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UTILIZATION OF HAZELNUT SKIN AND HAZELNUT FLOUR IN GLUTEN-FREE CAKES: CORRELATION OF BATTER RHEOLOGY WITH CAKE QUALITY

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ABSTRACT
The effects of rice flour substitution with hazelnut skin (HS), hazelnut flour (HF), and HS-HF blend (1:1, w/w) at percentages of 0%, 5%, 10%, 15% (w/w) on gluten-free cake batters were studied from a rheological standpoint. Replacement with 5% HS increased Power-Law consistency index (K), reduced specific gravity and resulted in the highest cake volume. Increasing levels of HS gradually increased specific gravity, water activity, and reduced tan δ, leading to cakes with lower volume, darker (lower L*) color, harder texture. HF addition increased tanδ (at >5%) and specific gravity, producing cakes with lower volume, but similar color and texture to those of control. HS-HF blend improved cake color and hardness compared to HS added alone. Strong correlations were found between G′(ω) slope and cake volume (r=0.9939 for added HS, r=-0.9408 for added HF), the exponent *a* and cake volume (r=0.9447 for added HS, r=-0.8668 for added HF).
Key words: Rice cake, hazelnut skin, fiber, rheology, baking

GLUTENSİZ KEKLERDE FINDIK UNU VE FINDIK ZARI KULLANIMI: HAMUR REOLOJİSİNİN KEK KALİTESİ İLE KORELASYONU

ÖZ
Pirinç ununun %0, %5, %10, %15 (g/g) oranlarında fındık zarı (FZ), fındık unu (FU) ve FZ-FU karışımı (1:1, g/g) ile değiştirilmesinin glutensiz kek hamurları üzerindeki etkileri reolojik açıdan değerlendirilmiştir. 5% oranında FZ ilavesi ile Power-Law konsistens indeksi artmış, özgül ağırlık azalmış ve en yüksek hacimli kek elde edilmiştir. Artan oranlarda FZ ilavesi hamurun özgül ağırlık ve su aktivitesinde kademeli bir artışa neden olurken, tanδ değerini azaltmıştır. Böylece daha düşük hacimli, koyu renkli (düşük L*), katı tekstüre sahip kekler elde edilmiştir. FU ilavesi tanδ (>5%) ve özgül ağırlığı artırarak daha düşük hacimli, fakat renk ve tekstür açısından kontrolle benzer özelliklerde kekler elde edilmesini sağlamıştır. FZ-FU karışımı ise, tek başına FZ ilavesine kıyasla, keklerin renk ve sertlik değerlerini geliştirmiştir. Ayrıca, G′(ω) eğimi ile kek hacmi (r=0.9939 FZ ilavesi için, r=-0.9408 FU ilavesi için), katsayı *a* ile kek hacmi (r=0.9447 FZ ilavesi için, r=-0.8668 FU ilavesi için) arasında kuvvetli korelasyonlar tespit edilmiştir.
Anahtar kelimeler: pirinç keki, fındık zarı, lif, reoloji, pişirme

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INTRODUCTION

Gluten-free baked products have been widely consumed due to increasing prevalence of celiac disease, non-celiac gluten sensitivity, and due to the growing trend towards following a healthier diet (Xu et al., 2020; Gazza and Nocente, 2022). Thus, these products constitute one of the most rapidly growing segments of food industry. Consumers demand gluten-free baked products with similar texture, color, and flavor to those of wheat flour-based baked products (Gasparre and Rosell, 2023). This demand triggers a technological challenge in food industry for the manufacturing of gluten-free baked products. Besides the technological issues encountered during the processing of gluten-free baked products due to the lack of gluten in dough/batter systems that result in poor physical characteristics in the product (Yazar et al., 2017; Yazar and Demirkesen, 2023), gluten-free baked products often tend to have reduced quantities of proteins, B vitamins, iron, and fiber compared with products containing gluten, as they are prepared with gluten-free cereals and commercial grain products (Gularte et al., 2012). Gluten-free diet is often characterized by an excessive consumption of energy, proteins, and fats, and a reduced intake of complex carbohydrates and dietary fiber (Sabanis et al., 2009). Therefore, it is an ongoing need to re-design gluten-free formulations to obtain gluten-free baked products with similar nutritional composition and physical quality characteristics to those of their wheat-based counterparts (Gularte et al., 2012; Özyiğit et al., 2020). For this purpose, replacing common gluten-free ingredients with nuts was suggested to be a valuable strategy to produce healthier gluten-free baked products (Tuna et al., 2023).

Hazelnut (*Corylus avellana* L.) is one of the most popular tree nuts consumed worldwide, ranking second in tree nut production after almond (Del Rio et al., 2011; Çıkrıkçı et al., 2016). Turkey is the major producer of hazelnuts with the production rate corresponding to 63.9% of the total production in the world in 2022 (FAO, 2024). Hazelnut consists of a green leafy cover, a hard shell with a smooth surface, dark brown pellicular pericarp (also known as skin or testa), and an edible kernel (Contini et al., 2008; Çıkrıkçı et al., 2016). Hazelnut kernel was reported to be a source of flavonoids including monomeric flavan-3-ols, B-type procyanidins, and prodelphinidins (Del Rio et al., 2011). Total dietary fiber content of hazelnut was found as 17.8%, the majority of which (>96%) was insoluble fibers. The dietary fibers hazelnut was suggested to have potential to improve large bowel function (Tunçil, 2020). Hazelnut skin constitutes around 2.5% of the whole hazelnut and it is a by-product obtained during the roasting process (Del Rio et al., 2011; Çıkrıkçı et al., 2016). Roasted hazelnut skin was found to be an excellent source of phenolics, and its dietary fiber content was reported as 69.8%, that was mainly composed of insoluble fibers including lignin (55%) and fiber polysaccharides such as cellulose, pectic polysaccharides, and xyloglucans (45%). Thus, hazelnut skin can be considered as a value-added co-product for use as a functional food ingredient with prebiotic properties and antioxidant activity (Pelvan et al., 2018; Tunçil, 2020).

The information discussed above have clearly showed that the addition of hazelnut flour and hazelnut skin could improve the nutritional value of gluten-free baked products. Besides their high nutritional value, hazelnuts were also suggested to contribute to the flavor and texture of bakery products (Dervişoğlu, 2006). For this purpose, hazelnut flour with skin were added in gluten-free bread (Tuna et al., 2023) and gluten-free cookie (Doğruer et al., 2023) formulations. These studies evaluated the impact of added hazelnut flour on the rheological properties of doughs using empirical methods and on the physical properties of the resulting baked products. On the other hand, different forms of fibers obtained from hazelnut skin was used in wheat flour-based cake formulations and the impact of these fibers were evaluated in terms of linear viscoelastic properties of batters, physical properties and staling rates of cakes (Çıkrıkçı et al., 2016). The impact of added hazelnut skin on the empirical rheological properties of wheat flour dough was studied (Anıl, 2007; Durmuş et al., 2021). These studies have revealed that hazelnut flour without skin and hazelnut skin were not used in gluten-free formulations. Therefore, this study focused on the impact of hazelnut flour (without skin) and hazelnut skin on the physical quality characteristics of a model rice flour-based gluten-free cake. For this purpose, flow and linear viscoelastic properties of cake batters with added hazelnut flour and hazelnut skin were studied and the correlations of the rheological properties with the physical cake characteristics were discussed.

MATERIALS AND METHODS

Materials

Rice flour (*Kenton*, Ankara, Türkiye) [11.78±0.19% moisture determined using the IR-35 rapid moisture analyzer, 8.78±0.62% protein determined according to the Kjeldahl method with the conversion factor of 6.25, AACC approved method no. 46-10.01 (AACC, 2010), 1.41±0.26 % fat determined according to the AACC approved method no. 30-20.01 (AACC, 2010), and 0.49±0.05% ash determined according to the AACC approved method no. 08-01.01 (AACC, 2010)], sugar, eggs, milk, sunflower oil, baking powder, and hazelnuts were purchased from a local market. Hazelnut flour (3.31±0.04% moisture, 17.5±0.56% protein, 64.6±0.42% fat and 2.43±0.04% ash) was produced by roasting at 105°C for 10 minutes, grinding, and grading the hazelnuts through a 10-mesh sieve (2 mm opening size). Hazelnut skin (HS) was obtained from *Fiskobirlik*- Hazelnut Agriculture and Sales Cooperatives (Giresun, Turkey). Hazelnut skin with 8.29±0.05% moisture, 1.8±0.08% protein, 11.8±0.25% fat, 2.1±0.02% ash, and 68±1.11% dietary fiber [determined according to the AOAC method no. 991.43 (AOAC, 2000)] was also graded using a 10-mesh sieve prior to its use in gluten-free cake formulations.

Methods

Batter and cake preparation

A gluten-free cake formulation containing 100% rice flour, 87.5% sugar, 51.5% egg, 50% sunflower oil, 27.5% milk, and 2.5% baking powder was used in the experiments (all percentages are given on flour weight basis, w/w). Hazelnut skin (HS), hazelnut flour (HF), and a mixture of both [HS:HF, 1:1 (w/w)] were added in gluten-free cake formulations at different percentages (0%, 5%, 10%, and 15%). The recipes for control and other gluten-free cake samples with hazelnut skin and flour were given in Table 1. The basic recipe used for control was adapted from the rice flour-based gluten-free cake formulations used in previous studies (Gómez et al., 2010; Ronda et al., 2011; Gularte et al., 2012). For the preparation of gluten-free cake batters, eggs were mixed for 4 minutes at high-speed using a mixer (Kitchen Aid K45, St. Joseph, MI, USA). Then, sugar was added, and the mixture was mixed for 3 minutes again at high speed. Sunflower oil and milk were then added into this mixture as mixing continued at medium speed for 2 minutes. Finally, all other dry ingredients were added into the mixture and mixed at low speed for 1 minute.

Table 1. Formulations of Gluten-free Cakes with Hazelnut Skin and Hazelnut Flour (on rice flour basis, w/w)

Formulation	Control	HS (5%)	HS (10%)	HS (15%)	HF (5%)	HF (10%)	HF (15%)	HS-HF (5%)	HS-HF (10%)	HS-HF (15%)
Rice flour	200	190	180	170	190	180	170	190	180	170
Hazelnut skin	0	10	20	30	0	0	0	5	10	15
Hazelnut flour	0	0	0	0	10	20	30	5	10	15
Egg	103.05	103.05	103.05	103.05	103.05	103.05	103.05	103.05	103.05	103.05
Sugar	175	175	175	175	175	175	175	175	175	175
Sunflower oil	100	100	100	100	100	100	100	100	100	100
Milk	55	55	55	55	55	55	55	55	55	55
Baking powder	5	5	5	5	5	5	5	5	5	5
Total (g)	638.05	638.05	638.05	638.05	638.05	638.05	638.05	638.05	638.05	638.05

HS: hazelnut skin, HF: hazelnut flour

Cake batter samples of 300 g were baked in duplicates in a convection oven (Vestel- AFB 902E, Türkiye) using disposable aluminum cake pans with the diameter of 14 cm. The baking mode of top-bottom heating was chosen, and the temperature was set to 170°C for 35 minutes. After baking, cake samples were removed from the pans and set aside at room temperature for 1 hour to cool down. The cakes were then covered with plastic wrap to prevent them from drying.

Cake batter properties

Moisture content and water activity

The moisture contents of cake batters were determined using the IR-35 Moisture Analyzer (Denver Instrument, Denver, CO, USA). This method is based on drying the sample under infrared bulb and measuring the percent moisture on a gravimetric balance once the sample weight is stabilized (McCartney and Tingley, 1998). Water activity of cake batters was measured using a water activity meter (Testo AG 400, Lenzkirch, Germany) to evaluate how the free water in the batter systems changed when rice flour was replaced with HS and HF.

Flow behavior

The rheological testing to characterize the flow behavior of gluten-free cake batter samples with added HS and HF was conducted at 25°C with Brookfield RVDV III ultra-rheometer (Brookfield Engineering, MA, USA) using the small size sample adaptor with the spindle SC4-28. Shear stress and apparent viscosity were measured as a function of shear rate over the range of 0.1-10 s^{-1} (Christaki et al., 2017). The obtained data were fitted to the Power Law model (Eq. 1):

$$\tau = K.\dot{\gamma}^{n} \tag{1}$$

where K is the consistency index (Pa.s), n is the flow behavior index, τ is the shear stress (Pa) and $\dot{\gamma}$ is the shear rate (1/s).

Linear viscoelastic behavior

Small amplitude oscillatory shear tests were conducted at 25 °C using the Haake Mars Rheometer (Thermo-Fisher Scientific, Germany). Batter samples were prepared just before the rheological testing. A 40 mm parallel plate geometry with smooth surface and a gap of 1 mm were used. Strain sweep tests were conducted to within the strain range of 0.01% to 100% at 1 Hz frequency to determine the linear viscoelastic region for the gluten-free cake batter samples studied. Frequency sweep tests were conducted within the frequency range of 0.1 to 10 Hz at a constant strain amplitude (γ: 0.1%) determined in the linear viscoelastic region. Frequency sweep data [G′ (Eq. 2), G″ (Eq. 3), tan δ (Eq. 4)] were fitted to the Power Law model (Yazar and Demirkesen, 2023):

$$G'(\omega) = G'_{\omega 1} \, . \, \omega^{a} \tag{2}$$

$$G''(\omega) = G''_{\omega 1} \, . \, \omega^{b} \tag{3}$$

$$\tan\delta(\omega) = \frac{G''(\omega)}{G'(\omega)} = \left(\frac{G''}{G'}\right)_{\omega 1} . \, \omega^{c} = (\tan\delta)_{\omega 1} \, . \, \omega^{c} \tag{4}$$

where $G'_{\omega 1}$ is the elastic modulus (Pa), $G''_{\omega 1}$ is the viscous modulus (Pa), and $(\tan\delta)_{\omega 1}$ represents the loss tangent at a frequency of 1 Hz; while ω is the angular frequency (rad/s). The *a*, *b*, and *c* exponents quantify the dependence degree of the moduli and the loss tangent to the oscillation frequency (Ronda et al., 2017; Yazar and Demirkesen, 2023).

Specific gravity

Specific gravity values of gluten-free cake batter samples were measured by dividing the weight of a certain volume of cake batter by the weight of distilled water with the same volume (Turabi et al., 2008). The measurements were conducted in duplicates.

Cake quality evaluation

Volume and density

Cake volume was determined according to rapeseed replacement method [AACC method 10-05.01 (AACC, 2010)]. After the cake samples were baked and cooled down for 1 hour, their weights were measured. Cake density was calculated as the ratio between the weight of the cake and its volume (Gómez et al., 2010; Gularte et al., 2012).

Volume, symmetry, and uniformity indices

Volume, symmetry, and uniformity indices of the cake samples was measured according to the AACC method 10-91.01 (AACC, 2010). For the evaluation of these parameters, cake samples were cut vertically through the center and the heights of cake samples were measured at three different points (*B*, *C*, and *D*) along the cross-sectioned cakes using the template provided by the method. Volume index (Eq. 5), symmetry index (Eq. 6), and uniformity index (Eq. 7) were calculated as follows:

$$\text{Volume index} = B + C + D \qquad (5)$$

$$\text{Symmetry index} = 2C - B - D \qquad (6)$$

$$\text{Uniformity index} = B - D \qquad (7)$$

where *C* is the height at center, *B* and *D* are the heights at three-fifths of distance from center to edge (Cloke et al., 1984).

Textural properties

Crumb texture was determined by TA-XT2 texture analyzer (Stable Microsystems, Surrey, UK), 24 h after baking. Center of cake samples were cut into cube shapes with the dimensions of 35 x 35 x 35 mm and were compressed to 50% of their original thickness at a speed of 2 mm/s, with a 30 s delay between first and second compressions. A 75-mm aluminum compression platen probe and a load cell of 50 N were used. Hardness (N), springiness, cohesiveness and resilience values for the gluten-free cake crumb samples were calculated on the "Texture Profile Analysis" test graph (Gulerta et al., 2012). Mean values of eight measurements (2 cubic slices from the central part of the cake halves were collected from the duplicates of each baking test) were presented along with the standard deviations.

Color analysis

The surface and the crumb color of the cake samples were determined using the Minolta CR-400 chromameter (Minolta, Osaka, Japan). Readings were obtained in quadruplicate for each sample to quantify the differences in color between the cake samples with the addition of HS and HF, and they were provided as L*, a*, b* parameters according to the CIELAB system of color measurement. The a* value is a measure of greenness (-100) to redness (+100), the b* value ranges from -100 (blueness) to +100 (yellowness), while the L* value indicates the lightness on a scale ranging from 0 (black) to 100 (white) (Sabanis et al., 2009).

Statistical analysis

OriginPro 8.6 (Northampton, MA, USA) was used for statistical analyses with 95% confidence level. One-way analysis of variance (ANOVA) and Tukey's comparison tests were applied ($P < 0.05$) to compare the data obtained for gluten-free batter and cake samples with HS and HF. Lettering system was used to show significant difference between samples.

RESULTS AND DISCUSSION

Cake batter flow behavior

The apparent viscosity curves of cake batters with added HS, HF, and HS-HF blend on an equal weight basis in comparison to control were shown in Figure 1. A decrease in apparent viscosity with increasing shear rate was observed for all cake batters (Figure 1a,b,c), suggesting a shear thinning behavior for gluten-free cake batters with and without HS and HF. Shear thinning behavior mainly arises from the alignment of microstructures in a material being deformed in the direction of flow (Duvarcı et al., 2019). As the shear rate is increased further, the alignment with the flow becomes more complete, and the shear viscosity decreases further (Hyun, 2002). Similar behavior was previously found for gluten-free cake batters (Şakıyan et al., 2004; Turabi et al., 2008; Ronda et al., 2011). Gluten-free cake batter with 15% added hazelnut skin showed the highest apparent viscosity values within the studied shear rate range (Figure 1a) when compared to control and other batter samples.

Flow curves of cake batters were given in Figure 2. Batters with HS, especially at 15% (Figure 2a), and control showed slightly higher shear stress values when compared to batters with HF (Figure 2b) and HS-HF blend (Figure 2c). The shear stress (σ) versus shear rate ($\dot{\gamma}$) data obtained for the gluten-free cake batters provided a good fit ($r^2 = 0.9930$-0.9998) for the Power Law model (Eq.

1). The consistency index (K) and flow behavior index (n) for different batter formulations were shown in Table 2. The flow behavior index of batters ranged from 0.43 to 0.66. Flow behavior index values less than 1.0 indicates shear thinning behavior (Şahin, 2008), suggesting all gluten-free batter samples showed shear thinning behavior as also revealed by the apparent viscosity curves (Figure 1). The gluten-free cake batter with 15% hazelnut skin showed the lowest flow behavior index (0.43) and the highest consistency index (61). Addition of HS resulted in higher K values in gluten-free cake batters (42.2- 61.0) compared to control (42.5), batters with HF (34.0- 40.3), and batters with HS-HF blend (36.6-40.6). However, a decrease was found in K with the addition of HS at 10%, which was indicative of a more fluid-like behavior (Table 2). Insoluble dietary fibers, especially of a coarse particle size, was suggested to create rupture points in the dough matrix (Föste et al., 2020). Thus, the decrease in K with 10% added HS could be attributed to the disruptive effect of insoluble fibers on the continuity of the batter system. Insoluble fibers have been characterized by their water binding capacities (Föste et al., 2020) and this capacity was reported to increase with the increasing particle size of the fiber (Gómez et al., 2010). As the added HS (particle size ≤ 2 mm) increased to 15%, the high water absorption capacity of fibers suppressed the disruptive effect on the batter matrix and thus, K significantly increased ($p<0.05$). Consequently, shear stress, apparent viscosity, and Power Law indexes collectively pointed out to a decrease in the flow behavior of rice flour-based gluten-free cake batters with 15% added hazelnut skin, while suggesting an increase in the flowability with the addition of hazelnut flour.

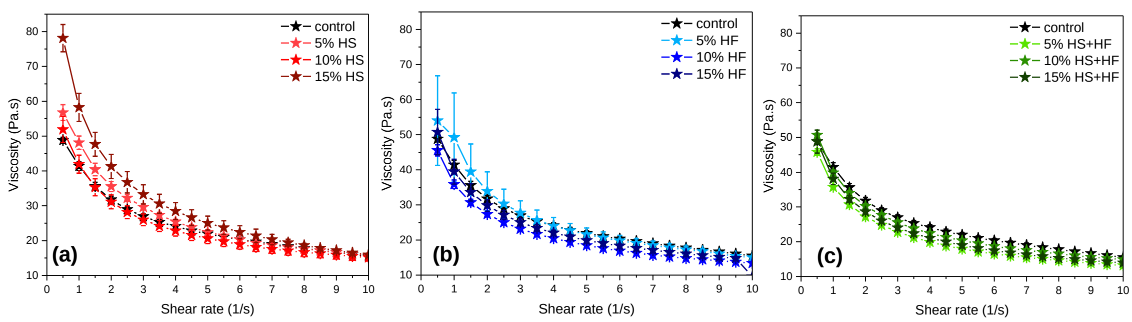

Figure 1. Apparent viscosity versus shear rate for the rice flour-based gluten-free cake batters with hazelnut skin (a), hazelnut flour (b), and blends of hazelnut skin and flour [1:1, w/w (c)] at different percentages (0%, 5%, 10%, 15%, w/w)

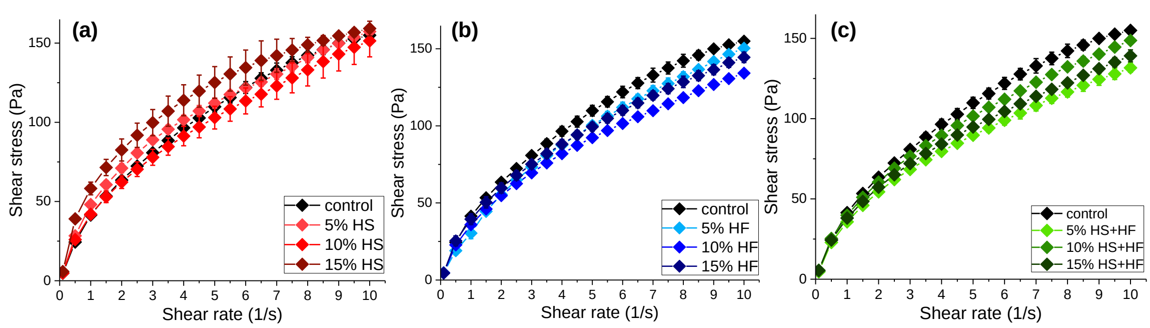

Figure 2. Flow curves of the rice flour-based gluten-free cake batters with hazelnut skin (a), hazelnut flour (b), and blends of hazelnut skin and flour [1:1, w/w (c)] at different percentages (0%, 5%, 10%, 15%, w/w)

Batter viscosity and flow behavior mainly depends on the water binding capacity of the dry ingredients (Doğan et al., 2005). Hazelnut skin was considered to increase batter viscosity by decreasing the amount of free water in the batter system due to its rich fiber content (≈68%), that was reported to range between 58.3%- 69.8% (Montella et al., 2013; Tunçil, 2020). Even though the moisture contents of cake batters were comparable to each other (Table 3), the significantly lower ($p<0.05$) water activity (a_w) found for the gluten-free cake batter with 15% HS (Table 3) supported the idea behind the higher viscosity observed for this cake batter. An increase in cake batter viscosity was also reported in other studies with the addition of insoluble fibers (Lee et al., 2004; Gómez et al., 2010) in cake formulations. On the other hand, the decrease in K values of gluten-free cake batters with added hazelnut flour was attributed to its high oil content. Hazelnuts contain around 57-69% of oil (Turan et al., 2015) and increasing the oil/fat content in cake formulations was previously shown to decrease batter viscosity (Prakash et al., 2001; Şakıyan et al., 2004).

Table 2. Properties of Cake Batters with Hazelnut Skin and Hazelnut Flour. The index and moduli presented correspond to the fitting of experimental measurements to Power Law Model [$\tau = K.\dot{\gamma}^n$; $G'(\omega) = G'_{\omega1}.\omega^a$; $G''(\omega) = G''_{\omega1}.\omega^b$; $\tan\delta(\omega) = (\tan\delta)_{\omega1}.\omega^c$]

Sample	*Flow behavior*			*Viscoelastic behavior*							
	K (Pa.s^n^)	*n*	*r²*	$G'_{\omega1}$(Pa)	*a*	*r²*	$G''_{\omega1}$(Pa)	*b*	*r²*	$(\tan\delta)_{\omega1}$	*c*
Control	42.5	0.57	0.9981	98.01	0.64	0.9948	112.57	0.62	0.9998	1.15	-0.01
Hazelnut skin											
5%	49.9	0.50	0.9978	90.31	0.72	0.9763	111.88	0.64	0.9938	1.26	-0.07
10%	42.2	0.55	0.9998	75.27	0.71	0.9846	91.44	0.67	0.9961	1.21	-0.04
15%	61.0	0.43	0.9939	98.70	0.64	0.9842	111.65	0.62	0.9968	1.15	-0.02
Hazelnut flour											
5%	34.0	0.66	0.9930	99.32	0.61	0.9923	107.75	0.57	0.9997	1.08	-0.03
10%	36.8	0.56	0.9991	61.17	0.65	0.9960	74.67	0.61	0.9988	1.22	-0.03
15%	40.3	0.55	0.9995	64.98	0.70	0.9826	77.45	0.62	0.9971	1.19	-0.07
Hazelnut skin + hazelnut flour											
5%	36.6	0.55	0.9995	79.29	0.66	0.9854	85.85	0.62	0.9964	1.08	-0.03
10%	40.6	0.56	0.9996	69.05	0.69	0.9600	74.15	0.63	0.9884	1.10	-0.06
15%	38.7	0.55	0.9997	61.17	0.68	0.9912	79.01	0.64	0.9980	1.30	-0.04

Viscoelastic behavior of gluten-free cake batters

Viscoelastic parameters fitted to the Power-Law model along with the exponents were also provided in Table 2 to describe the viscoelastic responses of gluten-free cake batters with added HS and HF. Control batter had the highest $G'_{\omega1}$ and $G''_{\omega1}$ values, and the cake batter with 15% HS showed almost identical viscoelastic behavior to that of control. Increasing percentages of HF in gluten-free cake batters resulted in a decrease in both $G'_{\omega1}$ and $G''_{\omega1}$. For all batter formulations, viscous modulus $G''_{\omega1}$ values were higher than elastic modulus $G'_{\omega1}$, which resulted in $(\tan\delta)_{\omega1}$ values greater than 1, ranging between 1.08 and 1.30 (Table 2). Ronda et al. (2011) also fitted the frequency sweep data obtained for rice flour-based glute-free cake batters with added proteins to the Power-Law model and found $(\tan\delta)_{\omega1}$ values above 1. It should be noted that the tanδ obtained for gluten-free cake batters might vary depending on the cake formulation and the frequency sweep testing protocol, including the type of geometry and the gap used. Loss tangent (tanδ) has been described as the ratio of viscous to elastic components of a viscoelastic behavior (G''/G'). Since $0 \leq \delta \leq 90°$ for viscoelastic materials, tanδ can range from zero to infinity. A solid-like viscoelastic material exhibits phase angle smaller than 45° (tanδ<1), while a liquid-like viscoelastic material exhibits phase angle greater than 45° (tanδ>1) (Duvarcı et al., 2019). The loss tangent data obtained for the gluten-free cake batters through the frequency sweeps [tanδ (ω)] were shown in Figure 3. Tanδ values ranged from 1 to 2 for all batter samples, suggesting liquid-like linear viscoelastic behavior (G″>G′). The lowest tanδ values were obtained for the batters with 5% HF, 5% HS+HF, and 10% HS+HF, while the highest tanδ was found for the batter with 15% HS+HF (Figure 3). These results showed that the highest degree of liquid-like viscoelastic behavior in gluten-free cake batters occurred with the addition of 15% HS+HF. On the other hand, tanδ values of control and batter with 15% HS overlapped throughout the whole frequency range (Figure 3), which was indicative of a similar viscoelastic response for these gluten-free cake batters.

The lowest exponent values, especially a and b, were observed for the gluten-free cake batter with 5% HF (Table 2), suggesting the least degree of frequency dependency for this sample. Considering the lowest $(\tan\delta)_{\omega 1}$ was also found for cake batter with 5% HF (Table 2), it can be concluded that replacing 5% of rice flour with hazelnut flour in the given gluten-free cake formulation contributed to the molecular interactions in the batter system.

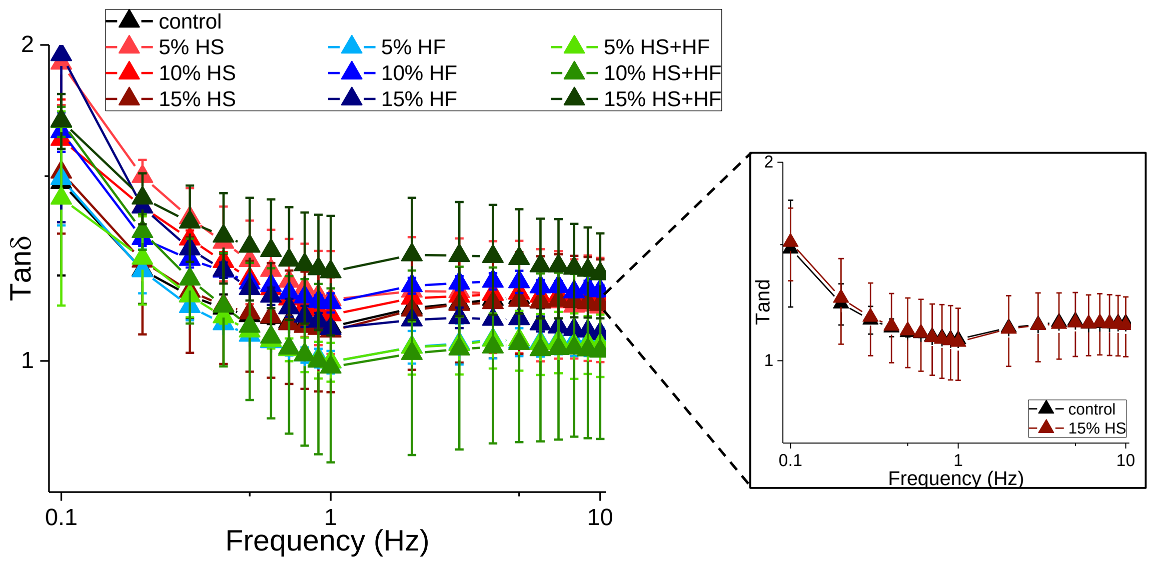

Figure 3. Tanδ values for gluten-free cake batters with added hazelnut skin (HS) and hazelnut flour (HF) versus frequency (ω: 0.1-10 Hz)

The magnitude of the slope of log G′ versus log ω in the frequency sweeps provides useful information about the structures of biopolymers. Strong gels (elastic gels or true gels) with a 3D network when log G′ versus log ω or log G″ versus log ω plots give nearly zero slopes, while for weak gels and highly concentrated solutions the plots have positive slopes approaching 2 (Georgopoulos et al., 2004). In other words, the increase in G′ slope versus frequency is indicative of an increase in viscous flow properties. The slope of G′ versus the applied frequency for the gluten-free cake batters analyzed in this study ranged from 0.62153±0.01 to 0.83181±0.02 (Figure 4). The lowest G′ slope was found for the batter with 5% hazelnut flour, which was even slightly lower than that of control. The slope of G′ remained the same with the added 10% hazelnut flour, but significantly increased when the hazelnut flour percentage increased to 15% (Figure 4). These findings revealed the slight thickening of the rice flour-based gluten-free cake batter when hazelnut flour was added up to 10%.

On the other hand, addition of hazelnut skin even at 5% resulted in a sharp increase in the slope of G′ versus frequency. However, as the percentage of added hazelnut skin increased to 10% and 15%, the slope of G′ gradually decreased, suggesting an increase in the elastic component of the cake batter that resulted in a viscoelastic response similar to that of control (Figure 4). Fiber macromolecules were suggested to impact the linear viscoelastic properties of dough/batter systems by competing for water due to their varying water binding and gelling capacities (Yazar and Demirkesen, 2023). Thus, the decrease in the G′ slope of the cake batter with 15% hazelnut skin was attributed to the significantly lower water activity when compared to batters with lower percentages of added HS (Table 3). The decrease observed in the G′ slope with respect to increasing percentages of added HS concurred with the decreasing tanδ values as the added HS percentage increased from 5% to 15% (Table 2 and Figure 3). Addition of fibers in different gluten-free dough/batter systems was also reported to cause a decrease in tanδ (Ronda et al., 2013; Djordjević et al., 2018).

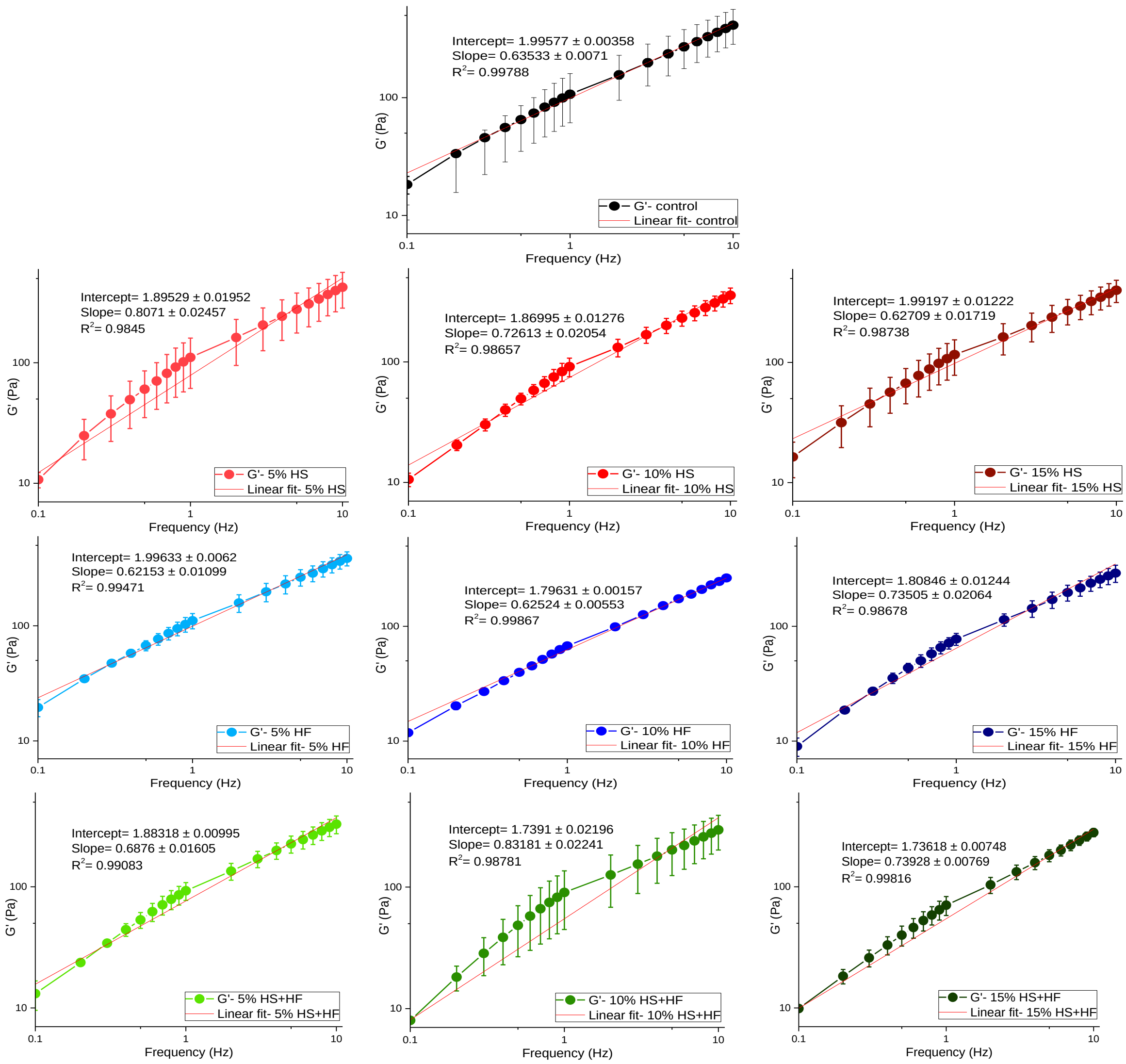

Figure 4. G′ slopes for rice-flour based gluten-free cake batters with added hazelnut skin (HS) and hazelnut flour (HF) versus frequency (ω: 0.1-10 Hz)

The highest G′ slope versus frequency was found for the gluten-free cake batter with 10% HS+HF (Figure 4), indicating the highest degree of fluid-like behavior occurred when the combination of HS+HF (1:1, w/w) was added at 10%. This finding revealed that the fluidity enhancing effect of 5% HS addition on the rheological properties of gluten-free cake batter became even more pronounced when 5% of rice flour was replaced with HF.

Specific gravity

The specific gravity values of the gluten-free cake batters were given in Table 3. Control batter had a specific gravity of 0.89. Replacing 5% of rice flour in cake batters with hazelnut skin resulted in a significant decrease (*P* <0.05) in the specific gravity of batters compared to that of control. Low specific gravity is desired in cake batters as it is associated with higher degree of air incorporation in the batter (Turabi et al., 2008). Thus, the results obtained in this study showed that the addition of hazelnut skin at 5% improved air incorporation in cake batters. The contribution of fibers to air incorporation into batter systems was attributed to the networks being formed upon the hydration of fibers, which might show emulsifying properties (Sabanis et al., 2009). However, specific gravity of batters started to increase gradually (*P* <0.05) as the percentage of added hazelnut skin increased above 5% up to 15% (Table 3), suggesting a decrease in the amount of air incorporated in batters.

Table 3. Quality parameters of cake batters with hazelnut skin and hazelnut flour

Sample		Moisture (%)	a_w	specific gravity
Control		$24.19 \pm 0.04^{a,b}$	0.89 ± 0.0014^{e}	0.890 ± 0.00^{b}
Hazelnut skin				
	5%	24.32 ± 0.04^{b}	0.87 ± 0.0028^{d}	0.850 ± 0.00^{a}
	10%	$23.97 \pm 0.13^{a,b}$	$0.86 \pm 0.0028^{c,d}$	0.865 ± 0.00^{a}
	15%	24.33 ± 0.18^{b}	0.81 ± 0.0007^{a}	0.895 ± 0.00^{bc}
Hazelnut flour				
	5%	23.68 ± 0.08^{a}	0.87 ± 0.0021^{d}	0.910 ± 0.00^{cd}
	10%	$24.10 \pm 0.16^{a,b}$	0.87 ± 0.0042^{d}	0.915 ± 0.00^{d}
	15%	$23.74 \pm 0.20^{a,c}$	$0.85 \pm 0.0014^{b,c}$	0.940 ± 0.00^{e}
Hazelnut skin + hazelnut flour				
	5%	24.86 ± 0.16^{d}	0.85 ± 0.0000^{b}	0.860 ± 0.00^{a}
	10%	$24.20 \pm 0.06^{b,c}$	0.85 ± 0.0007^{b}	0.865 ± 0.00^{a}
	15%	$24.11 \pm 0.05^{a,b}$	$0.86 \pm 0.0084^{c,d}$	0.885 ± 0.00^{b}

Columns with different letters are significantly different (*P* <0.05).

On the other hand, replacing rice flour with hazelnut flour resulted in higher specific gravity values in gluten-free cake batters when compared to control batter (*P* <0.05). And the specific gravity values of gluten-free cake batters continued to increase gradually as the added hazelnut flour percentage increased (Table 3). These results pointed out to a reduction in air incorporation in batters with hazelnut flour when compared to control, in opposite to what was observed with the addition of hazelnut skin. Hazelnut flour particles were not able to aerate the batter system as they were dense due to their high oil contents.

Cake quality evaluation

Quality characteristics of cakes with HS, HF, and HS+HF blend (1:1, w/w), including density, volume index, crust and crumb color, were provided in Table 4.

Volume, symmetry, and uniformity indices

Fiber enriched gluten-free cake sample with 5% HS had significantly higher (*P* <0.05) volume index when compared to control (Table 4), concurring with the lower specific gravity found for the batter with 5% HS (Table 3). When added at low percentages, HS was found to favor the air incorporation in the batter, leading to an increase in volume index. Besides, the increase observed in the consistency index, K (Table 2) and apparent viscosity (Figure 1a) with the addition of 5% HS seemed to favor the entrapment of air bubbles in the batter during baking, which also improved the volume index. The consistency of batters, like specific gravity, is a very important physical property affecting end-product quality since it controls retention of the small bubbles that have been initially incorporated into the batter during mixing (Turabi et al., 2008). Replacing the rice flour in cake formulations with HS at 10% and 15% resulted in volume index similar to that of control (*P* >0.05), pointing out to a gradual decrease in volume index as the percentage of added HS increased above 5%. Sudha et al. (2007) also reported a decrease in cake volume with respect to increasing levels of added apple pomace in the formulation due to strong water binding properties of this fiber. Besides, insoluble dietary fibers, especially those with a coarse particle size, were suggested to create rupture points in dough/batter matrix, favoring gaseous release caused by an impaired gas retention capacity (Föste et al., 2020). The findings in this study showed that replacing rice flour with HS at percentages above 5% gradually diminished gas retention in the batter.

Table 4. Quality Parameters of Cake Samples with Hazelnut Skin and Hazelnut Flour

Sample	Density (g/cm^3)	*B* (cm)	*C* (cm)	*D* (cm)	Volume index (cm)	Color (crust)			Color (crumb)		
						L*	a*	b*	L*	a*	b*
Control	0.56±0.009^{b,c}	3.4±0.00^{a,b}	3.55±0.07^{a,b}	3.3±0.00^{a,b}	10.25±0.07^{a,b,c}	47.02±1.95^{d,e}	12.58±0.37^{d}	18.93±0.62^{g}	69.65±0.61^{h}	-2.52±0.39^{a}	19.91±0.48^{g}
Hazelnut skin											
5%	0.51±0.008^{a}	3.55±0.21^{a}	3.85±0.07^{a}	3.6±0.14^{a}	11±0.28^{d}	42.10±0.17^{b}	10.74±0.22^{c}	15.99±0.27^{e}	46.26±0.44^{e}	3.83±0.34^{d}	11.17±0.41^{e}
10%	0.54±0.006^{a,b}	3.5±0.00^{a}	3.7±0.14^{a,b}	3.45±0.07^{a,b}	10.65±0.21^{b,c,d}	41.09±1.21^{b}	9.58±0.30^{b}	15.25±0.42^{e}	36.72±0.98^{b}	5.10±0.15^{e}	8.08±0.43^{d}
15%	0.56±0.001^{b,c}	3.3±0.00^{a,b}	3.55±0.07^{a,b}	3.45±0.07^{a,b}	10.3±0.00^{b,c}	37.46±2.02^{a}	8.60±0.08^{a}	13.42±0.42^{d}	33.96±0.14^{a}	6.06±0.15^{g}	7.34±0.34^{c}
Hazelnut flour											
5%	0.57±0.004^{b,c}	3.4±0.00^{a,b}	3.45±0.07^{b}	3.3±0.00^{a,b}	10.15±0.07^{a,b,c}	48.17±0.40^{e}	15.44±0.27^{f}	23.43±0.19^{h}	71.03±0.33^{i}	0.06±0.24^{b}	20.15±0.17^{g}
10%	0.58±0.006^{c,d}	3.25±0.07^{a,b}	3.45±0.07^{b}	3.4±0.00^{a,b}	10.1±0.00^{a,b}	52.74±0.66^{f}	14.65±0.54^{e}	22.98±0.82^{h}	69.35±0.64^{h}	0.21±0.18^{b}	20.03±0.46^{g}
15%	0.61±0.009^{d}	3.1±0.00^{b}	3.4±0.00^{b}	3.2±0.00^{b}	9.7±0.00^{a}	51.94±0.63^{f}	14.38±0.17^{e}	17.75±0.36^{f}	65.63±0.09^{g}	2.55±0.26^{c}	15.53±0.29^{f}
Hazelnut skin + Hazelnut flour											
5%	0.54±0.007^{a,b}	3.4±0.00^{a,b}	3.7±0.14^{a,b}	3.6±0.14^{a}	10.7±0.00^{c,d}	45.61±0.33^{c,d}	11.37±0.33^{c}	12.13±0.23^{c}	52.14±1.29^{f}	3.46±0.24^{d}	8.21±0.29^{d}
10%	0.55±0.009^{b}	3.5±0.14^{a}	3.6±0.14^{a,b}	3.5±0.14^{a,b}	10.6±0.14^{b,c,d}	45.10±0.81^{c,d}	9.76±0.40^{b}	11.17±0.61^{b}	44.29±0.60^{d}	5.29±0.25^{e,f}	6.69±0.06^{b}
15%	0.56±0.012^{b,c}	3.35±0.07^{a,b}	3.65±0.07^{a,b}	3.35±0.07^{a,b}	10.3±0.21^{b,c}	44.57±0.91^{c}	8.39±0.67^{a}	9.8±0.37^{a}	40.41±0.72^{c}	5.62±0.30^{f,g}	4.96±0.22^{a}

Columns with different letters are significantly different (*P* <0.05).

The volume index values of gluten-free cakes decreased gradually with the increasing percentages of added HF ranging from 5% to 15%. However, this decrease was not significant (*P* >0.05), indicating the volume indices of cakes were not significantly affected by the replacement of rice flour with HF at percentages up to 15% (*P* >0.05). The increasing specific gravity of cake batters with added HF, which was indicative of reduced aeration in batter, was concurrent with the lower volume index values obtained with the addition of HF. However, it should be noted that starch gelatinization occurring during baking played a major role in determining cake quality (Wilderjans et al., 2008).The proximate analyses conducted for the rice flour used in this study suggested a carbohydrate content of 77.5% based on the "by difference" method introduced by Atwater and Woods (1896). Rice flour was reported to contain around 78% of starch on 14% moisture basis (Amagliani et al., 2017), concurring with the carbohydrate content of the rice flour used in this study. On the other hand, the proximate analyses revealed a much lower carbohydrate content for the hazelnut flour (without skin) used in this study, that was around 12%. Ultimately, denser hazelnut flour particles that were rich in fat and low in starch content could be the reason behind the decrease in the volume indices of cakes with added HF. Even though, hazelnut flour particles lacked the ability to aerate the batter (Table 3), the high amount of starch in rice flour might have compensated the detrimental effects of hazelnut flour on cake volume for the replacement ratios of up to 15%. Thus, addition of HF caused a significant increase

(P <0.05) in cake batter specific gravity, while resulting in no significant decrease (P >0.05) in cake volume index.

The volume index values suggested a significant difference (P <0.05) in comparison to control only for the cake sample with 5% added HS. Therefore, replacing the rice flour in cakes with the HS+HF blend on an equal weight basis (1:1, w/w) caused no significant change in the volume index of cakes at percentages up to 15% (P >0.05).

The AACC template method (10-91.01) parameters (*B*, *C*, *D*) used to determine the volume index values of cake samples were also provided separately in Table 4. These parameters indicated that none of the gluten-free cake samples with added HS, HF, and HS+HF blend collapsed after baking, as evidenced by the *C* values being higher than *B* and *D* values leading to positive symmetry index values for all cake samples. The uniformity index was 0.1 cm for control; while it ranged between -0.15- 0.05 cm, -0.15- 0.1 cm, and -0.2- 0 cm for the cakes with HS, HF, and HS+HF blend, respectively (Table 4). For the optimum cake, the uniformity index was suggested to be zero because positive or negative values occurred when one side of the cake was higher than the other one (Cloke et al., 1984). Thus, the optimum uniformity index values were obtained for the cakes with 10% and 15% of added HS+HF blend (Table 4).

Cake density

The decrease in cake density expresses that more air was incorporated into the batter, which results in higher cake volume, suggesting a negative correlation between cake density and volume index (Sabanis et al., 2009; Gómez et al., 2010). Cake sample with 5% HS, which had the highest volume index (11.0±0.28 cm), also had the lowest density with 0.51±0.008 g/cm^3 (Table 4). A gradual increase was recorded in cake density as the percentage of HS increased from 5% to 15% (Table 4). Increasing levels of fiber in cake formulations was suggested to increase batter density by disrupting the batter structure and thus leading to the release of the trapped air or CO_2 from the batter system (Föste et al., 2020; Kırbaş et al., 2019). Thus, cake volume decreases and results in an increase in cake density. Even though, increasing HS levels in cakes gradually increased cake density, the density and volume index of the cake with 15% HS were not significantly different (P >0.05) from those of control (Table 4). On the other hand, the cake sample prepared with 15% HF addition showed the highest density (0.61±0.009 g/cm^3), while having the lowest volume index (9.7±0.00 cm).

Crust and crumb color characteristics

Color is an important characteristic for baked products as, along with texture and aroma, it contributes to consumer preference. It depends on physicochemical characteristic of the dough (water content, pH, reducing sugars and amino acid content) and on the operating conditions applied during baking such as temperature, relative humidity, modes of heat transfer (Sabanis et al., 2009). The L*, a*, b* values for crust and crumb of the cakes with added HS and HF were given in Table 4. A significant decrease was observed in the L*, a*, b* values for crust as the percentage of added HS increased (P <0.05). These results showed that the cake crust became darker, as evidenced by the lower L*, with increasing percentages of added HS. The darkening of the crust for gluten-free breads (Sabanis et al., 2009; Gül and Şen, 2017) and layer cakes (Gómez et al., 2010) with increasing levels of added fiber was also reported in literature. The darker crust color obtained for cakes in the presence of added fibers was not reported to be due to the original color of the fiber; instead, it was mainly associated with the Maillard and caramelization reactions (Gómez et al., 2003). Fibers were suggested to change the pH of the batter by acting as a buffer or to change the available water in the batter, which might both affect the Maillard reactions and their resulting effects on crust color (Gómez et al., 2010). The decrease found in the a* values of the cake crust with increasing levels of HS pointed out to a decrease in the redness of crust color, that led to the formation of a brownish red. This was indicative of more brownish crust formation with added HS. The decrease in the b* values with increasing levels of HS was indicative of a tendency towards the blue hue, suggesting a darker yellow color.

Crumb color depends to a high extent on raw materials since the increase in temperature is not high enough to give Maillard or caramelization reactions (Gómez et al., 2010). The L*, b* values for crumb decreased as the percentage of added HS increased (*P* <0.05), while the a* values for crumb showed an increasing trend (*P* <0.05). These parameters suggested a darker, less yellowish (brownish), and more reddish crumb in cakes due to the natural brown color of HS. Cıkrıkçı et al. (2016) also reported a decrease in L*, and an increase in a* values of cake crumbs when 10%-20% of wheat flour was replaced with different forms of HS. A decrease in b* values were only found with the addition of microfluidised HS. Anıl (2007) replaced 5% and 10% of wheat flour in bread with HS and found lower L* and b* values along with higher a* values for the crumb, concurring with the findings of this study.

Replacing the rice flour with HF in gluten-free cake formulations resulted in closer L*, a*, b* values of both crust and crumb to those of control when compared to cakes with added HS (Table 4). This was indicative of lighter crust and crumb colors for the cakes with HF than those of the cakes with HS (*P* <0.05). At higher levels of added HF (>10%), lower L* and b* values were obtained for the crumb when compared to those of control (*P* <0.05), suggesting a slightly darker creamy color formation in the cake crumb. When the color parameters for the cakes with the blend of HS and HF (1:1, w/w) were evaluated, a similar trend to that observed with the addition of HS was found for both crust and crumb, indicating the dominant effect of HS on the color characteristics of cakes.

Textural properties of cakes

Addition of increasing percentages of HS (5% to 15%) in rice flour-based gluten-free cakes resulted in a gradual increase (*P* <0.05) cake hardness (Table 5). A sharp increase was found in the resilience, cohesiveness, and springiness of cakes when 5% of rice flour in the formulation was replaced with HS. However, the values for these textural quality parameters decreased gradually as the amount of added HS in cakes increased up to 15% (Table 5). Nevertheless, the resilience, cohesiveness, and springiness values of cakes with HS even at 15% were higher than those of control (*P* <0.05). Gularte et al. (2012) also reported an increase in the hardness and cohesiveness, but a decrease in the resilience and springiness of rice flour-based gluten-free cakes when rice flour was replaced with fibers. The reason behind the decrease they found in the resilience and springiness of cakes with added fibers could be the higher replacement ratio [20% (w/w)] they used. Replacing flour with fiber (50, 80, 250 μm sized) at ratios up to 20% was suggested to improve the volume of wheat flour-based cakes (Gómez et al., 2010). The hazelnut skin used in this study was coarser with the particle size ≤ 2 mm and the best cake quality in terms of volume and texture was obtained with 5% added HS (Tables 4 and 5). Small sized fibers were found to better improve cake quality (Gómez et al., 2010). Thus, these findings revealed that the percentage of the insoluble fiber added in cake formulations should be lower (i.e., 5%, w/w, on flour weight basis) for an improved cake quality, if the fiber particles are coarse.

Replacing rice flour with HF up to 15% did not significantly affect the hardness of gluten-free cakes (*P* >0.05). However, an increase was found in the resilience, cohesiveness, and springiness of cakes with HF when compared to control (*P* <0.05). The increase in hardness observed for the cakes with HS was reduced (*P* <0.05) with the addition of HS-HF blend (1:1, w/w), but the hardness values were still higher than that of control (*P* <0.05).

A strong negative correlation was found between cake density and volume index (Table 4) with the addition of HS, HF, and HS-HF blend (r=-0.9908, r=-0.9902, and r=-0.9637, respectively). Cakes with relatively lower volume were found to be denser and had a packed crumb structure, which resulted in harder texture (Sabanis et al., 2009; Aydoğdu et al., 2018). However, cake hardness and cake density obtained in this study for the cakes with added HS (r=-0.3094) and HF (r=-0.4630) provided weak correlations. This was due to the simultaneous contribution of HS to air incorporation in the batter and to cake hardness resulting from its water absorption ability. On the other hand, HF did not significantly alter cake hardness due to its high oil content; however, it showed detrimental effect on cake volume that led to an increase in cake density. Thus, cake density and hardness did not show a clear correlation for the cakes with added HS and HF.

Table 5. Textural quality parameters of gluten-free cakes with hazelnut skin and hazelnut flour

Sample		Hardness (N)	Resilience	Cohesiveness	Springiness
Control		1.017±156.62[a]	0.151±0.00[a]	0.410±0.21[a]	0.542±0.03[a]
Hazelnut skin					
	5%	1.69±118.12[c,d]	0.214±0.00[h]	0.521±0.00[e]	0.726±0.01[e]
	10%	1.85±57.98[d]	0.193±0.00[e,f]	0.479±0.01[c]	0.682±0.02[c,d]
	15%	1.88±158.34[d]	0.176±0.00[b]	0.450±0.01[b]	0.673±0.01[c,d]
Hazelnut flour					
	5%	1.067±86.41[a]	0.189±0.00[d]	0.478±0.01[c]	0.627±0.02[b]
	10%	1.021±171.87[a]	0.181±0.00[c]	0.469±0.01[c]	0.614±0.02[b]
	15%	1.007±49.87[a]	0.198±0.00[g]	0.504±0.00[d]	0.662±0.01[c]
Hazelnut skin + hazelnut flour					
	5%	1.366±51.35[b]	0.232±0.00[i]	0.548±0.00[f]	0.732±0.01[e]
	10%	1.471±108.81[b]	0.197±0.00[f,g]	0.502±0.01[d]	0.704±0.01[d,e]
	15%	1.522±63.92[b,c]	0.194±0.00[e,f,g]	0.474±0.00[c]	0.696±0.03[c,d,e]

Columns with different letters are significantly different ($P < 0.05$).

Predicting cake quality through batter properties

Correlations of the linear viscoelastic properties of cake batters with cake quality

It has been well established that rheological properties of dough/batter systems are used to predict baked product quality (Ronda et al., 2017; Marchetti et al., 2020; Yazar and Demirkesen, 2023). In this section, the correlations of the Power-Law model parameters obtained in the linear viscoelastic region for cake batters with added HS, HF, and HS-HF blend with the volume and textural properties of the resulting cakes.

A positive correlation was found between the Power-Law exponent value "*a*" and volume indices (r = 0.9447) of cakes with the addition of HS, while addition of HF resulted in a negative correlation between these parameters (r=-0.8668). Ultimately, no strong correlation was found between *a* and cake volume (r=0.3481) when the rice flour in cake formulations was replaced with the HS-HF blend (1:1, w/w). When the correlations of the exponent *a* and $(\tan\delta)_{\omega 1}$ were evaluated, the Pearson coefficients were r=0.9552, r=0.7061, and r=0.1927 for cake batters with HS, HF, and HS-HF blend (1:1, w/w), respectively. High Pearson coefficient, as in the case for the batters with HS and HF, was suggested to allow the prediction of loss tangent from the exponent *a* and vice versa (Ronda et al., 2017). The positive correlations between *a* and $(\tan\delta)_{\omega 1}$ revealed that the more frequency-dependent the doughs were, the more fluid-like behavior they had. Thus, these correlations led us to the fact that the increase in the fluid-like behavior of the batter resulted in an increase in volume for the cakes with added HS at 0-10% (w/w), while causing a decrease in volume for those with added HF at 0-15% (w/w). This finding emphasized the contribution of fibers to the air incorporation in batter, and thus to cake volume, as previously reported by others (Gómez et al., 2010; Kırbaş et al., 2019; Özyiğit et al., 2019). This effect was more evident when HS was added at 5% and then at 10%, as evidenced by the specific gravities of these batters (Table 3). The water binding ability of HS became more dominant when rice flour was replaced with HS at concentrations above 10%. And thus, the cake batter with 15% HS became less fluid-like and it had lower tanδ compared to those with 5% and 10% HS (Figure 3). Viscosity of cake batter is the controlling factor for the final cake volume. Higher cake batter viscosities help to retain more air bubbles in the batter and retard the rise of bubbles to the surface during baking. A highly viscous batter (less fluid-like) can hold the air bubbles inside; however, the expansion of this batter is restricted because of its high viscosity (Şahin, 2008). For this reason, cake batters became less fluid-like (tanδ decreased) as the percentage of HS increased from 5% to 15%, while the volumes of the resulting cakes decreased. The strong positive correlation between the loss tangent and cake volume (r=0.9978) for the cakes with HS (0%-15%, w/w) supported this finding. Among the cake batters with added HS, the highest tanδ was found for the batter with 5% (Table 2). And the resulting cake with 5% HS had the highest volume index (Table 4). Besides, tanδ values of the batter with 15% HS and control were the same as shown in Figure 3, whereas the cakes resulting from these batter samples had similar ($p>0.05$) volume indices (Table 4).

The volume of cakes with added HS showed strong positive correlation with the slope of G′ obtained versus frequency (r=0.9939), while a negative correlation was found between these parameters for the cakes with HF (r=-0.9408) and a weak correlation (r=0.4079) was found for the cakes with HS-HF blend. The correlations of cake volume index with the slope of G′ versus frequency were similar to its correlations with the Power-Law exponent *a*. And thus, strong positive correlations between *a* and the slope of G′ were found for the cakes with HS (r=0.9533), with HF (r=0.8985), and with HS-HF blend (r=0.9462). These correlations revealed that the Power-Law exponent *a* acted as a marker of elastic stability versus frequency.

The crumb hardness for the cakes with added HF (0%-15%, w/w) negatively correlated with the Power-Law exponent "*b*" (r=-0.9875). A negative correlation between crumb hardness and *b* (r=-0.68) was also provided by Ronda et al. (2015). The correlations between cake hardness and *b* were positive and weaker for the samples with added HS (r=0.4772) and HS-HF blend (r=0.7392). These correlations showed that the increase in the exponent *b*, indicative of viscous decay versus frequency, resulted in the reduction of cake hardness when the rice flour in cake formulation was replaced with HF. The correlation between these parameters shifted from negative to positive when rice flour was replaced with HS due to the water binding ability of HS. This means the viscous decay of cake batter might increase with added HS; however, it absorbs the available water in the batter system during baking, leading to an increase in cake hardness. Insoluble dietary fibers, such as HS, were reported to have high water absorption and high swelling properties without an increasing effect on viscosity (Föste et al., 2020). However, at percentages as high as 15% of rice flour replacement with HS, the binding of the available water in batter became evident even before baking (Table 3) and thus the exponent *b* showed a drop (Table 2), which explains the reason behind the weaker correlation obtained between *b* and cake hardness for the cakes with HS.

Correlation of specific gravity of cake batter with cake volume

Specific gravity has been regarded as an important batter property that helps predicting the resulting cake volume. Specific gravity values found in this study showed strong negative correlations with the volume indices of cakes with added HS (r=-0.9798), HF (r=-0.9563), and HS-HF blend (r=-0.9978) at ratios ranging from 0% to 15% (w/w) to replace rice flour in formulations. Low specific gravity in cake batters was associated with high volume in the resulting cakes, suggesting a negative correlation between the specific gravity of batter and the volume of the resulting cake (Turabi et al., 2008; Matos et al., 2014; Kırbaş et al., 2019). The highest specific gravity was obtained for the cake batter with 15% HF (Table

3) and thus the resulting cake with 15% HF showed the lowest volume index (Table 4). On the other hand, the cake batter with 5% HS having the lowest specific gravity (Table 3) resulted in the cake sample with the highest volume (Table 4).

CONCLUSION

Replacing rice flour with hazelnut skin (particle size ≤ 2 mm) in gluten-free cake formulations improved air incorporation into batter at 5%, as evidenced by the lower specific gravity of this batter compared to control. The specific gravity of batters with HS increased gradually as the percentage of HS increased. Increasing levels of HS, especially at 10%, disrupted the continuity of batter and imparted a more fluid-like behavior as evidenced by the decrease in K, G′, and G″. However, above 10% of rice flour replacement with HS, water activity increased, viscosity increased, tanδ dropped, and all these changes in batter collectively pointed out to the dominating effect of water binding ability of hazelnut skin. Thus, the highest volume in the resulting cakes was obtained with 5% HS. Even though, the cake with 5% HS had the highest volume, its hardness increased compared to control, which could be attributed to the high water binding and swelling properties of insoluble fibers during baking. The color parameters L*, b* were lower, while a* was higher for the crumb of the cakes with added HS, suggesting a darker and brownish crumb color in comparison to that of control.

Rice flour-based cakes became denser and had lower volumes compared to control when rice flour was replaced with HF at percentages up to 15%. However, the hardness of cakes was not affected by the addition of HF due to its high oil content. Besides, the color characteristics of the cakes with HF were similar to those of control. And therefore, to balance the conflicting effects of HS and HF on gluten-free cake volume and texture, this study showed that replacing 5% to 15% of rice flour with the blend of HS-HF on an equal weight basis (1:1, w/w) could be an alternative to improve the volume, texture, taste, while enhancing the nutritional profile of gluten-free cakes. The only drawback in terms of consumer acceptance has been considered to be the darker color imparted by the added hazelnut skin to the cakes, especially to the crumb, which can be easily eliminated by the addition of cocoa.

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CONFLICT OF INTEREST

The author has declared no conflict of interest.

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