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ORIGINAL PAPER

The effects of different baking methods on the textural, physicochemical and sensory properties, and in vitro antioxidant bioaccessibility of gluten-free muffins formulated with egg and various egg replacers

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Abstract

The growing demand for gluten-free and vegan bakery products has driven research into alternative formulations. This study developed novel gluten-free, vegan, and refined sugar-free muffins using tahini, dates, and carob, with chia, flaxseed, and psyllium as plant-based egg replacers. Muffins were prepared by steaming and oven baking, and their physical, nutritional, antioxidant, and sensory properties were evaluated. Steamed muffins showed significantly higher moisture (up to 14.10%) and water activity (Aw = 0.746) than baked samples (moisture as low as 1.70%, Aw = 0.444, $p < 0.05$). Baked muffins were firmer, with higher HMF (up to 81.60 mg/kg), lighter crust color (L = 34.49), and greater total color difference (ΔE = 25.9), while steamed samples were softer, darker, and exhibited higher browning index (BI = 70.2). Total phenolic content (TPC) and total antioxidant activity (TAA) were highest in baked chia muffins (TPC = 1258.19 mg GAE/100 g, FRAP = 212.27 µmol TE/g), though steamed muffins better preserved phenolics post-digestion. Sensory evaluation favored steamed flaxseed muffins (acceptability = 4.50/5), while baked psyllium muffins scored lowest. This is the first study to combine tahini, dates, carob, and multiple egg substitutes in steamed and baked muffins. Results highlight steam cooking and plant-based binders as effective strategies to enhance nutritional, antioxidant, and sensory qualities for health-conscious consumers.

Keywords Egg replacement · Gluten-free Muffin · HMF · in vitro bioaccessibility · Tahini

Introduction

Muffins are among the most popular bakery products due to their affordability, variety, and soft texture, appealing to all age groups. Their high energy value comes from substantial carbohydrates, protein, and fat, yet they lack dietary fiber, vitamins, and minerals [1, 2]. In response to rising health awareness, food allergies, celiac disease, and vegan or religious dietary restrictions, there is growing demand for functional, gluten-free, and vegan products [2]. Consequently, the bakery industry is exploring alternative ingredients to enhance nutritional and sensory qualities.

Muffins are suitable carriers for health-promoting components, given their favorable texture and structure. Their porous volume is achieved with ingredients like eggs, milk proteins, and fats that stabilize air bubbles and improve moisture [3]. In this study, we targeted gluten-free, refined sugar-free, and vegan muffins using tahini as a flour and fat substitute, dates as a natural sweetener, and carob powder to enhance flavor and phytonutrients. To replace eggs, chia seeds, flax seeds, and psyllium husk were incorporated for their gelling and binding properties.

Tahini, made from sesame seeds, is rich in protein, healthy fats, and micronutrients like calcium and iron. Its emulsifying properties improve batter homogeneity and

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shelf life while enabling gluten-free baking [4]. Dates contribute natural sweetness, fiber, vitamins, minerals, and antioxidants, enhancing both nutrition and stability [5]. Carob, high in fiber and polyphenols, adds cocoa-like flavor and further improves the muffins' nutritional profile [6].

Eggs are widely used in bakery products for their multifunctional roles, but the growing plant-based market drives the search for alternatives. Egg replacers such as chia, flax, and psyllium provide functional properties while meeting vegan and allergen-free needs [7, 8]. Chia and flax are rich in dietary fiber, omega-3 fatty acids, proteins, vitamins, and antioxidants, while psyllium mimics gluten's texture-enhancing qualities [9, 10].

Plant-derived polysaccharides from chia, flax, and psyllium contribute to improved stability, texture, and sensory properties [11]. Chia seeds, with their high insoluble fiber and α-linolenic acid, supply essential amino acids and minerals [10]. Flax seeds, abundant in lignans, fiber, and phytoestrogens, offer antioxidant and health-promoting benefits [12]. Psyllium, known for its digestive health benefits, also enhances gluten-free formulations [13].

Baking significantly influences muffins' quality, with oven and steam methods producing distinct textures and appearances. Steam baking yields a denser, smoother surface compared to the crusty texture of oven-baked products [14, 15].

This study compares the effects of two cooking methods and three egg replacers on the physical, nutritional, and sensory properties of gluten-free, vegan muffins. Evaluations included water activity, texture, color measurement (L*, C*, H*, ΔE, BI), protein, antioxidant capacity, phenolic content, and bioaccessibility, highlighting how baking method and egg replacer type influence the muffins' overall quality. To the best of our knowledge, this is the first study to systematically investigate the combined effects of tahini, dates, carob, and different egg replacers in both steamed and baked gluten-free vegan muffins, offering novel insights into their quality characteristics and nutritional value.

Materials and methods

Materials

The ingredients used for muffin samples- including tahini, dates, carob powder, egg, chia seeds, ground flax seeds, ground psyllium husk, apple vinegar, and baking soda- were obtained from a local market in Bursa, Turkey.

Methods

Production method

The Muffin production flow chart is presented in Fig. 1. Dates, whose skins were removed by soaking in hot water, were pitted and chopped into small pieces. Tahini, date and carob powder were weighed and mixed, and the resulting batter was divided into four parts Fig. 2.

Egg and egg replacers gels, as described in Table 1, were added to each batter sample, flowed by the addition of baking soda dissolved in vinegar. All batters sample were mixed using a Felix Sposa mixer and portioned into silicone muffin molds (Porlistan) at 15 g each prior to baking.

Muffin samples were cooked using two different methods: steam baking and oven baking. In both methods, the baking time was set at 15 min. An INOKSAN FKE−006 convection oven was used for the baking process, with a heat capacity of 10 kW, an electrical input of 380–400 V 3 N AC 50 Hz, and internal volume 0.12 m^3.

For oven baking, the temperature was set at 160 °C, while in the steaming method, muffin molds were placed in boiling water to complete the cooking process.

Analysis methods

Physical analysis

Muffin height and width

The muffin was removed from the baking case, and its height was measured as the vertical distance from the bottom to highest point at the center using calipers. The width of the muffin was determined by measuring the distance between the two farthest opposing points using calipers as described by Lee et al. [16].

Muffin weight

The weight of the cakes was assessed using a precision scale to recorded in grams.

Muffin volume

The volume of the muffin was assessed using the rapeseed displacement method. This method involved placing each muffin in a plastic beaker with a known total volume (Vt) and filling the remaining space in the beaker with rapeseed. The volume of rapeseed used (Vs) was measured using a graduated cylinder.

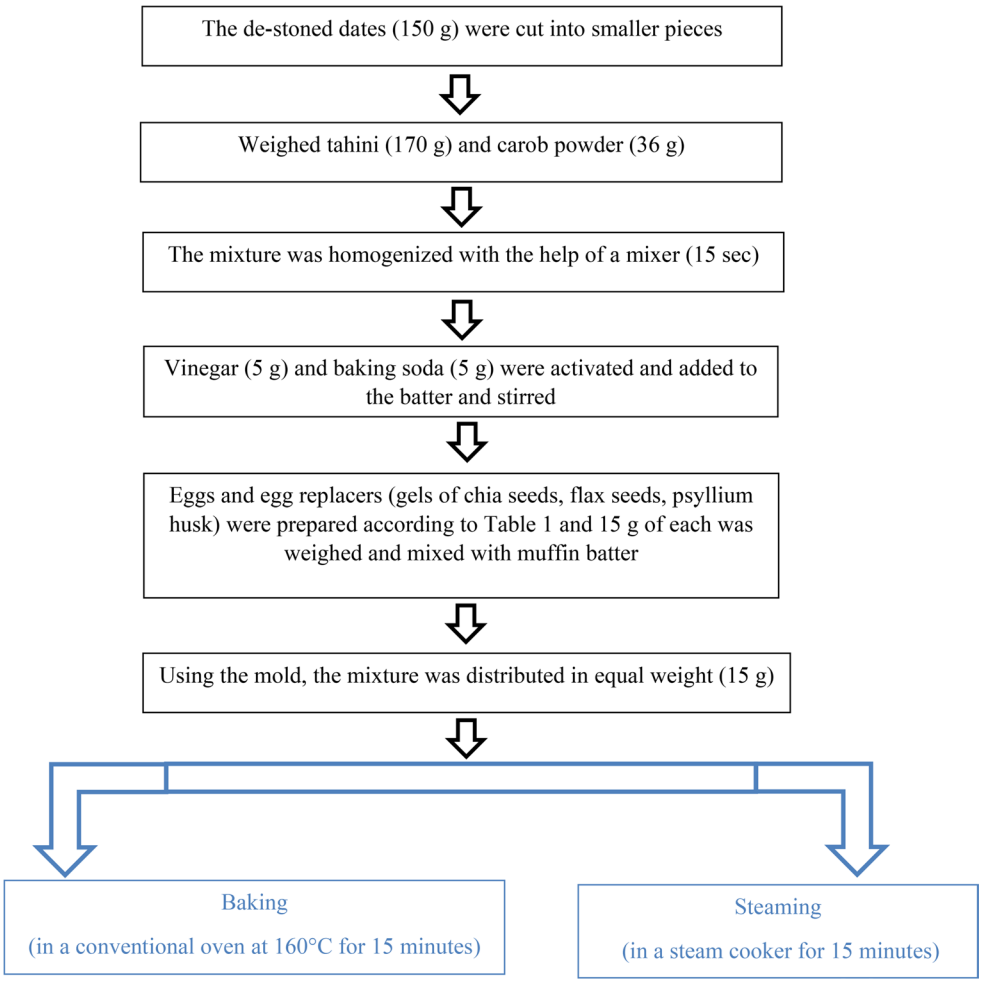


Fig. 1 Muffin production flow chart

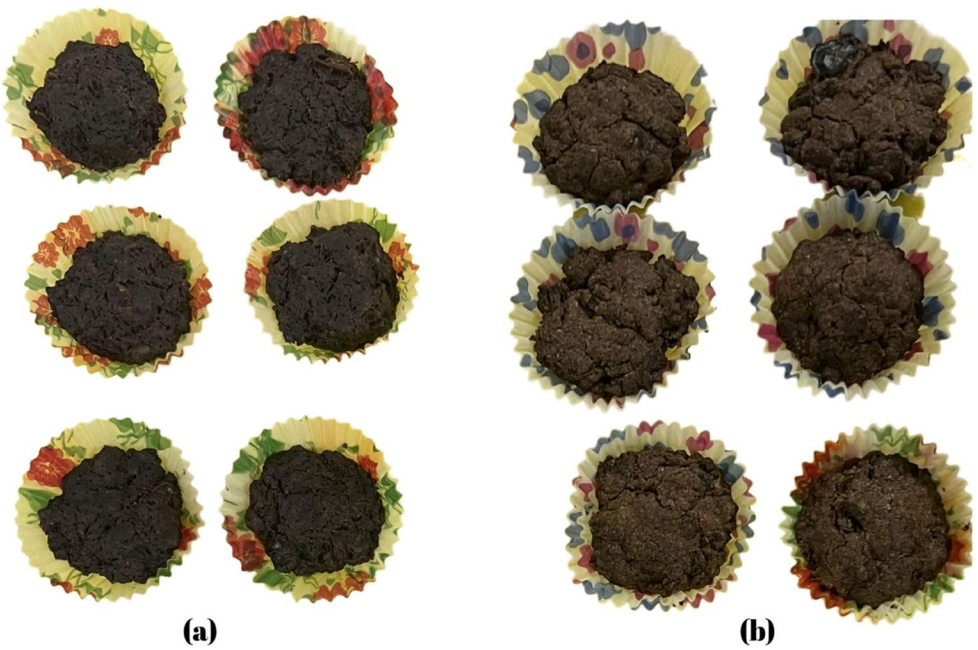


Fig. 2 (**a**) Baked muffins, (**b**) Steamed muffins

Table 1 Preparation of eggs and egg substitutes

Materials	Preparation methods
Egg	The egg white and yolk were homogenized.
Chia seed	8 g of chia seeds were mixed with 20 mL of water to from a gel.
Flax seed	8 g of ground flax seed were mixed with 20 mL of water to from a gel.
Psyllium husk	8 g of ground psyllium husk were mixed with 200 mL of water to from a gel.

The muffin volume was then calculated by subtracting the volume of the rapeseed from the total volume of the beaker as expressed by the equation according to Lin et al. [17]:

$$\text{Muffin volume} = Vt - Vs \tag{1}$$

Determination of water activity

Water activity (Aw) was measured at 25 °C in triplicate using an AQUALAB PRE water activity meter (Meter Group, WA, USA), following the method of Wie et al. [18].

Color measurement

Color parameters (L^* (lightness), a^* (redness), b^* (yellowness), C^* (chroma), H* (hue), ΔE (color variation index) and BI (browning index)) were determined on both crust and crumb surfaces using a 3nh NR145 handheld colorimeter (3nh, Shenzhen, China), as described by Ali et al. [19]. Three points per surface were measured, and ΔE, C*, h°, and BI were calculated using the following equations:

$$E = [(L^*)^2 + (a^*)^2 + (b^*)^2 2]^{1/2} \tag{2}$$

$$\boldsymbol{C*} = \sqrt{\boldsymbol{a^{*2}} + \boldsymbol{b^{*2}}} \tag{3}$$

$$h^\circ = \arctan\frac{b*}{a*} \tag{4}$$

$$\text{BI} = \frac{100}{0.17}\left(\frac{a^* + 1.75\,L^*}{5.645\,L^* + a^* - 0.012\,b^*} - 0.31\right) \tag{5}$$

Moisture

The moisture content of the muffin samples was determined using a digital moisture analyzer (MA150, Sartorius, Göttingen, Germany).

Protein analysis

Protein content will be determined using the Kjeldahl method as outlined in AOAC 992.23 (2019). Approximately 1.00 ± 0.01 g of sample will be incinerated to denature proteins, followed by distillation for 2.5 min and titration with 0.1 N HCl. The nitrogen content (%) will be calculated and converted to crude protein (%) using a conversion factor.

Texture profile analysis (TPA)

Texture properties (hardness, springiness, cohesiveness, and chewiness) were determined using a Lamy Rheology TX 700 texture analyzer (Lamy Rheology Instruments, France) equipped with a 500 N load cell and 34 mm flat compression probe. A double-compression test (4 mm distance, 0.2 mm/s) was conducted at 25 ± 1 °C, and force–distance curves were recorded for three replicates per sample [20].

The process of preparing extracts for the analysis of total phenolic content (TPC) and total antioxidant activity (TAA)

The muffin samples were extracted using the methodology outlined by Kamiloglu and Capanoglu [21]. Extraction was performed using 75% aqueous methanol containing 0.1% formic acid. A 2 g sample was mixed with 5 mL of the extraction solution and sonicated for 15 min. After centrifugation at 2700 g and 4 °C for 10 min, the supernatant was collected. This extraction step was repeated three times, yielding a total of 20 mL extract, which was stored at − 20 °C until analysis.

TPC and TAA

The TPC of muffins was analyzed using a UV-VIS spectrophotometer (UV-1800, Shimadzu) and determined through the Folin-Ciocalteu method. A mixture of 100 µL of extract and 0.75 mL of Folin-Ciocalteu (1:10) was incubated for 5 min, followed by the addition of 0.75 mL of sodium carbonate (6%) in test tubes. The tubes were then left at room temperature for 90 min, and the results were expressed as 'mg gallic acid equivalent (GAE)/100 g dry matter (dw) [21]. The TAA of muffins was analyzed using a UV-VIS spectrophotometer (UV-1800, Shimadzu). The TAA value of muffins was analyzed using the DPPH and FRAP methods. For the DPPH assay, a mixture of 0.1 mL of extract and 2 mL of DPPH solution was vortexed for 30 seconds using the Vortex Mixer Classic, followed by a 30 minute incubation period in dark condition. A calibration curve was constructed using various concentrations of trolox, yielding results expressed as µmol trolox equivalent (TE) per g dry weight (R^2 = 0.9972) [22]. In the FRAP method, a mixture of 100 µL extract and 900 µL FRAP solution was incubated for 4 minutes at room temperature, with results reported as µmol trolox equivalent (TE) per g dry weight (R^2 = 0.9992) [23].

Hydroxymethylfurfural (HMF) determination

HMF content was measured spectrophotometrically using the Winkler method [24]. Ground muffin samples (2 g) were homogenized in 10 mL distilled water, vortexed, incubated at 40 °C for 15 min, and centrifuged. The supernatant was clarified with Carrez I and II reagents, re-centrifuged, filtered (0.45 μm), and absorbance was recorded at 284 nm and 336 nm. HMF concentration (mg/kg) was calculated against a standard calibration curve ($R^2 \geq 0.994$).

In vitro gastrointestinal (GI) digestion

The in vitro gastrointestinal (GI) digestion extracts were prepared following the method described by Minekus et al. (2014) [25] with some adjustments. This procedure involved simulating the processes of gastric and intestinal digestion in a laboratory setting. To simulate gastric digestion, a mixture was prepared using simulated gastric fluid, porcine pepsin (25,000 U/mL, Sigma-Aldrich P6887; USA), and calcium chloride. The pH of the gastric phase was maintained at 3.0 by adding hydrochloric acid, and the mixture was incubated in a shaking water bath at 37 °C for 2 h. Samples of 4 mL were then collected. For the intestinal phase, the residue from the gastric phase was combined with simulated intestinal fluid, pancreatin solution (800 U/mL, Sigma Aldrich P3292), and bile solution (160 mM). The pH of the intestinal phase was adjusted to 7.0 with NaOH, and the mixture was again incubated at 37 °C for 2 h in a shaking water bath. The solutions were then centrifuged at 3500 rpm for 10 min to separate solid particles, and the supernatant was collected after filtration. The in vitro gastric and intestinal digested phases were stored at -20 °C.

Sensory evaluation

The evaluation of the sensory attributes and characteristics of a product. A sensory evaluation was conducted by seven panelists affiliated with the Food Engineering Department at Bursa Uludag University. Each sample was assigned a three-digit code and evaluated using a 5-point scale. Sensory analysis was carried out in 3 different sessions and panelists evaluated and scored the same samples in 3 sessions. The panelists assessed various attributes of muffins including outer color, interior color, chewability, hardness, odor, flavor and general acceptability. In this study, participants were informed about the product content and the relevant principles and guidelines for the sensory evaluation of muffin samples. This study involved sensory analysis conducted by a trained panel. Although there was no formal ethics commitie, informed consent was obtained from all participants to ensure ethical treatment of the study participants. This information sheet explained the study procedures, potential risks, and participants' rights.

Statistical analysis

The statistical analysis was carried out using the IBM SPSS Statistics 23 software (USA). ANOVA and Duncan's multiple range test were employed to identify significant differences between means at $p < 0.05$. Each evaluation was repeated three times, and the values were presented as mean ± SD.

Results and discussion

Physical analysis

Muffin height and width

The physical analysis results of muffin samples are presented in Table 1. Among the samples, the highest width value was observed in Sample 7. This measurement, which provides information about the extent of batter spread after baking, indicates that steamed muffins exhibited greater spreading than baked muffins across all samples.

Nezhad and Butler (2009) [26] conducted a study on the post-baking spread of cookies produced using various types of flour. Their findings demonstrated a direct correlation between batter viscosity and the extent of cookie spread.

In terms of height, the highest values were found recorded in both Sample 4 and Sample 6.

Muffin weight

After cooking, the greatest weight loss was determined in Sample 2.

Muffin volume

Volume measurement shows the rising capacity of the batter after baking. Accordingly, the baked muffin with egg (Sample 2) exhibited the highest volume. This sample was followed by steamed muffin containing psyllium husk (Sample 3), steamed muffin containing chia seeds (Sample 5) and baked muffin containing flax seed (Sample 8).

Steamed samples containing psyllium husk and chia seeds had higher volume than their baked counterparts. However, baked muffins containing egg and flaxseed showed higher volume than their steamed versions.

In a previous study, sweet potato-oat cakes were developed and it was reported that the specific volume of sweet potato-oat cakes increased with increasing oat flour addition

to the batter. The inclusion of oat flour had a significant effect on the specific volume of the product ($p < 0.05$). This may be attributed to the progressive formation of protein network structure as oat flour content increases. With further oat flour, incorporation, this structure is strengthened, enhancing the gas product's gas-holding capacity and thus increasing its volume [27].

The presence of proteins in cake products plays an important role in determining its volume by forming a stable thermal gel that supports the structural integrity of the cake during baking. Achieving a high cake volume often depends on the efficiency of gel formation, especially the use of egg proteins. Although it was initially hypothesized that cakes made without egg may lack this important gel-forming capacity, studies have shown no clear difference in volume between cakes made with egg substitutes and those made with egg [28].

Determination of water activity

Water activity (Aw) of muffin samples significantly ($p < 0.05$) varied depending on the type of egg replacer and cooking method (Table 2). Steamed muffins consistently exhibited higher Aw values than their baked counterparts, consistent with the known effect of steam cooking in preventing surface drying and crust formation. This higher Aw in steamed samples aligns with their elevated moisture content, indicating that moisture retention during cooking directly influences the amount of free water available in the product, as previously noted by [29].

Among the samples, the muffin containing psyllium husk exhibited the highest Aw, despite having the lowest fat content. This finding supports literature suggesting that lipids reduce Aw by encapsulating free water [20], whereas hydrocolloids such as psyllium enhance Aw by increasing water retention through hydrogen bonding and by thickening the batter [29]. Similarly, muffins with other hydrocolloid-rich ingredients such as chia and flaxseed also showed elevated Aw, consistent with their ability to bind water and limit evaporation [29].

Egg-containing muffins, in contrast, displayed the lowest Aw values. This may be attributed to egg proteins tightly binding water within the matrix, reducing the proportion of free water available for microbial growth. The observed trend of Aw increasing with hydrocolloid content and steam treatment reflects both ingredient composition and processing effects, reinforcing that both formulation and cooking method significantly impact Aw and, consequently, product shelf life.

Color measurement

Color measurements of the muffin samples showed significant differences depending on the type of egg replacer and the cooking method (Table 3). In general, baked samples exhibited higher L* and C* values on the crust and cut surface compared to steamed samples, indicating a lighter and more vivid color. The highest L* value (34.49) was observed in the baked flaxseed muffin (Sample 8), while the lowest (12.52) was recorded in the steamed flaxseed muffin (Sample 7), reflecting the darkening effect of steaming and hydrocolloid-rich binders. Conversely, ΔE and BI values were markedly higher in baked muffins—especially in the baked psyllium muffin (Sample 4), which also had the highest BI (70.2) and HMF content (81.6 mg/kg), suggesting a strong link between Maillard reaction, browning and HMF formation.

Samples containing chia and flaxseed displayed darker and less saturated crust colors when steamed, likely due to their high phenolic and mucilage content, which can interact with proteins and sugars during heating and influence color development [30, 31]. Notably, steamed samples consistently showed lower BI and HMF values than baked ones, consistent with the milder temperatures and higher moisture of steam cooking, which limit Maillard browning reactions [32].

Table 2 Physical analysis results of muffin samples

Samples*	Width (cm)	Height (cm)	Weight (g)	Volume (mL)	Water activity (Aw)
1	4.03 ± 0.05^{ab}	1.76 ± 0.11^{c}	13.86 ± 0.86^{a}	7.50 ± 0.10^{c}	$0.662 \pm 0.021^{Ab**}$
2	4.00 ± 0.10^{abc}	1.90 ± 0.10^{bc}	12.46 ± 0.18^{b}	8.63 ± 0.15^{a}	0.482 ± 0.011^{Bd}
3	3.86 ± 0.20^{bcd}	1.83 ± 0.05^{c}	14.27 ± 0.58^{a}	8.10 ± 0.10^{b}	0.746 ± 0.004^{Aa}
4	3.76 ± 0.50^{d}	2.13 ± 0.15^{a}	13.59 ± 0.89^{ab}	7.50 ± 0.10^{c}	0.459 ± 0.005^{Be}
5	3.90 ± 0.10^{bcd}	1.86 ± 0.11^{bc}	14.23 ± 0.81^{a}	8.16 ± 0.25^{b}	0.742 ± 0.021^{Aa}
6	3.80 ± 0.10^{cd}	2.13 ± 0.05^{a}	13.32 ± 0.55^{ab}	7.50 ± 0.10^{c}	0.444 ± 0.002^{Be}
7	4.13 ± 0.15^{a}	2.03 ± 0.02^{ab}	14.22 ± 0.78^{a}	7.53 ± 0.05^{c}	0.744 ± 0.006^{Aa}
8	3.90 ± 0.1^{cd}	2.03 ± 0.05^{ab}	13.65 ± 0.62^{ab}	8.06 ± 0.15^{b}	0.519 ± 0.010^{Bc}

**Different uppercase superscripts in the same column and lowercase superscripts in the same row indicate statistically significant differences ($p < 0.05$)

*1: Steamed muffin containing egg, 2: Baked muffin containing egg, 3: Steamed muffin containing psyllium husk, 4: Baked muffin containing psyllium husk, 5: Steamed muffin containing chia seeds, 6: Baked muffin containing chia seeds, 7: Steamed muffin containing flax seed, 8: Baked muffin containing flax seed

Table 3 Color measurements of muffin samples

Samples*	Crust color					Cut surface color				
	L*	ΔE	C*	h°	BI	L*	ΔE	C*	h°	BI
1	15.08±0.58^{Bd}	0.00±0.00^{C}	27.50±1.07^{Acd}	60.70±2.13^{Abc}	50.9±0.40^{C}	31.59±0.62^{Aa}	0.00±0.00^{C}	35.36±0.70^{Bc}	47.88±0.44^{Abc}	48.7±0.3^{C}
2	24.47±1.44^{Ac}	13.9±0.60^{B}	30.90±2.00^{Abc}	53.71±1.87^{Bcd}	62.4±0.50^{A}	27.59±0.60^{Ba}	7.4±0.5^{B}	41.75±1.56^{Ac}	46.92±0.95^{Ac}	55.6±0.4^{A}
3	13.04±2.07^{Bd}	4.4±0.40^{C}	30.64±1.70^{Bbc}	51.11±5.03^{Ad}	57.1±0.60^{B}	18.46±3.57^{Ab}	13.2±0.6^{A}	26.47±2.36^{Bd}	56.84±3.65^{Aa}	52.8±0.5^{B}
4	28.99±0.34^{Ab}	22.3±0.80^{A}	39.74±0.53^{Aa}	48.31±0.16^{Ad}	70.2±0.70^{A}	26.88±4.68^{Aa}	19.1±0.9^{A}	37.38±2.00^{Ac}	51.47±1.82^{Aabc}	60.9±0.6^{A}
5	13.63±0.16^{Ad}	2.9±0.30^{C}	24.99±0.05^{Ade}	67.61±0.20^{Aab}	48.5±0.50^{C}	7.27±1.12^{Ac}	10.3±0.4^{B}	54.08±3.07^{Bb}	20.77±0.65^{Ae}	42.6±0.4^{D}
6	21.08±5.90^{Ac}	13.1±1.20^{B}	35.14±0.36^{Aab}	46.78±0.54^{Bd}	58.7±0.80^{B}	4.38±3.40^{Ac}	14.7±1.1^{A}	75.61±0.16^{Aa}	6.25±0.02^{Af}	50.4±0.6^{B}
7	12.52±0.72^{Bd}	5.6±0.50^{C}	20.05±1.93^{Be}	72.10±3.88^{Aa}	44.8±0.40^{D}	6.45±3.01^{Bc}	16.4±0.7^{A}	20.78±0.67^{Bd}	55.51±1.61^{Aab}	41.2±0.3^{D}
8	34.49±3.23^{Aa}	25.9±1.10^{A}	28.29±0.89^{Acd}	53.18±3.01^{Bcd}	55.9±0.70^{B}	20.37±0.29^{Ab}	20.8±1.0^{A}	42.59±6.98^{Ac}	36.99±0.51^{Bd}	53.5±0.7^{B}

**Different uppercase superscripts in the same column and lowercase superscripts in the same row indicate statistically significant differences ($p<0.05$)

*1: Steamed muffin containing egg, 2: Baked muffin containing egg, 3: Steamed muffin containing psyllium husk, 4: Baked muffin containing psyllium husk, 5: Steamed muffin containing chia seeds, 6: Baked muffin containing chia seeds, 7: Steamed muffin containing flax seed, 8: Baked muffin containing flax seed

These findings align with prior studies reporting that high-temperature, dry-heat baking promotes Maillard reaction products, resulting in higher browning index and HMF, whereas steaming helps preserve a lighter appearance and reduces undesirable browning [30–32]. The darker and more intense hues of baked muffins are therefore attributable to both the dry heat of baking and the presence of fiber- and phenolic-rich ingredients like psyllium and flaxseed, which can intensify browning reactions.

In summary, both the baking method and the choice of egg replacer significantly affected the color attributes of muffins, with baked samples showing lighter but more browned surfaces, and steamed samples being darker yet with lower BI and HMF, reflecting the interplay between formulation and cooking method in controlling appearance and chemical browning.

Moisture

The moisture content of the muffin's samples varied significantly ($p<0.05$). When comparing the samples, it was observed that the steamed muffins exhibited higher moisture values than baked counterparts (Table 4).

In a study conducted by Altamirano-Fortoul et al. [33], it was reported that oven-baked samples exhibited increased porosity, as well as the formation due to airflow. In contrast, the muffins baked using steam in our study did not develop an outer crust, which likely enhanced moisture retention and resulted in higher moisture content in steam-baked muffins.

Protein analysis

The protein content of the muffin samples ranged from 11.50% to 16.94% (Table 4). The differences between protein content of the samples were statistically significant ($p<0.05$). The highest amount of protein was found in steamed

Table 4 Proximate composition of muffin samples

Samples*	Moisture (%)	Protein (%)
1	9.36±0.02^{d}	16.94^{a**}
2	2.54±0.01^{g}	14.00^{c}
3	12.76±0.01^{b}	13.31^{d}
4	3.43±0.02^{f}	11.81^{f}
5	11.01±0.01^{c}	13.01^{e}
6	1.7±0.00^{h}	11.50^{h}
7	14.10±0.02^{a}	14.68^{b}
8	5.61±0.02^{e}	11.72^{g}

**Values followed by different superscripts within the same column are significantly different ($p<0.05$)

*1: Steamed egg muffin, 2: Baked egg muffin, 3: Steamed psyllium husk muffin, 4: Baked psyllium husk muffin, 5: Steamed chia seed muffin, 6: Baked chia seed muffin, 7: Steamed flax seed muffin, 8: Baked flax seed muffin

muffin containing egg (Sample 1), while the lowest protein content was detected in baked muffin containing chia seed (Sample 6). As expected, the samples containing egg had higher protein content. As an ingredient, eggs are widely recognized as a superior protein source due to their high protein content and excellent amino acid profile. Unlike many plant-based proteins, which often contain lower overall protein levels and may lack one or more essential amino acids, eggs provide all nine essential amino acids in sufficient quantities to meet human dietary requirements [34].

Tahini also made a significant contribution to protein content of the muffin samples. A research study carried out by Sakketeu and colleagues [35] revealed that the protein content of tahini was 24%. Furthermore, the amino acid composition of tahini demonstrates a substantial abundance of essential amino acids, notably showcasing elevated levels of sulfur-containing amino acids such as methionine and cysteine, aromatic amino acids like phenylalanine and tyrosine, and tryptophan [36]. A study focused on the incorporation of tahini into baguette bread, with particular emphasis on the protein content of tahini. Results indicated that the protein content of the tahini-extensioned baguette bread was measured as 16% [37].

In other respects, other ingredients used muffin production like egg replacers and carob powder affected the protein content of the samples. For example the protein content of carob powder was reported as 5.54% in the literature. Also, flaxseed has a crude protein content of approximately 23%. The protein in flaxseed is particularly abundant in arginine, aspartic acid, and glutamic acid, while lysine, methionine, and cysteine are considered to be the limiting amino acids. Chia seeds and psyllium husk are known to have 15% and 20% protein content, respectively [38].

All of the steamed samples had higher protein content than their baked ones. The process of steaming food helps to retain its moisture and prevent it from becoming dehydrated, thereby aiding in the preservation of protein structure. Steaming is conducted at lower temperatures compared to alternative cooking techniques such as frying or baking, which mitigates the denaturation of proteins. The alterations in protein structure caused by thermal processing significantly affect the degradation and absorption of proteins. Heat exposure can modify the tertiary structure of proteins, thereby impacting their ability to be digested [39].

Texture profile analysis (TPA)

The texture properties of muffin samples, evaluated by force–strain compression tests (strain ~ 20%), showed significant differences depending on binder type and cooking method ($p < 0.05$). Detailed results of the compression test, including representative photographs and force–strain curves of the muffin samples, are presented in Fig. 3. The elastic modulus (stiffness indicator) of the samples decreased in the order: Sample 4 > 6 > 2 > 1 > 8 ≈ 7 > 5 > 3, indicating that baked muffins, particularly those with psyllium husk, exhibited the highest firmness and load-bearing capacity. In contrast, steamed muffins, especially with psyllium (Sample 3), had the softest structure. This difference is attributed to the high fiber content of psyllium forming rigid structures under dry heat, while moisture retention during steaming preserved a softer crumb.

Muffins with chia seeds also showed distinct behaviors: baked chia muffins (Sample 6) had higher force values than steamed ones (Sample 5), likely due to water loss and matrix densification during baking, while mucilage retained water in steamed samples, enhancing softness. Similarly, egg-containing muffins (Samples 1 and 2) demonstrated moderate to high firmness, consistent with the known gelling behavior of egg proteins during baking.

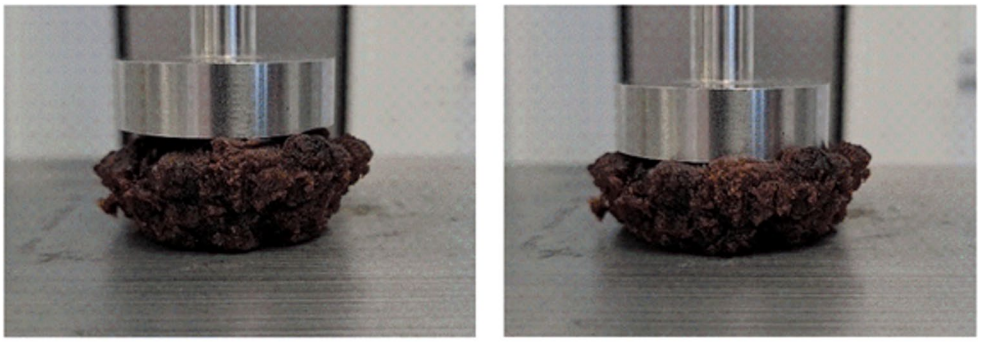
Flaxseed muffins displayed intermediate textures; the baked version (Sample 8) was firmer than the steamed one (Sample 7), suggesting that fat and mucilage content contributed to structural integrity differently under varying moisture conditions. Overall, baked samples were firmer and drier, while steamed samples were softer and more elastic, highlighting the impact of both formulation and processing.

These findings align with previous reports that higher moisture and fat content, as in chia- and flaxseed-rich steamed muffins, result in softer textures [29, 40]. Increased fat and hydrocolloid levels were associated with greater springiness [29, 41] and lower cohesiveness [29, 42], due to increased porosity and reduced internal bonding. In contrast, egg-based samples showed higher cohesiveness, reflecting their compact matrix and lower MOS (mannan–oligosaccharides) content. Together, these results confirm that texture is influenced by the interplay of moisture, protein, fat, hydrocolloids, and cooking method, and support the need for careful selection of binders and processing to achieve desired textural properties in gluten-free muffins.

Total phenolic content (TPC)

TPC values of undigested phase of muffin samples varied between 105.64 and 261.82 mg GAE/100 g dw (Table 5). The highest TPC value was determined in Samples 4, while the lowest TPC values were determined in Samples 3.

In one study, carob powder was added to muffin batter at 5, 10, 15 and 20% (w/w) and then baked at 180 °C for 20 min. The TPC values of the muffins obtained as a result of this study varied between 193.2 µg GAE/g dw and 829.1 µg GAE/g dw. TPC values increased as the amount of carob powder added to the batter increased [43].



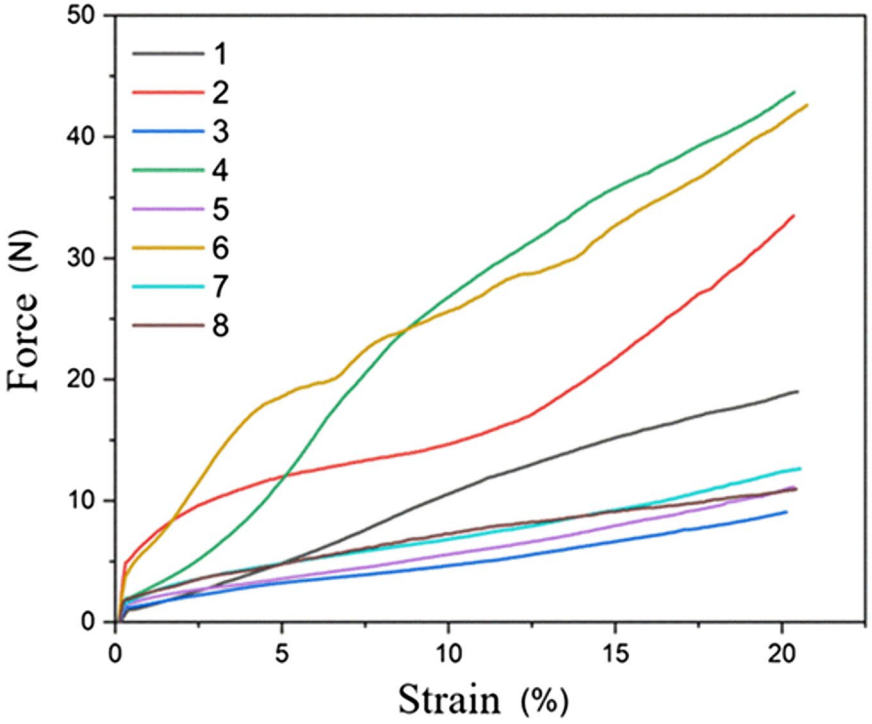


Fig. 3 Representative compression test photographs and force-strain curves of muffin samples, *1: Steamed egg muffin, 2: Baked egg muffin, 3: Steamed psyllium husk muffin, 4: Baked psyllium husk muffin, 5: Steamed chia seed muffin, 6: Baked chia seed muffin, 7: Steamed flax seed muffin, 8: Baked flax seed muffin

Similar to our study, Hao and Trust (2012) [44] reported that the TPC values of a flaxseed muffin and muffin containing egg were 128.4 mg GAE/100 g and 102.65 mg GAE/100 g, respectively. A study on Chinese steamed bread (CSB) enriched with flaxseed husk extracts revealed a significant increase in TPC, increasing from 170 mg GAE/100 g to 405 mg GAE/100 g. This increase in TPC is attributed to the high phenolic levels found in flaxseed, measured at 536.22 mg GAE/100 g [44].

Phenolic compounds are susceptible to oxidation and heat treatments; however, the processing of food can result in the release of these compounds from the food matrix, leading to an increase in TPC.

When the samples prepared with egg and different egg substitutes were compared, the steamed samples containing egg and flaxseed showed higher TPC values than those baked in the oven. Steaming is generally more effective in preserving the TPC of muffins compared to baking. The moist, lower-temperature environment of steaming minimizes the thermal and oxidative degradation of phenolic compounds, thus retaining their bioactive properties. In contrast, the high temperatures and dry conditions of baking lead to significant losses in phenolic content due to thermal degradation and oxidation. Consequently, for the purpose of maximizing phenolic retention and antioxidant capacity, steaming is the preferred cooking method [45]. In contrast, the baked samples containing chia seeds and psyllium husk had higher TPC values than the their steamed ones.

In a recent study by Kayacan et al. [46], the impact of different drying methods on dates was examined, revealing

Table 5 TPC values and its in vitro bioaccessibility in muffin samples

Samples*	UD (mg GAE/100 g dw)**	GD (mg GAE/100 g dw)**	ID (mg GAE/100 g dw)**
1	$167.92 \pm 4.84^{bC***}$	558.96 ± 6.56^{dA}	523.93 ± 1.92^{eB}
2	123.39 ± 8.03^{cC}	851.53 ± 0.57^{cA}	744.58 ± 6.72^{bB}
3	105.64 ± 5.60^{dC}	441.72 ± 3.44^{gB}	553.54 ± 0.22^{dA}
4	261.82 ± 4.43^{aC}	973.14 ± 6.35^{bA}	717.16 ± 6.54^{cB}
5	121.81 ± 4.44^{cC}	439.68 ± 3.44^{gB}	511.36 ± 1.05^{fA}
6	255.89 ± 4.04^{aC}	1258.19 ± 2.94^{aA}	799.53 ± 3.53^{aB}
7	164.32 ± 2.88^{bC}	504.22 ± 3.06^{eA}	490.07 ± 0.02^{gB}
8	106.92 ± 1.72^{dC}	469.39 ± 4.08^{fB}	475.34 ± 0.75^{hA}

*** Different uppercase superscripts in the same column and lowercase superscripts in the same row indicate statistically significant differences ($p < 0.05$)

*1: Steamed egg muffin, 2: Baked egg muffin, 3: Steamed psyllium husk muffin, 4: Baked psyllium husk muffin, 5: Steamed chia seed muffin, 6: Baked chia seed muffin, 7: Steamed flax seed muffin, 8: Baked flax seed muffin

**Undigested: Ud, In vitro gastric digested: GD, In vitro small intestinal digested: ID

Table 6 DPPH values of muffin samples

Samples*	UD (µmol trolox/g dw)**	GD (µmol trolox/g dw)**	ID (µmol trolox/g dw)**
1	$35.86 \pm 5.09^{cB***}$	52.2 ± 2.59^{fA}	59.03 ± 1.68^{dA}
2	45.89 ± 3.19^{bC}	107.56 ± 0.37^{cB}	112.24 ± 0.21^{bA}
3	36.3 ± 2.47^{cC}	71.68 ± 3.56^{eA}	62.71 ± 0.16^{dB}
4	53.19 ± 1.27^{aC}	210.91 ± 3.53^{aA}	170.05 ± 0.44^{aB}
5	29.54 ± 5.02^{cC}	96.04 ± 3.34^{dA}	58.76 ± 2.78^{dB}
6	57.53 ± 4.94^{aA}	32.31 ± 0.26^{gB}	34.37 ± 0.06^{fB}
7	45.79 ± 4.43^{bC}	109.33 ± 3.75^{cA}	52.92 ± 1.52^{eB}
8	17.79 ± 2.31^{dC}	137.02 ± 3.93^{bA}	79.58 ± 7.35^{cB}

*** Different uppercase superscripts in the same column and lowercase superscripts in the same row indicate statistically significant differences ($p < 0.05$)

*1: Steamed egg muffin, 2: Baked egg muffin, 3: Steamed psyllium husk muffin, 4: Baked psyllium husk muffin, 5: Steamed chia seed muffin, 6: Baked chia seed muffin, 7: Steamed flax seed muffin, 8: Baked flax seed muffin

**Undigested: UD, In vitro gastric digested: GD, In vitro small intestinal digested: ID

that the application of heat led to the release of bound phenolic compounds and an subsequent increase in TPC. Various levels of variability were found in the TPC values of the samples after in vitro GI. All of the undigested samples had lower TPC values than the post-digested samples. Both increases and decreases were determined when TPC values were compared after in vitro gastric and intestinal digestion. Samples 6 had the highest TPC values after in vitro gastric digestion and intestinal digestion. The observed rise in gastric digestion (GD) phase levels indicates ongoing extraction of phenolic compounds during GD, with the released compounds demonstrating stability in the stomach's acidic conditions. Previous studies have also noted an increase in TPC during intestinal digestion (ID), which was attributed to prolonged contact between the food and intestinal fluids, as well as the action of intestinal enzymes facilitating the release of phenolic compounds [47, 48]. When the TPC values of undigested samples were compared with the TPC values of samples after in vitro ID, increases between 173.91% (Sample 4) and 503.43% (Sample 2) were determined.

In a study conducted on cherry-capia pepper pestil, comparing the TPC values following in vitro GD and ID, a reduction ranging from 16.92% to 70.57% was identified. These findings offer valuable insights into the alterations experienced by phenolic compounds during the digestive process. It is important to highlight that the impact observed varies across different samples, and the presence of phenolics in conjunction with other compounds, like polysaccharides, may present obstacles in their absorption through membranes.

It was also observed that both the ingredients used and the cooking method had different effects on the TPC values of the samples after in vitro digestion. For example, when Samples 3 (steamed muffin containing psyllium husk) and Sample 4 (baked muffin containing psyllium husk) were compared, the increase in TPC in these samples after in vitro ID compared to the undigested phase was found to be 423.98% and 173.92%, respectively. This increase observed in Sample 3 was the 2nd highest increase among the samples and the increase in Sample 4 was the lowest. When the in vitro ID TPC value of the flax seed samples, Samples 7 and 8, was compared with the undigested phase, the increase was 198.24% and 344.57%, respectively.

In psyllium husk containing samples, the increment of TPC value after ID of the steamed sample (Sample 3) was higher than the baked sample (Sample 4). However, the baked flaxseed muffin sample (Sample 8) had higher percentage of TPC after ID digestion than the steamed sample (Sample 7). This difference between the two samples reveals that the cooking method is highly influential on the post-digestion TPC value.

Total antioxidant activity (TAA)

The TAA values of muffin samples were determined by using the DPPH and FRAP methods. The DPPH and FRAP values of the samples are given in Tables 6 and 7, respectively.

The DPPH values of the pre-digested muffin samples varied between 17.79 µmol trolox/g dw and 57.53 µmol trolox/g dw and the highest DPPH value was determined in Sample 6. FRAP values of undigested samples ranged between 16.30 µmol trolox/g dw and 56.83 µmol trolox/g

Table 7 FRAP values of muffin samples

Samples*	UD (µmol trolox/g dw)**	GD (µmol trolox/g dw)**	ID (µmol trolox/g dw)**
1	$26.12 \pm 0.87^{dC***}$	69.95 ± 2.88^{cA}	42.56 ± 2.88^{fB}
2	33.62 ± 1.76^{bC}	105.90 ± 2.00^{bA}	99.27 ± 2.36^{cB}
3	19.86 ± 1.01^{fC}	58.32 ± 1.23^{deA}	44.78 ± 3.63^{efB}
4	56.83 ± 1.71^{aC}	208.89 ± 1.64^{aA}	112.00 ± 5.67^{bB}
5	22.55 ± 1.45^{eB}	62.39 ± 4.89^{deA}	60.69 ± 1.29^{dA}
6	55.67 ± 1.77^{aC}	212.27 ± 0.79^{aA}	147.34 ± 0.52^{aB}
7	29.20 ± 1.64^{cC}	57.30 ± 5.71^{eA}	48.12 ± 3.56^{eB}
8	16.30 ± 1.66^{gC}	63.74 ± 3.97^{dA}	37.21 ± 0.97^{gB}

*** Different uppercase superscripts in the same column and lowercase superscripts in the same row indicate statistically significant differences ($p < 0.05$)

*1: Steamed egg muffin, 2: Baked egg muffin, 3: Steamed psyllium husk muffin, 4: Baked psyllium husk muffin, 5: Steamed chia seed muffin, 6: Baked chia seed muffin, 7: Steamed flax seed muffin, 8: Baked flax seed muffin

**Undigested: UD, In vitro gastric digested: GD, In vitro small intestinal digested: ID

dw. Similar to the DPPH results, the highest FRAP value was determined in Sample 6. However, the lowest TAA value was observed in Sample 8 in both methods.

Červenka et al. [43] reported the DPPH values of muffin samples to which contain canola oil, egg and milk, carob powder was added to the muffin batter at ratios of 5, 10, 15 and 20% (w/w) and then baked in the oven (180 °C for 20 min) as between 222.9 µmol trolox/g dw and 1228.3 µmol trolox/g dw.

In addition, Bijami et al. (2020) [49] added palm kernel flour to muffin batter and reported that these muffins showed DPPH radical scavenging activity compared to the control sample. In the study, while the DPPH value was not determined in the control sample, the DPPH values of the samples to which 5% palm kernel flour was added were determined as 5 µmol trolox/g dw.

Kaur and Kaur [50], conducted a research study to investigate the effects of incorporating flaxseed from three different flaxseed varieties in place of wheat flour in cake production on different indicators of cake quality. The substitution of wheat flour with ground flaxseed at a level of up to 8% by weight resulted in a significant increase in DPPH free radicals in the cakes, with a 28% higher level compared to the control group.

Sample 6 (baked muffin containing chia seeds), and Sample 4 (baked muffin containing psyllium husk) which had higher TAA values in both methods, had higher TPC results again. These two samples performed much better than the other samples in terms of both TPC and AA.

Phenolic compounds are recognized for their beneficial characteristics, largely attributed to their antioxidant capabilities. These compounds are thought to significantly contribute to the antioxidant potential of diverse food items, thereby establishing them as a valuable reservoir of natural antioxidants [51].

When the DPPH values of the samples after in vitro GD and undigested samples were compared, both increases and decreases were determined. The DPPH values of the undigested phase of all samples except Sample 6, were the lowest compared to the post-digested phase. However, in Sample 6, the highest DPPH value was found in the undigested phase and there was no statistically significant difference between the DPPH values of the gastric and intestinal phases ($p > 0.05$).

When the undigested DPPH method samples were compared with the in vitro ID samples, the highest increase (347.32%) was determined in Sample 8. The lowest increase was determined in Sample 7 and this increase rate was determined as 15.57%. A 98.91% increase was observed in Sample 5. When Sample 6 was compared with Sample 5, the effect of the cooking method on DPPH values after in vitro digestion was significant.

The decrease in DPPH values during in vitro ID, compared to GD, could be described by the deprotonation of hydroxyl groups in phenolic compounds, which is influenced by the pH of the environment. The gastric stage has an acidic property, while the intestinal environment is mildly alkaline. The decrease in TAA values after simulated intestinal digestion may be attributed to the degradation of polyphenols and anthocyanins due to pH changes during the intestinal digestion process [52].

The elevation in DPPH values post-digestion can be attributed to various factors, including the liberation of phenolic compounds, heightened bioavailability, and enzymatic conversions. This phenomenon is closely linked to the antioxidative characteristics of phenolic compounds [53].

When the FRAP values of the samples after in vitro digestion were compared with the FRAP values of the undigested phase, the undigested muffin samples exhibited lower FRAP values. The FRAP values of all samples except Sample 5 after GD were higher than the FRAP values of the samples after ID. In Sample 5, there was no statistically significant difference between FRAP values after in vitro GD and FRAP values after ID ($p > 0.05$).

Moreira et al. (2023) [54] used chia mucilage as an egg replacer in their muffin formulation. In this study, mucilage was added at ratios of 2%, 4% and 6%. Similar to our result, FRAP values of muffin samples ranged between 5.22 µmol trolox/g dw and 30.87 µmol trolox/g dw.

In the study Kamiloglu et al. [55] black carrot pomace-enriched cakes, following the gastric digestion process, significant increases in the general phenolic content and

TAA, with enhancements of up to fivefold ($p < 0.05$), were observed through FRAP analysis. Subsequent simulated ID resulted in even more pronounced improvements in TAA, ranging from 75% to 159% (< 0.05). These findings are consistent with the results reported by Oliveira and Pintadon [56] indicating a substantial increase (up to 5.5-fold) in antioxidant activity throughout the gastric and intestinal phases of in vitro digestion in yogurt enriched with strawberries and peaches.

HMF content of muffin samples

As shown in Table 8, hydroxymethylfurfural (HMF) content varied significantly among samples depending on the binder type and cooking method ($p<0.05$). The highest HMF level was detected in Sample 4 (baked muffin with psyllium husk, 81.60 mg/kg), while the lowest was in Sample 8 (baked muffin with flaxseed, 20.55 mg/kg). Baked samples consistently showed higher HMF concentrations than their steamed counterparts, reflecting the stronger influence of dry heat on Maillard and caramelization reactions.

The elevated HMF in baked muffins, particularly in psyllium-containing samples, can be attributed to the combined effect of high temperature, low moisture, and oxidizable phenolic compounds, which are known to enhance browning pathways. Ingredients rich in polyphenols (e.g., psyllium, chia, flaxseed) may further contribute to HMF formation via oxidative and Maillard-related mechanisms [30, 31]. Additionally, the darker crust and browning index (BI) values observed in these samples support the link between HMF content and browning intensity, consistent with previous findings [32].

Table 8 HMF content of muffins samples

Samples*	HMF (mg/kg)
1	$31.00 \pm 1.13^{Bc**}$
2	56.85 ± 5.73^{Ab}
3	33.10 ± 0.71^{Bc}
4	81.60 ± 4.10^{Aa}
5	36.85 ± 2.19^{Bc}
6	57.45 ± 1.20^{Ab}
7	31.75 ± 1.20^{Ac}
8	20.55 ± 1.91^{Bd}

*1: Steamed egg muffin, 2: Baked egg muffin, 3: Steamed psyllium husk muffin, 4: Baked psyllium husk muffin, 5: Steamed chia seed muffin, 6: Baked chia seed muffin, 7: Steamed flax seed muffin, 8: Baked flax seed muffin

** Different uppercase superscripts in the same column and lowercase superscripts in the same row indicate statistically significant differences ($p<0.05$)

In vitro gastrointestinal (GI) digestion

The in vitro digestion results were reflected in the increases or decreases observed in TPC and TAA after simulated gastric and intestinal phases.

Sensory evaluation

The results of the sensory analysis of muffin samples (Fig. 4) are given in Table 9; Fig. 4. The color parameters of the samples were performed as both outer and inner colors. No statistically significant difference was found between the internal color parameters of the samples ($p > 0.05$). However, the most liked outer color of the samples was determined in Sample 4. When the results were evaluated in terms of chewability, the most popular samples were samples 1, 3, 5, 7 and 8. There was no statistically significant difference between these samples ($p > 0.05$). In all muffins except the ones with flax seed, steamed muffins were more popular than baked muffins in terms of chewiness. Sample 1 was the most appreciated sample in the hardness evaluation, while no significant difference was detected between the samples in the odor parameter ($p > 0.05$). Sample 5 and Sample 8 were the best for taste. When the general acceptability scores of the samples were evaluated, Sample 7 received the highest score. The steamed samples were more appreciated than the oven-baked ones of the same samples. This reveals that the cooking method has an effect on sensory appreciation.

Conclusions

This study demonstrated that gluten-free, refined sugar-free, and vegan muffins can be successfully produced using tahini, dates, and carob as functional ingredients and plant-based egg replacers (chia, flaxseed, psyllium). Steamed muffins retained more moisture, water activity, and phenolics, resulting in softer texture and higher antioxidant activity, whereas baked muffins were firmer, lighter in color, and had higher HMF content. Among formulations, flaxseed- and chia-containing samples showed favorable nutritional and sensory profiles, with steamed flaxseed muffins receiving the highest acceptance. These findings emphasize the combined role of plant-based ingredients and cooking method in improving the functional, nutritional, and sensory quality of clean-label, vegan bakery products suitable for health-conscious and gluten-intolerant consumers.

Moreover, these results provide insights that can guide industrial bakers in selecting appropriate ingredients and processing methods to develop innovative gluten-free and vegan muffins with enhanced consumer appeal.

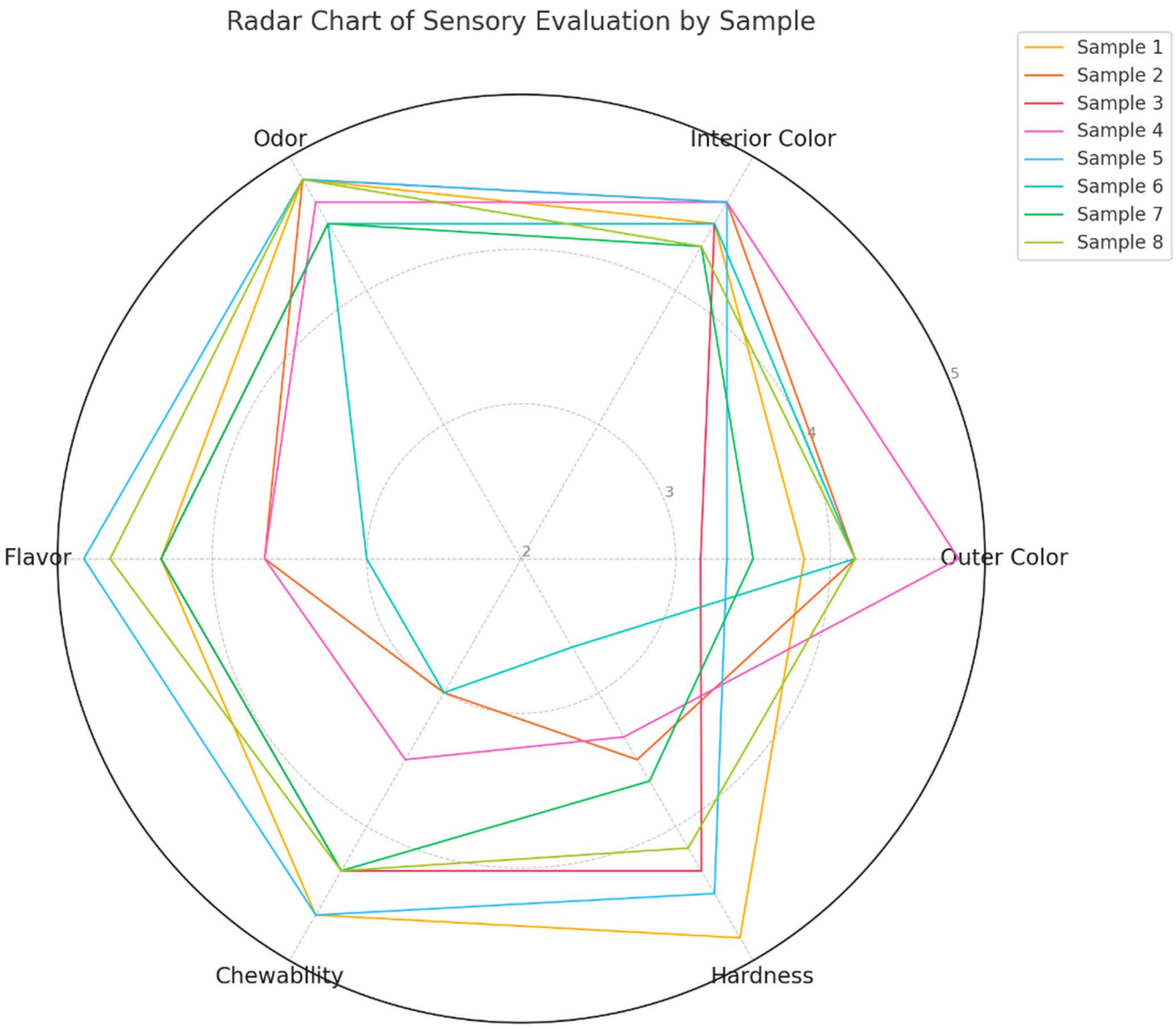


Fig. 4 Sensory evaluation of muffin samples

Table 9 Sensory evaluation of muffins

Samples*	Outer Color	Interior Color	Odor	Flavor	Chewability	Hardness	General Acceptability
1	$3.83 \pm 0.98^{bc**}$	4.50 ± 0.54^{a}	4.83 ± 0.40^{a}	4.33 ± 0.81^{ab}	4.66 ± 0.51^{a}	4.83 ± 0.40^{a}	4.16 ± 0.75^{ab}
2	4.16 ± 0.75^{ab}	4.66 ± 0.51^{a}	4.83 ± 0.40^{a}	3.66 ± 0.51^{bc}	3.00 ± 0.63^{b}	3.50 ± 0.83^{cd}	3.16 ± 0.75^{c}
3	3.16 ± 0.40^{c}	4.50 ± 0.54^{a}	4.50 ± 0.83^{a}	4.33 ± 1.03^{ab}	4.33 ± 0.51^{a}	4.33 ± 0.51^{abc}	4.16 ± 0.75^{ab}
4	4.83 ± 0.40^{a}	4.66 ± 0.51^{a}	4.66 ± 0.51^{a}	3.66 ± 0.81^{bc}	3.50 ± 0.54^{b}	3.33 ± 0.81^{de}	3.33 ± 0.51^{bc}
5	3.33 ± 0.51^{bc}	4.66 ± 0.51^{a}	4.83 ± 0.40^{a}	4.83 ± 0.40^{a}	4.66 ± 0.51^{a}	4.50 ± 0.54^{ab}	4.16 ± 0.40^{ab}
6	4.16 ± 0.98^{ab}	4.50 ± 0.54^{a}	4.50 ± 0.54^{a}	3.00 ± 0.00^{c}	3.00 ± 0.00^{b}	2.66 ± 0.51^{e}	3.16 ± 0.40^{c}
7	3.50 ± 0.54^{bc}	4.33 ± 0.81^{a}	4.50 ± 0.83^{a}	4.33 ± 0.81^{ab}	4.33 ± 0.51^{a}	3.66 ± 0.81^{bcd}	4.50 ± 0.83^{a}
8	4.16 ± 0.98^{ab}	4.33 ± 0.82^{a}	4.83 ± 0.40^{a}	4.66 ± 0.81^{a}	4.33 ± 0.51^{a}	4.16 ± 0.75^{abcd}	4.16 ± 0.75^{ab}

*1: Steamed egg muffin, 2: Baked egg muffin, 3: Steamed psyllium husk muffin, 4: Baked psyllium husk muffin, 5: Steamed chia seed muffin, 6: Baked chia seed muffin, 7: Steamed flax seed muffin, 8: Baked flax seed muffin

** Values followed by different superscripts within the same column are significantly different ($p < 0.05$)

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Data availability Data will be made available on request.

Declarations

Compliance with ethical standards Sensory evaluation performed in this study was carried out with ethical approval and consent to participate in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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