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Research Article

Nutritional, Textural, Color and Sensory Characteristics of Chips with Hazelnut Flour and Skin: Effects of Baking Conditions and Substitution Levels

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ABSTRACT

This study aimed to improve wheat chips' nutritional value by incorporating hazelnut flour and hazelnut skin. Chips were produced with wheat flour (control) and with partial substitution of wheat flour by hazelnut flour (HF) or hazelnut flour plus hazelnut skin (HFS) at 20, 30, and 40% concentrations, then baked at 180, 200, and 220 °C for various durations. The effects of HF/HFS addition on raw dough's physicochemical properties, as well as chips' moisture content, weight loss, color, texture, and sensory attributes, were studied. Adding HF/HFS increased protein, fat, ash, and mineral contents. Baking conditions and substitution levels significantly affected chips quality. Inclusion of HF/HFS resulted in higher weight loss during baking, a darker, more reddish-brown appearance, and lower fracture force and deformation at fracture values corresponding to a softer and more brittle structure. Significant correlations among instrumental and sensory properties were identified via Pearson's correlation and principal component analysis.

Keywords: Chips, Pearson's correlation, principal component analysis, textural analysis, sensory evaluation

Fındık Unu ve Zarı Eklenmiş Cipslerin Besinsel, Tekstürel, Renk ve Duyusal Özellikleri: Pişirme Koşulları ve İkame Seviyelerinin Etkileri

ÖZ

Bu çalışma, buğday cipslerinin besin değerini, fındık unu ve fındık zarı ekleyerek artırmayı amaçlamıştır. Cipsler, buğday unuyla (kontrol), buğday ununun kısmen fındık unuyla (HF) veya fındık unu ve fındık zarı karışımıyla (HFS), %20, %30 ve %40 konsantrasyonlarında kısmen ikame edilmesinin ardından, 180, 200 ve 220 °C'de farklı sürelerde pişirilmesi ile üretilmiştir. HF/HFS ilavesinin, çiğ hamurların bazı fizikokimyasal özellikleri ile cipslerin nem içeriği, ağırlık kaybı, renk özellikleri, tekstürel ve duyusal özellikleri üzerindeki etkileri çalışılmıştır. HF/HFS ilavesi, protein, yağ, kül ve mineral içeriklerinde artış sağlamıştır. Pişirme koşulları ve ikame seviyesi cips kalitesini önemli derecede etkilemiştir. HF/HFS ilavesi, pişirme sırasında daha yüksek ağırlık kaybına, daha koyu ve kırmızımsı-kahverengi bir görünüme, ayrıca daha yumuşak ve daha gevrek bir yapıya karşılık gelen daha düşük kırılma kuvveti ve kırılma deformasyonu değerlerine yol açmıştır. Pearson korelasyonu ve temel bileşen analizi ile enstrümantal ve duyusal özellikler arasında anlamlı ilişkiler belirlenmiştir.

Anahtar Kelimeler: Cips, Pearson korelasyon, temel bileşen analizi, tekstürel analiz, duyusal değerlendirme

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Nutritional, Textural, Color and Sensory Characteristics of Chips with Hazelnut Flour and Skin: Effects of Baking Conditions and Substitution Levels

Introduction

Hazelnuts (*Corylus avellana* L.) are among the most consumed nuts worldwide. Hazelnuts are rich in essential nutrients and bioactive compounds, making them a highly valued food with potential health benefits (Brown et al., 2022). They are an excellent source of unsaturated fatty acids, proteins, dietary fiber, vitamins (especially vitamin E), minerals, and antioxidants like phenolic compounds (Karaosmanoglu, 2022). Türkiye is the largest producer of hazelnuts in the world, with a total production of approximately 765,000 tonnes in 2022 (FAOSTAT, 2022). Hazelnuts are typically enjoyed raw or roasted as snacks though this accounts for only a small portion of total hazelnut consumption. Globally, the majority of hazelnuts are processed, which enhances their shelf life and broadens their usage in various food industries. Hazelnut flour is one of the most important hazelnut products. It is obtained by finely grinding natural or roasted hazelnuts. Its use as a substitute for traditional flours has gained interest due to its high nutrient density, gluten-free nature, and its potential to improve the functional and sensory qualities of food. Hazelnut flour has been successfully incorporated into, cakes, cookies, bread to increase fiber, protein, and healthy fat content, making the resulting products more nutritious and satisfying (Dogruer et al., 2023; Tuna et al., 2023; Pycia and Ivanišová, 2020; Yazar, 2024).

Hazelnut processing generates several types of waste, primarily during the shelling, oil extraction, and roasting processes. Hazelnut skin, the brown skin surrounding the kernel, constitutes about 2.5% of the kernel's weight and becomes a by-product after roasting (Ceylan et al., 2022). Hazelnut skin gained attention due to its nutritional and functional properties. Hazelnut skins are particularly rich in dietary fiber, phenolic compounds, known for their antioxidant properties, vitamin E, oleic and linoleic acids (Ceylan et al., 2023; Zhao et al., 2023). Studies have shown that hazelnut skins contain 168 to 378 times more total phenolic compounds and approximately 69.8% more total dietary fiber compared to hazelnut kernel (Zhao et al., 2023). Incorporating hazelnut skins into food products can boost their fiber content and enhance their antioxidant activity, contributing to better health outcomes. Some researchers investigated the potential use of hazelnut skin in different foods including yoghurt, ice cream, chicken burger, pork burger, chocolate spread (Ceylan et al., 2023; Ollani et al., 2024). Several researchers have explored the use of hazelnut flour in bakery products including cake (Yazar, 2024), crackers (Kömürcü, 2023), shortbread cookie (Costantini et al., 2023). While previous studies have explored the use of hazelnut skin in different food systems, limited research has been conducted on its application in wheat-based snacks like cookies and chips. Costantini et al. (2023), investigated adding hazelnut skin (5, 10%) to shortbread cookies as a partial butter replacement, analyzing fatty acid composition and conducting sensory evaluations. Their findings revealed the potential of hazelnut skin to enhance the nutritional value of cookies by increasing unsaturated fats, while maintaining acceptable sensory characteristics at a 5% addition level. Durakli Velioglu et al. (2017), assessed the color, total phenolic content, and sensory properties of bread, cookie, and cake samples made with hazelnut skin. Cookies with an 8% addition of hazelnut skin received the highest scores for color, aroma, and taste. These studies focus on sensory and nutritional aspects and do not include instrumental textural measurements. The texture of bakery products is often one of the most affected properties when by-products rich in fiber or oil are added to formulation (Gagneten et al., 2023). Instrumental textural measurements provide objective, repeatable, and quantifiable data and help speed up the product development process by reducing the time required for extensive sensory testing.

The baking process is a complex interplay of physical and chemical reactions that fundamentally transforms raw ingredients into a desirable final product, with these reactions significantly influencing overall quality (Cappelli et al., 2021). Key processes, such as the Maillard reaction and starch gelatinization, contribute to the development of flavor, texture, and appearance (Cappelli et al., 2021). However, the efficacy of these reactions is heavily dependent on baking conditions, including temperature and time. Optimal management of these factors is crucial; poorly controlled conditions can lead to over- or under-baked goods, which not only compromise the quality of the product but also results in waste. Furthermore, inefficient baking practices can escalate energy consumption, negatively impacting both costs and environmental sustainability. By focusing on different formulations and baking conditions, this research could provide valuable insights into how hazelnut-derived ingredients can be effectively utilized to create healthier, more nutritious snack products.

The aim of this study was to investigate the effects of replacing wheat flour with hazelnut flour (HF) and hazelnut flour plus skin (HFS) at substitution levels of 20%, 30%, and 40%, as well as the effects of different baking conditions, including temperatures (180, 200 and 220 °C) and baking times (4, 5 and 6 min), on the moisture content, weight loss, texture, and color of the chips. Additionally, the physicochemical properties of the raw doughs were examined, and sensory analysis was conducted to evaluate the overall acceptability of the chips.

Materials and methods

Materials

Commercial wheat flour used for bread making was kindly provided by Ünsan Flour Factory (Ünye, Ordu, Türkiye). Hazelnut skin was generously supplied by Gürsoy A.Ş. (Perşembe, Ordu, Türkiye), and roasted hazelnut flour was obtained from Fiskobirlik Efit A.Ş. (Giresun, Ordu, Türkiye). Salt and sunflower oil in the formulation were purchased from local markets. All other chemicals used were of analytical grade. The water used for preparing dough mixtures and all solutions was deionized water.

Preparation of dough and baking procedure

Chips dough contained 100% of flour, 5% of sunflower oil, 2% of salt, and 35% of water on flour weight basis. While preparing the chips formulations, the percentages of water, oil, and salt were kept constant, and the total flour content was adjusted based on the addition of hazelnut flour and hazelnut skin, as shown in Table 1. The chips dough was prepared using a kitchen-type dough mixer (5K45SS, KitchenAid, Michigan, USA). After weighing all the ingredients except water into the mixing bowl, they were mixed at speed 2 for 30 seconds. The water in the dough formulation was added gradually in three stages, and the mixing process was repeated three times. After all the water was added, the mixture was kneaded first at speed 2 for 120 seconds, followed by speed 4 for 90 seconds to obtain the chips dough. The prepared chips dough was wrapped with plastic wrap and left to rest in the dark for 30 min at room temperature to ensure proper hydration. The rested dough was rolled out progressively using a pasta machine (Atlas 150, Marcato, Italy). The dough, rolled out to a suitable thickness (1 mm), was cut using a cylindrical mold with a 4.5 cm diameter. To prevent puffing during baking, 50 small holes were made on the surface of the raw chips. The shaped doughs were baked in a home-type conventional oven (MF44EI, Arçelik, Türkiye) with adjustable temperature and baking time settings. The baking time and temperature were determined based on preliminary trials, and the raw chips were baked at three different temperatures (180, 200 and 220 °C) and for three different durations (4, 5 and 6 min). Nine chips were baked at a time in the oven, which was preheated to the specified temperature, and then, cooled at room temperature for 3 minutes on a paper towel.

Table 1. Chips formulations

Ingredients (%)	**C***	**HF20**	**HF30**	**HF40**	**HFS20**	**HFS30**	**HFS40**
Wheat flour	100	80	70	60	80	70	60
Hazelnut flour	-	20	30	40	16	24	32
Hazelnut skin	-	-	-	-	4	6	8
Water	35	35	35	35	35	35	35
Oil	5	5	5	5	5	5	5
Salt	2	2	2	2	2	2	2

*C (control) denotes chips made from only wheat flour; HF20, HF30 and HF40 denote chips made from 20%, 30% and 40% of hazelnut flour substituted with wheat flour, respectively; HFS20, HFS30 and HFS40 denote chips made from 20%, 30% and 40% of hazelnut flour+ hazelnut skin substituted with wheat flour, respectively.

Protein, fat, ash and mineral content of doughs

Ash, fat, and protein content of samples were determined according to AOAC official methods 942.05, 991.36 and 955.04, respectively (AOAC, 2000). The protein content (N x 6.25) was determined utilizing the Kjeldahl method based on the total nitrogen (N) content. The fat analysis was conducted using a Soxhlet apparatus (SER 148, Velp Scientifica, Italy) with n-hexane as the solvent. The ash content of the samples was determined through incineration in an ash furnace (2h at 600 °C). Pre-dried samples (for moisture determination) were utilized for the ash analysis. The analysis of K, Ca, Mg, and Na elements was performed using Inductively Coupled Plasma - Mass spectrometry (ICP-MS) (820-MS; Bruker, Germany) (Tokalıoğlu, 2012).

Moisture content of chips

The moisture content of chips samples was determined using a moisture analyzer equipped with a halogen lamp (MAC 50/1, Radwag, Radom, Poland) at 110°C. For this analysis, 1 g of chips sample cut into small pieces was utilized. The results were reported as the arithmetic mean of the moisture content data obtained from five chips (Kanar and Mazı, 2019).

Weight loss of chips

The percentage of weight loss was determined by calculating the difference between the initial weight of the chips and their weight after baking. The mass of the baked chips was measured following a one-hour cooling period at ambient temperature (Akyüz, 2016).

Textural analysis

The textural properties of the chips samples were determined one hour after baking, using a texture analyzer (TA-XT plus, Stable Micro System, England) while maintaining their original shape. The chips sample was horizontally centered on a 2-inch cylindrical platform, and the analysis was performed using a 1-inch (P/1S) spherical aluminum probe. The test parameters were as follows: pre-test speed: 3 mm/s, test speed: 1 mm/s, post-test speed: 10 mm/s, compression distance: 15 mm, and trigger type: automatic 0.05 N. The maximum force (N) at break was expressed as the fracture force (FF) value. Deformation distance (mm) was expressed as deformation at fracture (DF) (Taşkırdı, 2011). The results were reported as the arithmetic mean of the textural data obtained from five chips.

Color analysis

The color measurements of the chips samples were conducted using L* (lightness-darkness), a* (redness-greenness), and b* (yellowness-blueness) values with a PCE CSM1 color measurement device (Wrolstad and Smith, 2010). Prior to the color measurements, a white calibration plate was used to standardize the device. Color measurements were taken at five different points on both the upper and lower surfaces of four randomly selected samples.

Sensory analysis

The sensory properties of the samples were evaluated by a semi-trained panel consisting of 10 individuals. Panelists were selected from male and female candidates who do not smoke and do not have allergies to hazelnuts or other components. The panelists were asked to evaluate the surface color, hardness (the force necessary to bite the chips), crispness (the sharp sound when the chips is bitten), fracturability (how easily chips break when it is bitten) (Segnini et al., 1999), odor, and overall liking of the samples using a 9-point hedonic scale (9: Like extremely, 8: Like very much, 7: Like, 6: Like moderately, 5: Neither like nor dislike, 4: Dislike slightly, 3: Dislike, 2: Dislike very much, 1: Dislike extremely). The average scores given by the panelists for each sample were calculated and analyzed (Onoğur Altuğ and Elmacı, 2015). Sensory results which were used in Pearson's correlation and principal component analysis, were not shown.

Statistical Analysis

The data were assessed using a one-way and/or two-way analysis of variance (ANOVA). Differences among individual means were compared by using Tukey Comparison test ($p \leq 0.05$) (Minitab, Version 17). Pearson's correlation coefficients were calculated between all instrumental and sensory data. A principal component analysis (PCA) of the measured properties of the chips was conducted for identification of the number of principal components that have a significant impact on differentiating between the various chips samples and also for a clear visualization of the relationships among the samples.

Results and Discussion

Physico-chemical properties of the doughs

Dough formulations containing HF or HFS showed 4.0–13.1% higher protein, 8.9–17.8% higher ash, and 2.5–4.5 times higher fat content compared to the control (Table 2). The higher protein and fat contents in doughs containing HF/HFS were as expected, as hazelnut flour typically provides more protein and fat than wheat flour, thereby boosting the overall protein and fat levels in the dough formulations. The major commercial Turkish hazelnut varieties are reported to contain protein levels ranging from 18.3% to 22.1% and fat content between 57.4% and 62.9% (Ozdemir and Akinci, 2004). On the other hand, the protein and fat contents of flours from different wheat cultivars range from 9.0% to 12.3% and 2.6-3.5%, respectively (Punia et al., 2019). Hazelnut skins typically have a lower protein and fat contents compared to the kernels. According to Ceylan et al. (2023), the protein content of hazelnut skins ranges from 7.5% to 9.4% (wt%, db.), while the fat content ranges from 10.98% to 21.20% (wt%, db.). Overall, there was no statistically significant difference between the moisture, protein, and ash contents between HF and HFS-containing doughs; however, the fat content differed significantly. As the substitution levels increase, more hazelnut oil is incorporated into the dough, explaining the gradual fat increase. At comparable substitution levels, HF-containing doughs had higher fat content than HFS-containing ones. This is because the skin of the hazelnut (present in HFS) has less fat than the kernel itself.

HF or HFS-containing doughs had significantly higher mineral (K, Ca, Mg, Na) content compared to the control (Table 2). The largest difference was observed in K content, with HF or HFS doughs showing 2.5–4.1 times higher K levels, 1.6–2.3 times higher Ca, 1.8–2.8 times higher Mg, and 1.3–1.7 times higher Na compared to the control. Wheat flour contains approximately 1400-3000 mg/kg of K, 200-400 mg/kg of Ca, 15.8-30.4 mg/kg of Mg (Ekinci and Ünal, 2002). Hazelnut kernels are known to contain higher amounts of these minerals, with concentrations of K ranging from 5516 to 6637 mg/kg, Ca from 2228 to 2665 mg/kg, Mg from 1588 to 1867 mg/kg, and Na from 379.5 to 508.5 mg/kg (Ozdemir and Akinci, 2004). Hazelnut skin is also a rich source of essential minerals, though its mineral content is lower compared to that of the hazelnut kernel (K:159 mg/kg; Ca:858 mg/kg; Mg:1140 mg/kg; Na: 605 mg/kg) (Ceylan et al., 2023). This accounts for the significant increases observed in HF and HFS containing-doughs compared to control. The overall trends suggest that the substitution of wheat flour with hazelnut flour (with or without skin) increased the nutritional profile of the dough.

The addition of HF or HFS led to a notable reduction in L* values (lightness) and an increase in a* (redness) with greater HF or HFS levels further decreasing L* (Table 2). Roasted hazelnut flour was used in this study. Roasting process causes a reduction in L* value and an increase in a* and b* values of hazelnut kernels. These changes in color parameters depend on the roasting conditions (Turan et al., 2015). In this study, the L*, a*, b *values of the hazelnut flour were measured as 72.3±0.6, 7.2±0.4, and 25.2±0.6, while the L*, a*, b* values of the wheat flour were measured as 95.8±0.1, -3.7±0.7, and 10.8±0.3, respectively. Consequently, doughs containing HF had a darker, more red, and more yellow color. HFS-containing doughs had lower lightness and yellowness values than control and HF- containing doughs. This was due to the natural brown color of hazelnut skin. Hazelnut skin had L*, a*, b* values of 29.1±0.9, 18.8±0.5, and 22.7±0.9, respectively. Brown color of hazelnut skin caused darker color and can overshadow the natural yellowness from other ingredients in the dough formulation. This can result in a lower b* value (indicating less yellowness) in the hazelnut skin-containing formulations.

Table 2. Physico-chemical properties of the doughs on dry weigh basis

Property(%)	**C**	**HF20**	**HF30**	**HF40**	**HFS20**	**HFS30**	**HFS40**
Moisture	29.2±1.5a′	25.7±1.2b	25.2±0.5b	23.3±1.3b	24.9±0.6b	25.2±1.4b	23.8±1.3b
Protein	12.0±0.5c	12.8±0.1abc	13.2±0.2ab	13.6±0.0a	12.5±0.2bc	12.7±0.0abc	12.9±0.2abc
Fat	7.1±0.4g	19.9±0.1e	26.0±0.4c	32.1±0.7a	17.7±0.0f	22.8±0.3d	27.8±0.5b
Ash	2.8±0.0b	3.1±0.1ab	3.2±0.1a	3.3±0.1a	3.1±0.1ab	3.2±0.1a	3.3±0.1a
Mineral (mg/100g)							
K	84.6±6.3c	217.0±23.0b	283.2±31.3ab	349.4±39.7a	210.2±21.5b	273.1±29.2ab	335.9±36.8a
Ca	13.0±3.4b	21.5±5.2a	25.7±6.1a	30.0±7.1a	21.0±5.1a	25.0±6.0a	29.0±6.9a
Mg	25.6±2.1d	48.4±1.6c	59.8±3.4abc	71.2±5.2a	47.1±1.4c	57.8±3.1bc	68.6±4.8ab
Na	7.8±0.1b	10.4±0.5ab	11.8±0.8a	13.1±1.0a	10.3±0.5ab	11.5±0.8a	12.8±1.0a
Color							
L*	73.9±0.6a	63.0±0.4b	61.7±1.4b	59.6±0.9c	41.3±0.3d	37.2±0.6e	30.7±0.4f
a*	3.5±0.2e	6.5±0.1d	6.9±0.1c	7.8±0.2ab	8.0±0.2a	7.6±0.2b	6.8±0.0cd
b*	15.7±0.3b	20.0±0.8a	20.5±0.3a	20.8±0.6a	8.5±0.2c	7.2±0.2d	4.5±0.2e

Values represent mean±standard deviation. ′Different small case letters in the same row indicates significant difference between doughs (p≤0.05).

Weight loss and moisture content

The moisture contents of raw doughs ranged from 23.84 to 29.19% (Table 2). Control dough had 11.9–20.3% lower moisture compared to HF/HFS-containing doughs. During baking, a substantial amount of moisture is lost, primarily due to the evaporation of water from the dough. This evaporation is a major factor contributing to the weight loss of samples during baking. Additionally release of other volatile compounds associated with Maillard reaction may occur, further reducing the mass (Canali et al., 2020). In this study, baking resulted in weight losses ranging from 13.8 to 30.9% (Table 3). Weight loss increased almost linearly with baking time and temperature ($R^2 \geq 0.78$). Final moisture contents of chips ranged from 0.97 to 18.96% (Table 4). Baking temperature and time had a significant influence on both weight loss and moisture content of all samples (Table 3,4). As expected, higher baking temperatures and extended baking times led to greater weight loss and, consequently, reduced moisture content in the final product. The decrease in moisture content with increasing baking time was almost linear, with $R^2 \geq 0.91$ at 180°C, $R^2 \geq 0.84$ at 200°C, and $R^2 \geq 0.79$ at 220°C.

Inclusion of HF or HFS in formulation led to greater weight loss compared to the control, although this increase was not statistically significant under all baking conditions. For example, at baking conditions of 200 °C or 220 °C for 6 min, the weight loss of the control was statistically similar to the other samples; however, at 200 °C for 4 or 5 min, the control showed significantly lower weight loss. Accordingly, the HF and HFS chips generally had less moisture content than the control under the specified baking condition. However, an exception occurred at 220 °C for 6 min, where all chips exhibited similar moisture levels, ranging from 0.97% to 1.40% (Table 4). The water retention of dough is significantly influenced by its protein, fiber, and fat content (Gomez et al., 2008). Fats in hazelnut flour may interfere with water retention by altering the dough structure and reducing the water-binding capacity of the matrix (Arepally et al., 2020). Agyare et al. (2005), reported that the addition of shortening to soft wheat flour dough caused a significant reduction in dough resistance to deformation, dough extensibility, and baking strength, indicating a less developed gluten network. Moreover, hazelnut flour contains high amount of non-gluten proteins. Gluten can form a network capable of trapping water and gases, which helps in moisture retention. The incorporation of non-gluten proteins weakens wheat dough, as observed by Roccia et al. (2009) and Ribotta et al. (2006). This weakening is attributed to the competition between non-gluten proteins and gluten for water molecules, which disrupts the gluten network formation. The higher fat content and absence of gluten and in hazelnut flour could lead to a weaker structure, leading to increased evaporation of water and higher weight loss during baking. On the other hand, at high temperatures and longer baking times, all samples, regardless of composition, lose most of their moisture, making any additional effects from HF or HFS minimal.

Table 3. Weight loss (%) of chips

T(°C)	t(min)	C	HF20	HF30	HF40	HFS20	HFS30	HFS40
180	4	13.86±1.88c*	16.90±1.34bc	19.10±1.72ab	22.79±1.76a	17.91±0.74bc	20.41±0.87ab	23.73±0.26a
	5	19.37±1.98c	19.99±1.55bc	24.57±0.02ab	25.50±1.68a	25.04±0.61a	25.11±1.80a	25.66±0.66a
	6	23.34±1.55b	26.38±1.44ab	27.52±0.81a	28.15±0.50a	27.06±1.07a	27.95±1.09a	28.47±0.63a
200	4	14.73±0.68c	20.11±1.78b	23.72±0.80ab	25.99±0.92a	22.88±0.56ab	26.50±0.84a	24.58±1.28a
	5	22.64±1.53b	27.38±1.08a	28.19±1.01a	27.28±1.07a	27.35±0.82a	27.71±0.99a	27.11±0.48a
	6	28.85±0.14a	29.14±0.51a	30.09±0.64a	28.85±0.73a	29.93±0.45a	29.73±0.39a	28.94±0.88a
220	4	20.93±1.41b	26.79±1.83a	24.09±0.75ab	27.26±1.01a	25.54±1.48a	28.04±0.70a	24.93±0.67ab
	5	27.33±1.38b	28.31±0.35a	29.53±0.76ab	28.27±0.54ab	29.99±0.38ab	29.43±0.59ab	29.07±1.19ab
	6	29.85±1.04a	30.48±0.59a	30.80±0.70a	29.93±0.44a	30.20±0.13a	30.90±0.48a	30.68±0.98a
Source		*p-value* (R^2 =0.96)	*p-value* (R^2 =0.95)	*p-value* (R^2 =0.96)	*p-value* (R^2 =0.85)	*p-value* (R^2 =0.97)	*p-value* (R^2 =0.93)	*p-value* (R^2 =0.92)
T		0.000**	0.000	0.000	0.000	0.000	0.000	0.000
t		0.000	0.000	0.000	0.000	0.000	0.000	0.000
T x t		0.068	0.001	0.432	0.376	0.011	0.014	0.315

*Different small case letters in the same row indicates significant difference between chips ($p \leq 0.05$).** $p \leq 0.05$ denotes significant effect of main factors. T: Temperature; t: time.

Table 4. Moisture contents (%) of chips

T(°C)	t(min)	C	HF20	HF30	HF40	HFS20	HFS30	HFS40
180	4	18.96±1.25a*	13.55±0.35b	10.41±0.31c	7.20±0.22d	13.73±0.37b	10.81±0.38c	7.01±0.39d
	5	12.56±0.19a	11.18±0.29b	7.04±0.17c	4.55±0.16e	5.70±0.28d	5.96±0.13d	4.29±0.13e
	6	8.70±0.26a	5.05±0.20b	3.76±0.09c	1.33±0.06g	3.35±0.06d	2.92±0.13e	1.72±0.17f
200	4	15.35±0.76a	11.32±0.32b	8.03±0.22d	3.56±0.11f	9.78±0.39c	5.49±0.14e	5.08±0.02e
	5	10.30±0.15a	4.57±0.04b	3.20±0.08c	1.70±0.00e	3.40±0.10c	2.64±0.20d	1.77±0.10e
	6	4.45±0.11a	2.77±0.13b	1.57±0.12c	1.00±0.10e	1.50±0.10c	1.17±0.09de	1.33±0.06cd
220	4	9.80±0.36a	4.64±0.26c	6.06±0.36b	1.59±0.20e	4.96±0.23c	3.36±0.06d	5.24±0.06c
	5	3.69±0.00a	2.87±0.13b	2.04±0.05c	1.13±0.06f	1.90±0.00cd	1.72±0.09d	1.32±0.05e
	6	1.15±0.17ab	1.40±0.10a	0.97±0.05b	1.00±0.28ab	1.03±0.11ab	1.00±0.08b	1.07±0.15ab
Source		*p-value* (R^2 =0.99)	*p-value* (R^2 =0.99)	*p-value* (R^2 =0.99)	*p-value* (R^2 =0.99)	*p-value* (R^2 =0.99)	*p-value* (R^2 =0.99)	*p-value* (R^2 =0.99)
T		0.000**	0.000	0.000	0.000	0.000	0.000	0.000
t		0.000	0.000	0.000	0.000	0.000	0.000	0.000
T x t		0.000	0.000	0.000	0.000	0.000	0.000	0.000

*Different small case letters in the same row indicates significant difference between chips ($p \leq 0.05$).** $p \leq 0.05$ denotes significant effect of main factors. T: Temperature; t: time.

Except for 220 °C/ 6 min baking condition, among the HF-containing chips, higher HF substitution levels corresponded to lower moisture content. This finding aligns with the results of Dogruer et al. (2023) who reported that higher amounts of raw hazelnut flour with skin caused lower moisture content in cookies. They attributed this to the high oil content of hazelnut flour. For the HFS-containing chips, while an overall decrease in moisture content was observed with increasing HFS levels at both 180 °C and 200 °C, the differences were not statistically significant in all cases. At equivalent substitution levels, differences between the moisture contents of HF and HFS-containing chips varied depending on the baking conditions. Specifically, when baked at 180 °C for 4 min or 220 °C for 6 min, chips with equal amounts of HF and HFS exhibited similar moisture contents. Under all other baking conditions, the general trend was observed as HF20>HFS20, HF30>HFS30, and HF40≤HFS40. This difference was caused by the hazelnut skin present in HFS-containing doughs. Hazelnut skin contains approximately 54-70% dietary fiber, predominantly insoluble (Ceylan et al., 2023). It has been reported that the addition of fibers to wheat flour significantly impacts the rheological properties of dough (Wang et al., 2002).

Fracture Force (FF)

The fracture force (FF) values of the chips are presented in Table 5. FF is related to the material resistance to penetration. A higher FF value indicates higher resistance to fracture. Except for the HFS40 chips, baking time significantly influenced the FF values. The effect of time was particularly pronounced at 180 °C. Baking temperature was also found to be an important factor affecting FF of the chips. Overall, FF values tended to increase with increasing temperature and time due to moisture loss. The effect of temperature was less pronounced in chips baked for 6 min compared to those baked for 4 min. As the chips are baked at higher temperatures for longer periods, they lose more moisture, leading to a firmer texture. The less pronounced effect of temperature at longer baking times suggests that after a certain point, the chips may reach a texture limit where further heat does not significantly increase FF value.

Among all samples, the control chips baked at 180 °C for 4 min had the lowest FF value (0.99 N) while those baked at 220 °C for 6 min had the highest FF value (28.81 N). When extending baking time from 4 to 6 min or increasing the temperature from 180 °C to 220 °C, the most substantial increase in FF was observed in the control chips. That is why it was difficult to draw clear conclusions when comparing the FF of the control chips with those containing HF or HFS. For example, under baking conditions of 180°C for 4/5 min or 200 °C for 4/5 min, control chips had similar or lower FF values compared to HF or HFS-containing ones while under baking conditions of 200/ 220 °C for 6 min, control chips had significantly higher FF values compared to HF or HFS-containing ones. Hazelnut flour and hazelnut skin contain greater amounts of components including fat and fiber, and the presence of these components influence the texture. Many authors stated that higher amount of proteins and fibers cause higher hardness in cookies (Artz et al., 1990; Larrea et al., 2005; Zouari et al., 2016). On the other hand, fat coats the flour, inhibits gluten development, which leads to a more tender and crumbly texture (Arepally et al., 2020). While hazelnut flour/hazelnut skin contain substantial amounts of proteins/fibers that absorb moisture and lead to chips hardening, their high fat content simultaneously contributes to softening, counterbalancing the hardness effect. With the exception of certain conditions (180 °C for 4/5 min and 200 °C for 4 min), the FF values decreased with increasing amount of HF or HFS. This shows that the chips with higher content of HF or HFS had a more fragile structure. This result is in accordance with the results of Dogruer et al. (2023) who found that increasing amount of raw hazelnut flour with skin in cookie formulation provided a lowering effect in hardness value. The general decrease in FF with higher proportions of HF or HFS could be due to the fat content of hazelnut flour/hazelnut skin, which tends to soften the structure of the chips (Arepally et al., 2020). Fat acts as a tenderizing agent, reducing the rigidity of the chips. This effect might be less noticeable in samples baked for shorter times or at lower temperatures but becomes more apparent under extended baking conditions. There were no statistically significant differences in FF for chips with similar amounts of HF and HFS, except for chips baked at 180 °C for 4 and 5 min. This suggests that the presence of the hazelnut skin did not drastically alter the hardness of the chips. The skin's impact on FF may be minor compared to the overall fat composition of the hazelnut flour, which primarily influences the texture.

Deformation at fracture (DF)

The deformation at fracture (DF) values of chips ranged from 0.75 mm to 8.54 mm (Table 6). DF indicates the sample deformation before rupture. A lower DF value corresponds to a more brittle or fragile structure. Both baking time and temperature significantly impacted the DF of the chips, with DF decreasing as baking time and temperature increased. This is as expected since as the chips bake longer or at higher temperatures, they become drier and more brittle, reducing their ability to deform before fracturing. The influence of baking time on DF was more noticeable at 180°C compared to other temperatures, except for the HFS40 sample. Specifically, DF decreased by 35.6–86.9% at 180 °C and by 18.0–46.2% at 220 °C when baking time was extended from 4 to 6 min. This suggests that at lower temperatures, the structure of the chips is more sensitive to extended baking times. Increasing the temperature from 180

°C to 220 °C had a less pronounced effect on DF when baking time was set at 6 min. Some chips exhibited notably higher DF values than others. These included the control samples baked at 180 °C for 4/5 min and at 200 °C for 4 min (8.10–8.54 mm), as well as the HF20 (8.46 mm), HF30 (8.15 mm), HFS20 (7.66 mm), and HFS30 (5.72 mm) samples baked at 180 °C for 4 min, and the HF20 sample baked at 180 °C for 5 min (7.54 mm). This suggest that these chips retained more moisture under given baking conditions, allowing for greater flexibility before breaking. DF values for the other chips ranged from 0.75 mm to 3.33 mm.

Table 5. Fracture force (N) values of chips

T(°C)	t(min)	C	HF20	HF30	HF40	HFS20	HFS30	HFS40
180	4	0.99±0.18c*	5.85±0.71a	3.80±0.85b	4.40±0.74ab	5.78±0.85ab	5.81±1.35a	5.88±1.52a
	5	6.20±1.01d	5.97±0.67d	8.60±0.67c	6.13±0.47d	16.20±3.09a	12.72±0.41b	7.58±1.05cd
	6	16.85±1.72ab	18.51±2.47a	10.29±0.46cd	6.91±1.69d	18.73±1.93a	13.230±0.98bc	7.73±0.64d
200	4	3.26±1.00d	6.70±1.00c	10.83±2.57ab	6.78±1.32c	9.42±1.49bc	13.78±1.78a	9.18±0.90bc
	5	11.02±2.37bc	19.72±3.27a	11.73±1.96b	6.84±1.14c	19.05±2.77a	12.57±0.19b	8.88±0.75bc
	6	25.33±2.34a	18.78±0.70b	12.06±2.05cd	8.86±2.36d	19.25±3.89b	14.51±1.20bc	9.27±1.00d
220	4	14.90±1.76ab	18.53±3.80a	11.17±2.47bc	8.43±2.14c	16.61±2.09a	11.36±1.26bc	8.56±0.96c
	5	27.99±0.93a	20.77±2.16b	12.53±1.14cd	9.60±1.17d	19.77±2.52b	15.99±2.02c	9.40±0.39d
	6	28.81±2.69a	21.16±3.31b	12.99±2.63de	9.98±1.47ef	21.05±1.37bc	16.04±1.40cd	7.13±0.80f
Source		*p-value* (R^2 =0.98)	*p-value* (R^2 =0.93)	*p-value* (R^2 =0.76)	*p-value* (R^2 =0.63)	*p-value* (R^2 =0.86)	*p-value* (R^2 =0.91)	*p-value* (R^2 =0.63)
T		0.000**	0.000	0.000	0.000	0.000	0.000	0.000
t		0.000	0.000	0.000	0.000	0.000	0.000	0.160
T x t		0.000	0.000	0.032	0.629	0.003	0.000	0.006

*Different small case letters in the same row indicates significant difference between chips (p≤0.05).** p≤0.05 denotes significant effect of main factors. T: Temperature; t: time.

Table 6. The values of deformation at fracture (DF)

T(°C)	t(min)	C	HF20	HF30	HF40	HFS20	HFS30	HFS40
180	4	8.54±0.43a*	8.46±1.20a	8.15±1.16a	1.94±0.22b	7.66±3.33a	5.72±3.32a	1.63±0.14b
	5	8.10±0.38a	7.54±1.24a	1.37±0.10 b	1.56±0.28b	1.19±0.22b	1.33±0.18b	1.22±0.16b
	6	1.60±0.47a	1.41±0.22ab	1.27±0.18ab	0.93±0.21b	1.00±0.29b	1.01±0.19b	1.05±0.18b
200	4	8.51±0.72a	2.16±0.40b	1.40±0.21b	1.24±0.05b	3.33±2.86b	1.36±0.32b	1.29±0.04b
	5	1.99±0.73a	1.28±0.08b	1.03±0.28b	1.09±0.05b	0.96±0.05b	1.05±0.19b	1.02±0.07b
	6	1.22±0.16a	1.19±0.27ab	0.81±0.11c	0.90±0.03bc	0.95±0.09abc	0.82±0.12c	0.95±0.11abc
220	4	1.44±0.08a	1.32±0.20ab	1.48±0.23a	0.97±0.14c	1.20±0.08abc	1.08±0.13bc	1.33±0.06ab
	5	1.28±0.19a	1.21±0.14ab	0.91±0.15c	0.80±0.07c	0.90±0.17c	0.98±0.18bc	0.85±0.09c
	6	1.12±0.26a	1.08±0.33ab	0.80±0.09ab	0.75±0.09b	0.92±0.09ab	0.89±0.11ab	0.80±0.14ab
Source		*p-value* (R^2 =0.98)	*p-value* (R^2 =0.96)	*p-value* (R^2 =0.97)	*p-value* (R^2 =0.88)	*p-value* (R^2 =0.72)	*p-value* (R^2 =0.65)	*p-value* (R^2 =0.85)
T		0.000**	0.000	0.000	0.000	0.001	0.002	0.000
t		0.000	0.000	0.000	0.000	0.000	0.001	0.000
T x t		0.000	0.000	0.000	0.000	0.000	0.001	0.204

*Different small case letters in the same row indicates significant difference between chips (p≤0.05).** p≤0.05 denotes significant effect of main factors. T: Temperature; t: time.

In general, the control samples had similar or higher DF values compared to the HF and HFS-containing chips. The presence of HF and HFS likely alters the structural matrix, prevent gluten formation, making the chips less elastic and more prone to fracture at lower deformations. A decreasing trend in DF was observed as substitution levels increased in HF-containing chips, but this trend was not valid in the HFS-containing chips. The substitution level did not influence the DF of HFS-containing chips. The highest DF value was recorded in the control chips baked at 180 °C for 4 min (8.54 mm), while the lowest DF value was found in the HF40 chips baked at 220 °C for 6 min (0.75 mm

Color

Surface color is an important quality feature in bakery products. The development of color in bakery products during baking is commonly referred to as browning, which occurs because of non-enzymatic chemical reactions (Maillard reaction and caramelization). Lightness (L*) is frequently used to describe changes in color during the baking process (Purlis, 2010). As baking progresses, the L* value typically decreases, indicating that the product is becoming darker. Control chips had L* values ranging from 67.9 to 78.5 (Table 7). HF20 chips baked at 180 °C and 200 °C exhibited L* values similar to the control. However, all other chips had significantly lower L* values compared to the control at the given baking conditions. It is thought that this is primarily caused by the darker color of doughs containing hazelnut flour and hazelnut skin compared to control dough (Table 2). Additionally, the Maillard reactions that occur during the baking process also play an important role in color formation. The Maillard reaction is a chemical process that occurs when proteins (amino acids) react with reducing sugars under heat, leading to the browning of the food. This reaction is responsible for developing the characteristic brown color, flavor, and aroma in baked goods. High protein content of hazelnut flour may enhance the Maillard reaction, leading to a deeper browning. As the substitution level increased, HF or HFS contributed more to the overall darkness of the chips. Under a specified baking condition, HFS-containing chips showed lower L* values than HF-containing ones. This was more pronounced at 20% and 30% substitution levels. The darker color of HFS-containing chips was attributed to the presence of hazelnut skin in the formulation. With a few exceptions, it was observed that the L* values decreased with increasing temperature and time. As stated before, Maillard reactions result in darker color in baked products. The degree of heat severity plays a critical role in controlling the extent of the browning reactions (Charissou et al., 2007). At higher baking times and temperatures, the Maillard reaction accelerates, leading to more intense browning.

Control chips showed generally lower a* values (2.9-10.6) than those containing HF (4.5-15.3) or HFS (7.1-10.7) (Table 7). This may be attributed to the higher protein content in HF or HFS-containing doughs which may intensify the Maillard reactions resulting in browning and increase in redness. In general, increasing baking time and temperature raised the a* values, with the highest values observed in chips baked at 200 °C and 220 °C for 6 min. It is widely known that higher temperature and time of heating allows

Table 7. The L*, a*, b*color parameters of chips

T(°C)	t(m@n)	C	HF20	HF30	HF40	HFS20	HFS30	HFS40
L* values								
180	4	72.58±2.28a′	74.26±0.72a	65.46±3.10b	61.99±1.45b	47.33±2.61c	43.12±0.89cd	39.63±0.98d
	5	72.47±0.27a	73.95±1.39a	66.22±3.66b	63.97±1.10b	48.45±1.62c	42.01±0.54d	37.64±1.93e
	6	69.45±2.42a	70.34±1.25a	62.92±1.15b	35.90±0.48e	48.47±1.51c	41.26±1.05d	36.94±1.42e
200	4	70.68±0.27ab	71.60±0.65a	67.30±3.01b	62.82±0.88c	49.35±0.15d	41.39±1.41e	37.15±1.80f
	5	70.61±1.63a	70.55±0.99a	63.46±1.47b	51.93±2.38c	49.18±0.70c	41.39±0.55d	39.09±1.31d
	6	67.96±1.82a	69.18±1.54a	55.74±1.66b	35.44±1.04d	40.66±1.21c	35.20±2.29d	32.27±1.76d
220	4	78.50±1.95a	71.03±0.84b	68.39±1.59b	38.91±4.03d	49.11±0.87c	42.22±1.29d	39.09±1.78d
	5	76.64±1.86a	68.90±1.33b	62.37±3.72c	33.32±3.62f	46.56±1.16d	41.29±1.29e	32.94±0.44f
	6	67.87±0.67a	53.80±2.55b	44.35±2.18c	33.21±1.95de	38.79±2.45cd	27.57±1.22ef	27.16±1.84f
a* values								
180	4	3.29±0.10d	4.55±0.08c	5.64±0.10b	7.32±0.14a	7.26±0.09a	7.49±0.15a	7.34±0.14a
	5	3.75±0.09e	4.50±0.22d	5.76±0.12c	7.46±0.07a	7.08±0.24b	7.40±0.08ab	7.07±0.15b
	6	4.11±0.17c	5.29±0.25c	6.85±1.01b	13.38±0.93a	7.35±0.24b	7.36±0.37b	7.59±0.61b
200	4	3.98±0.16d	5.28±0.15c	5.56±0.28c	7.87±0.59a	7.21±0.33ab	7.09±0.19b	6.90±0.12b
	5	3.83±0.08d	5.55±0.15c	7.07±0.73b	13.89±0.33a	7.21±0.31b	7.67±0.57b	7.60±0.31b
	6	7.50±0.78de	6.52±0.55e	12.39±0.11b	14.43±0.79a	9.03±1.26cd	9.60±0.50c	9.19±0.21c
220	4	2.86±0.15d	5.60±0.19c	5.44±0.11c	13.11±1.27a	6.96±0.10b	7.35±0.29b	7.14±0.17b
	5	3.67±0.65d	6.67±1.03c	10.07±0.52b	14.27±0.85a	8.54±0.70b	8.07±0.64bc	8.53±0.57b

	6	10.59±0.64c	12.88±0.65b	15.27±0.21a	14.69±0.30a	10.67±0.69c	8.33±0.50d	7.95±0.06d
b* values								
180	4	12.38±0.27d	16.05±0.06c	18.08±0.42b	19.51±0.37a	10.06±0.40e	9.76±0.41ef	9.05±0.29f
	5	14.24±0.25d	16.50±0.35c	18.51±0.62b	20.49±0.40a	10.99±0.24e	10.27±0.23e	8.66±0.42f
	6	15.13±0.15b	17.98±0.58a	19.58±0.78a	19.57±1.28a	12.11±0.58c	10.81±0.25c	10.46±1.06c
200	4	14.41±0.41c	17.57±0.20b	18.21±0.36b	20.94±0.77a	10.84±0.46d	9.60±0.30e	8.58±0.57e
	5	13.92±0.69d	18.28±0.50c	20.75±1.09ba	22.88±0.73a	12.20±0.51e	11.51±0.97e	11.01±0.51e
	6	21.41±0.92b	20.41±0.82b	24.89±1.62a	21.73±1.05b	14.65±0.18c	14.17±0.95c	11.77±0.88d
220	4	13.41±0.50c	18.68±0.14b	17.98±0.12b	22.26±1.46a	11.24±0.19d	9.82±0.08e	8.93±0.41e
	5	14.88±0.29c	20.11±1.44b	24.31±0.36a	13.84±0.59cd	14.57±0.48cd	12.47±0.47de	11.55±0.64e
	6	26.78±1.75a	26.06±0.48a	25.14±0.70a	14.83±0.99b	16.67±0.80b	9.50±0.89c	8.65±0.07c

ʹDifferent small case letters in the same row indicates significant difference between chips (p≤0.05). T: Temperature; t: time.

higher rate of Maillard reactions. a* values increased with HF content, but this trend did not apply to HFS-containing chips, where the a* values remained unaffected by the amount of HFS. For HFS-containing chips, the lack of noticeable differences in redness could be due to the dominant color of hazelnut skin masking variations. Except for chips baked at 200 °C and 220 °C for 6 min, HF20 and HF30 chips had similar or lower a* values than their HFS counterparts, but HF40 chips had higher a* values than HFS40, with HF40 chips showing the highest a* values overall. At a specified baking condition, control chips had lower b* values (12.4-26.8) than HF-containing chips (13.8-26.1) except for the HF-containing chips baked at 220 °C for 6 min (Table 7). These chips had similar or lower b* values than the control. Control chips had higher values than HFS-containing ones (8.6-16.7). As stated before, dark brown color of hazelnut skin can overshadow the yellowness parameter indicating less yellowness. At equivalent substitution levels, chips containing HF showed higher b* values than chips containing HFS. Regarding the impact of substitution level, it was found that b* values in HFS-containing chips declined as substitution level increased. In several samples, the reduction was not determined to be statistically significant. On the other hand, there was no discernible pattern in the HF-containing chips. An increase in baking time from 4 to 6 min generally raised the b* values, except for HF40, HFS30, and HFS40 chips baked at 220 °C. Likewise, increasing the baking temperature from 180 °C to 220 °C increased b* values, except for some HF40, HFS30, and HFS40 chips.

Overall, the results highlighted that baking conditions, substitution levels, and the presence of the hazelnut skin are crucial in determining the final appearance of the chips. Inclusion of hazelnut skin in the formulation can significantly impact the color of the final product, with the skin leading to darker, less yellow chips compared to those containing only hazelnut flour. In the sensory analysis regarding surface color, the samples that received the highest preference from panelists were those among the HFS-containing chips. This means that the brownish color of hazelnut skin may be advantageous during their incorporation into certain foods like chips.

Correlation analysis and principal component analysis (PCA) of the sensory and instrumental attributes

Pearson correlation coefficients of the measured instrumental and sensory attributes were presented in Table 8. The moisture contents of chips were positively correlated with the L* and DF values, while negatively correlated with a*, b*, and FF values. A significant positive correlation was found between the sensory texture parameters of hardness, crispness, and fracturability. Sensory texture parameters showed strong negative correlation with MC, L* and DF values and positive correlation with a* and FF values. It means that chips with high FF values and low DF values have higher textural preference. Similarly, there was a strong negative correlation between overall liking and DF of chips. The color preference had a negative correlation with the a* parameter. However, no correlation was found between the overall liking and color properties (instrumental or sensory) of chips.

The results of principle component analysis (PCA) were presented in Table 9. The first two principal components explained 64.5% of the variation. The first principal component (PC1) (with eigenvalue of 5.56) explained 46.3% of total variability, and the second principal component (PC2) (with eigenvalue of 2.18) explained 18.1%. PCA loadings, the correlation or contribution of each original variable to the PCs, above 0.3 was deemed important in this PCA analysis. Based on this, PC1 was strongly correlated with six of the original variables. PC1 increased with increasing hardness (0.389), crispness (0.389), fracturability (0.392), a* value (0.306) and decreased with moisture content (-0.397) and DF (-0.338). The PC2 correlates negatively with sensory parameters of color (-0.426), odor (-0.560), overall liking (-0.440) and instrumental L* parameter (-0.353). Among color parameters, the b* parameter on the PC1 and PC2 was the least prominent in explaining the variability. PC1 versus PC2 biplot of 49 of chips were given in Figure 1. Variables plotted close to the axes had lower contributions. Overall liking and DF located opposite to each other on the biplot showing negative correlation.

Table 9. Results of PCA on the instrumental and sensory attributes of 49 chips showing the loadings and percentage variance accounted for by the first five components

Variable	PC1	PC2	PC3	PC4	PC5
MC	-0.397	-0.004	0.053	-0.125	-0.241
L*	-0.231	-0.353	0.486	0.126	-0.133
a*	0.306	0.269	0.130	-0.275	0.474
b*	0.106	-0.168	0.688	-0.161	0.370
FF	0.191	-0.206	0.193	0.730	-0.120
DF	-0.338	0.133	0.128	-0.257	-0.282
Color	-0.081	-0.426	-0.424	0.169	0.479
Hardness	0.389	0.093	-0.022	0.015	-0.259
Crispness	0.389	0.111	-0.033	0.027	-0.294
Fracturability	0.392	-0.071	0.107	-0.138	-0.205
Odor	0.067	-0.560	-0.136	-0.385	-0.137
Overall liking	0.255	-0.440	-0.073	-0.266	-0.157
Variance (%)	**46.3**	**18.1**	**13.0**	**8.9**	**5.8**

MC: Moisture content; FF: Fracture force; DF: Deformation at fracture

Table 8. Pearson correlation coefficients between characterizing parameters of chips.

	MC	L*	a*	b*	FF	DF	Color	Hardness	Crispness	FR	Odor
Instrumental Parameters											
L*	0.555**										
a*	-0.678**	-0.602**									
b*	-0.219	0.457**	0.377**								
FF	-0.461**	0.130	0.043	0.227							
DF	0.845**	0.394**	-0.440**	-0.125	-0.493**						
Sensory parameters											
Color	0.066	0.103	-0.353**	-0.231	0.067	-0.102					
Hardness	-0.810**	-0.546**	0.614**	0.124	0.378**	-0.626**	-0.277				
Crispness	-0.811**	-0.566**	0.610**	0.089	0.382**	-0.630**	-0.305	0.923**			
FR	-0.798**	-0.356**	0.621**	0.334**	0.381**	-0.646**	-0.247	0.852**	0.864**		
Odor	-0.102	0.190	-0.165	0.122	0.013	-0.208	0.418**	0.035	0.030	0.269*	
Overall liking	-0.476**	-0.085	0.209	0.232	0.276*	-0.495**	0.237	0.477**	0.445**	0.655**	0.697**

Significance level: *p≤0.05; **p≤0.01.MC: Moisture content; FF: Fracture force DF: Deformation at fracture; FR: Fracturability

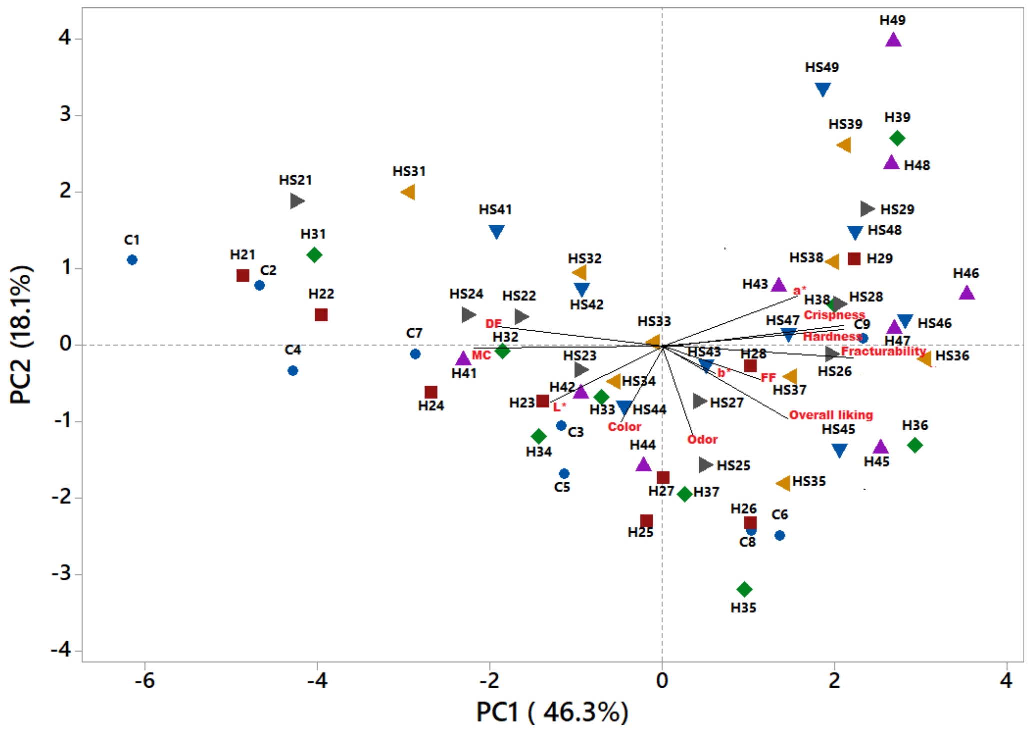

Figure 1. Biplot for first two components. In the notations, C, H, and HS stands for control samples, samples containing hazelnut flour and samples containing hazelnut flour and skin, respectively. The first number in the notations represents the ratio of H or HS in the formulation (2: 20%, 3: 30%, and 4: 40%), and the second number represents the baking conditions (1: 180°C/4 min, 2: 180°C/5 min, 3: 180°C/6 min, 4: 200°C/4 min, 5: 200°C/5 min, 6: 200°C/6 min, 7: 220°C/4 min, 8: 220°C/5 min, 9: 220°C/6 min).

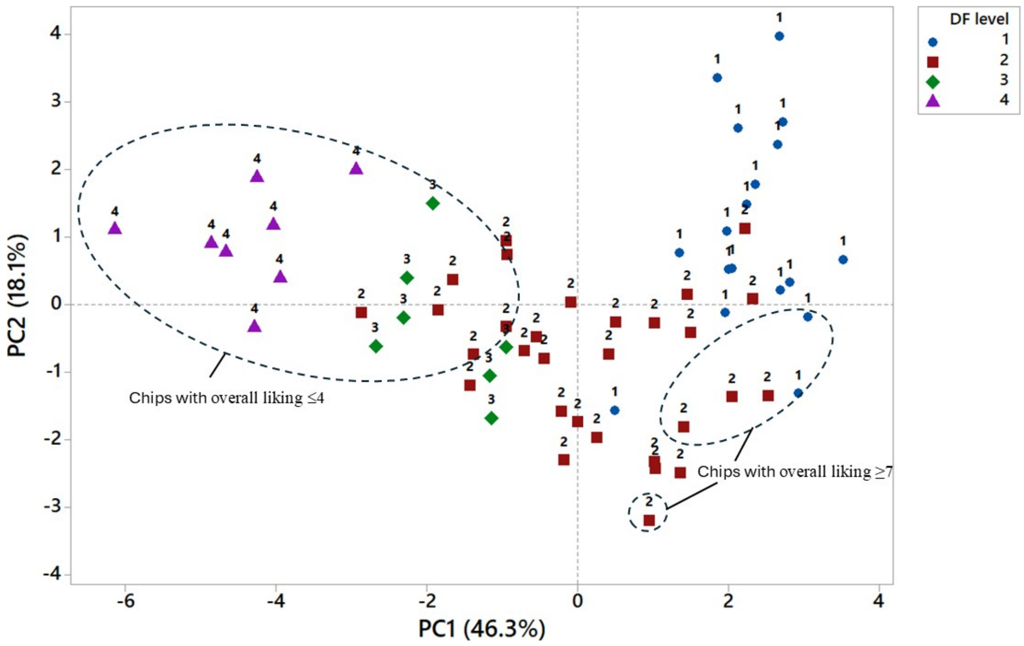

Figure 2. Scores plot from principal component analysis (PCA) of the 49 chips. Chips were divided into 4 clusters according to DF values. Cluster 1: DF<1; Cluster 2: 1≤DF<1.5; Cluster 3: 1.5≤DF<5; Cluster 4: 5≤DF; DF: Deformation at fracture

49 chips were divided into 4 clusters according to values of deformation at fracture (DF). The appearance of the grouped samples on the score plot was as shown in Figure 2. Chips with lower DF values received higher overall liking in sensory analysis. Chips with the highest overall liking (≥7) and the lowest overall liking (≤4.1) grouped on the opposite sides in score plot. Chips with the highest overall liking were the HF30/HFS30 chips baked at 200 °C for 5/6 min and the HF40/HFS40 chips baked at 200 °C for 5 mins. Chips that received the least preference in terms of overall liking were generally those baked at 180 °C for 4-5 min and at 220 °C for 6 min. Results of PCA and correlation matrix show that the instrumental DF parameter of chips can be used to predict the final textural quality. Lower DF values and may be an indicative of overall liking of chips.

Conclusion

Replacing wheat flour with hazelnut flour (HF) and hazelnut flour plus skin (HFS) significantly improved the nutritional value of the dough by increasing its protein, fat, and mineral content.

The substitution of wheat flour with HF/HFS increased weight loss during baking and reduced moisture content in chips, particularly under higher baking temperatures and longer baking times. Higher substitution levels of HF and HFS generally resulted in lower moisture content, with HF-containing chips showing slightly greater moisture retention than HFS-containing ones. Inclusion of HF/HFS in formulation influenced the textural properties of chips, with both baking conditions and ingredient composition playing significant roles. As baking temperature and time increased, chips became firmer, but the inclusion of hazelnut components tended to soften the texture due to their higher fat content. Lower deformation at fracture (DF) values observed in HF/HFS-containing chips, indicating a more brittle structure. Both baking time and temperature reduced DF values, with chips becoming more fragile as substitution levels increased in HF-containing chips but not in HFS-containing chips. Chips containing HFS had lower lightness (L*) and yellowness (b*) values, particularly at higher substitution levels, resulting in a darker, more reddish-brown appearance. While increased baking time and temperature enhanced the color changes in all samples, the presence of hazelnut skin was a key factor in producing a visually distinct product. Chips with high FF values and low DF values had higher textural preference. The highest overall liking observed in chips containing 30-40% HF or HFS, baked at 200 °C for 5 min and 30% HF or HFS, baked at 200 °C for 6 min. Significant correlations were found among the various measured properties, as demonstrated by Pearson's correlation and principal component analysis (PCA). Both the PCA results and the correlation matrix suggest that the instrumental DF parameter of the chips can serve as a predictor for final textural quality. Lower DF values may also indicate a greater overall liking of the chips.

Overall, the findings suggest that hazelnut flour and hazelnut skin can be used as a functional ingredient to develop nutrient-dense snack products. The findings provide valuable insights into optimizing hazelnut-based formulations for producing healthier snack alternatives.

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