use of modified starches with hazelnut skin improved the sensory properties, notably for crumb appearance. The findings in this study can conclude that the use of hazelnut skin in sourdough bread can help improve bread quality when used at certain levels and that modified starches positively affect bread texture and sensory properties due to their interaction with phenolic compounds and dietary fiber. In this study, the changes in bread quality characteristics were determined by using two different modified starches and hazelnut skin together. Future research could examine the effects of different modified starch types and side-products with phenolic compound content on bakery products.

ACKNOWLEDGMENTS

The authors would like to thank Kristin Whitney and DeLane Olsen for their technical help.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

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

ORCID

Senay Simsek https://orcid.org/0000-0003-0238-5947

REFERENCES

AACC. (2010). Approved methods of the American association of cereal chemists. 11th ed. Method 08-01.01. Ash-Basic method. Approved April 13, 1961. Method 44-15.02. Moisture-Air-oven methods. Approved April 13, 1961. revised November 3, 1999. Method 02-52.01. Hydrogen-Ion Activity (pH)-Electrometric Method. Approved April 13, 1961, revised November 3, 1999. Method 02-31.01 Titratable Acidity. Approved November 8, 2000. Method 46-30.01. Crude protein-combustion method. Approved November 8, 1995. Method 10-05.01. Guidelines for measurement of volume by rapeseed displacement. Approved October 17, 2001. Available online only. AACCI: St. Paul, MN, USA.

Akram, N., Pasha, I., Huma, N., & Asghar, M. (2017). Effect of modified cereal starches on dough and bread quality. *Pakistan Journal of Agricultural Sciences*, *54*(1), 145–151. https://doi.org/10.21162/Pakjas/17.5741

Anil, M. (2007). Using of hazelnut testa as a source of dietary fiber in breadmaking. *Journal of Food Engineering*, *80*(1), 61–67. https://doi.org/10.1016/j.jfoodeng.2006.05.003

AOCS. (1998). Official methods of analysis, 16th ed. Method Ba 3-38. American Oil Chemists' Society: Arlington, VA, USA.

Aplevicz, K. S., Ogliari, P. J., & Sant'Anna, E. S. (2013). Influence of fermentation time on characteristics of sourdough bread. *Brazilian Journal of Pharmaceutical Sciences*, *49*(2), 233–239. https://doi.org/10.1590/S1984-82502013000200005

Bemiller, J. N., & Whistler, R. L. (2009). *Starch chemistry and technology* (p. 853). Academic Press.

Boita, E. R., Oro, T., Bressiani, J., Santetti, G. S., Bertolin, T. E., & Gutkoski, L. C. (2016). Rheological properties of wheat flour dough and pan bread with wheat bran. *Journal of Cereal Science*, *71*, 177–182.

Bourekoua, H., Różyło, R., Gawlik-Dziki, U., Benatallah, L., Zidoune, M. N., & Dziki, D. (2017). Evaluation of physical, sensorial, and antioxidant properties of gluten-free bread enriched with Moringa Oleifera leaf powder. *European Food Research and Technology*, *244*(2), 189–195. https://doi.org/10.1007/s00217-017-2942-y

Chattopadhyay, S., Singhal, R. S., & Kulkarni, P. R. (1997). Optimisation of conditions of synthesis of oxidised starch from corn and amaranth for use in film-forming applications. *Carbohydrate Polymers*, *34*(4), 203–212.

Cikrikci, S., Demirkesen, I., & Mert, B. (2016). Production of hazelnut skin fibres and utilisation in a model bakery product. *Quality Assurance and Safety of Crops & Foods*, *8*(2), 195–206.

Coda, R., Varis, J., Verni, M., Rizzello, C. G., & Katina, K. (2017). Improvement of the protein quality of wheat bread through faba bean sourdough addition. *LWT - Food Science and Technology*, *82*, 296–302. https://doi.org/10.1016/j.lwt.2017.04.062

Contini, M., Baccelloni, S., Massantini, R., & Anelli, G. (2008). Extraction of natural antioxidants from hazelnut (*Corylus avellana L.*) shell and skin wastes by long maceration at room temperature. *Food Chemistry*, *110*(3), 659–669. https://doi.org/10.1016/j.foodchem.2008.02.060

De Vuyst, L., Vrancken, G., Ravyts, F., Rimaux, T., & Weckx, S. (2009). Biodiversity, ecological determinants, and metabolic exploitation of sourdough microbiota. *Food Microbiology*, *26*(7), 666–675.

Demirkesen, I., Campanella, O. H., Sumnu, G., Sahin, S., & Hamaker, B. R. (2013). A study on staling characteristics of gluten-free breads prepared with chestnut and rice flours. *Food and Bioprocess Technology*, *7*(3), 806–820. https://doi.org/10.1007/s11947-013-1099-3

Durmus, Y., Anil, M., & Simsek, S. (2021). Effects of hazelnut skin, cross-linked starch, and oxidized starch on wheat flour and dough quality. *Journal of Food Processing and Preservation*, *45*(2), e14919.

Durmus, Y., Anil, M., & Simsek, S. (2023). Discrimination of glutopeak test and mixograph parameters for evaluation of wheat flour supplemented with hazelnut skin, cross-linked starch, and oxidized starch. *Food*, *12*(2), 328.

Durmus, Y., Whitney, K., Anil, M., & Simsek, S. (2023). Enrichment of sourdough bread with hazelnut skin, cross-linked starch, or oxidized starch for improvement of nutritional quality. *Journal of Food Process Engineering*, e14361.

Gómez, M., Ronda, F., Blanco, C. A., Caballero, P. A., & Apesteguía, A. (2003). Effect of dietary fibre on dough rheology and bread quality. *European Food Research and Technology*, *216*(1), 51–56. https://doi.org/10.1007/s00217-002-0632-9

Ibrahim, O. (2016). Influence of corn and millet starches as fat substitutes on cake quality. *International Journal of Nutrition and Food Sciences*, *5*(5), 352. https://doi.org/10.11648/j.ijnfs.20160505.16

Júnior, M. S. S., Bassinello, P. Z., Lacerda, D. B. C. L., Koakuzu, S. N., Gebin, P. F. C., de Lima Junqueira, T., & Gomes, V. A. (2008). Technological and physical characteristics of breads made with toasted rice meal. *Semina: Ciências Agrárias*, *29*(4), 815–828.

Kang, N., Reddy, C. K., Park, E. Y., Choi, H.-D., & Lim, S.-T. (2018). Antistaling effects of hydrocolloids and modified starch on bread during cold storage. *LWT - Food Science and Technology*, *96*, 13–18. https://doi.org/10.1016/j.lwt.2018.05.009

Kuakpetoon, D., & Wang, Y.-J. (2001). Characterization of different starches oxidized by hypochlorite. *Starch*, *53*(5), 211–218. https://doi.org/10.1002/1521-379x(200105)53:5<211::Aid-star211>3.0.Co;2-m

Lebesi, D. M., & Tzia, C. (2011). Effect of the addition of different dietary fiber and edible cereal bran sources on the baking and sensory characteristics of cupcakes. *Food and Bioprocess Technology*, *4*(5), 710–722.

Lee Yeo, L., & Seib, P. A. (2009). White pan bread and sugar-snap cookies containing wheat starch phosphate, a cross-linked resistant starch. *Cereal Chemistry*, *86*(2), 210–220.

Mohapatra, D., Bira, Z. M., Kerry, J. P., Frías, J. M., & Rodrigues, F. A. (2010). Postharvest hardness and color evolution of white button mushrooms (Agaricus bisporus). *Journal of Food Science*, *75*(3), 146–152.

Ning, J., Hou, G. G., Sun, J., Wan, X., & Dubat, A. (2017). Effect of green tea powder on the quality attributes and antioxidant activity of whole-wheat flour pan bread. *LWT—Food Science and Technology*, *79*, 342–348. https://doi.org/10.1016/j.lwt.2017.01.052

Noort, M. W. J., van Haaster, D., Hemery, Y., Schols, H. A., & Hamer, R. J. (2010). The effect of particle size of wheat bran fractions on bread quality – Evidence for fibre–protein interactions. *Journal of Cereal Science*, *52*(1), 59–64. https://doi.org/10.1016/j.jcs.2010.03.003

Onyango, C., Mutungi, C., Unbehend, G., & Lindhauer, M. G. (2011). Rheological and textural properties of sorghum-based formulations modified with variable amounts of native or pregelatinised cassava starch. *LWT-Food Science and Technology*, *44*(3), 687–693.

Rodriguez-Sandoval, E., Otálvaro-Arenas, J. A., & Hernandez, V. (2017). Bread quality of flours substituted with modified cassava starches. *Starch*, *69*(5–6), 1600253. https://doi.org/10.1002/star.201600253

Różyło, R., Rudy, S., Krzykowski, A., & Dziki, D. (2015). Novel application of freeze-dried amaranth sourdough in gluten-free bread production. *Journal of Food Process Engineering*, *38*(2), 135–143.

Sandhu, H. P., Manthey, F. A., & Simsek, S. (2011). Quality of bread made from ozonated wheat (*Triticum aestivum L.*) flour. *Journal of the Science of Food and Agriculture*, *91*(9), 1576–1584. https://doi.org/10.1002/jsfa.4350

Scanlon, M., & Zghal, M. (2001). Bread properties and crumb structure. *Food Research International*, *34*(10), 841–864.

Shahidi, F., Alasalvar, C., & Liyana-Pathirana, C. M. (2007). Antioxidant phytochemicals in hazelnut kernel (*Corylus avellana L.*) and hazelnut byproducts. *Journal of Agricultural and Food Chemistry*, *55*(4), 1212–1220. https://doi.org/10.1021/jf062472o

Shukri, F. S. A., Refai, S. A., Shukri, R., Muhammad, K., Mustapha, N. A., Ibadullah, W. Z. W., & Ramli, N. S. (2017). Dough rheology and physicochemical properties of steamed buns fortified with cross-linked rice starch. *Bioactive Carbohydrates and Dietary Fibre*, *12*, 1–6.

Toufeili, I., Habbal, Y., Shadarevian, S., & Olabi, A. (1999). Substitution of wheat starch with non-wheat starches and cross-linked waxy barley starch affects sensory properties and staling of Arabic bread. *Journal of the Science of Food and Agriculture*, *79*(13), 1855–1860. https://doi.org/10.1002/(sici)1097-0010(199910)79:13<1855::Aid-jsfa446>3.0.Co;2-2

Turfani, V., Narducci, V., Durazzo, A., Galli, V., & Carcea, M. (2017). Technological, nutritional and functional properties of wheat bread enriched with lentil or carob flours. *LWT - Food Science and Technology*, *78*, 361–366. https://doi.org/10.1016/j.lwt.2016.12.030

Velioglu, S. D., Güner, K. G., Velioğlu, H. M., & Çelikyurt, G. (2017). The use of hazelnut testa in bakery products. *Journal of Tekirdag Agricultural Faculty*, *14*(3), 127–139.

How to cite this article: Durmus, Y., Anil, M., & Simsek, S. (2024). Innovative use of hazelnut skin and starch modifications in sourdough bread formulation. *Journal of Food Process Engineering*, *47*(1), e14517. https://doi.org/10.1111/jfpe.14517