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Original research

Physicochemical, textural, and sensory effects of replacing rice flour with Quinoa powder in gluten-free cake formulations

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A B S T R A C T

This study examined the impact of substituting rice flour with quinoa powder at varying proportions (0–100%) on the physicochemical, textural, and sensory attributes of gluten-free cakes. The cake batter exhibited pseudoplastic flow behavior, with viscosity increasing at higher substitution levels. Substitution with quinoa powder significantly increased cake weight and reduced baking loss ($p < 0.05$). Furthermore, it exerted a significant effect on cake volume and density ($p < 0.05$), with volume increasing from 11.4 to 20.3 cm^3 and density decreasing from 975.9 to 639.3 kg/m^3. Cakes formulated with higher levels of quinoa powder exhibited increased moisture (from 13.83% to 17.25%) and ash content (from 0.86% to 1.51%). The highest acidity (0.92%) and lowest pH (6.62) were recorded in the sample made with 100% quinoa powder. As the level of quinoa powder substitution increased, both the total phenolic content (TPC) and antioxidant capacity (AC) of the cakes showed a corresponding increase, with the sample containing 100% quinoa powder exhibiting the highest TPC (1222.5 µg GAE/g) and the lowest AC (91.64%). Replacing rice flour with quinoa powder significantly affected cake color indices, leading to reduced lightness and yellowness and increased redness in both crust and crumb. The protein content of the cakes also increased proportionally (up to 9.45% in the 100% quinoa). Quinoa powder substitution reduced crust hardness (from 0.54 to 0.28 N) and, up to a 50% level, maintained favorable sensory attributes. Quinoa powder substitution improved the textural properties of cakes by enhancing cohesiveness and springiness, while reducing firmness and chewiness.

Keywords: Apparent viscosity; Baking loss; Color indices; Protein; Total phenolic content.

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1. Introduction

Celiac disease is a chronic autoimmune disorder characterized by an abnormal immune response to gluten-derived peptides, primarily mediated by T-lymphocytes. This immune activation triggers inflammation in the small intestine, leading to villous atrophy, impaired nutrient absorption, and clinical manifestations associated with malabsorption. Among the various gluten-related disorders, celiac disease is the most prevalent and extensively studied condition (Elli et al., 2015; Karami et al., 2025).

Rice (*Oryza sativa* L.) is one of the most important staple foods globally, consumed by nearly 3 billion people particularly in Asian countries. Providing approximately 20% of the global caloric intake, rice is a major source of energy, carbohydrates, and essential nutrients (Abbasi & Torabizadeh, 2025). Rice flour, due to its naturally gluten-free composition, is commonly utilized in the formulation of food products intended for individuals with celiac disease or non-celiac gluten sensitivity. Its mild flavor, hypoallergenic nature, and high digestibility make it a suitable ingredient for specialized dietary applications, particularly in gluten-free food development (Wang et al., 2020; Baligh et al., 2024; Taromsari & Ghiassi Tarzi, 2024).

Quinoa is a naturally gluten-free grain that offers a high protein content with a well-balanced profile of necessary amino acids (Ogungbenle, 2003; Vejdanivahid & Salehi, 2024). It is an appropriate source of B vitamins, as well as vitamins E and C, and contains various bioactive compounds, including flavonoids (Martínez-Villaluenga et al., 2020). Moreover, quinoa is rich in

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important minerals such as calcium, iron, magnesium, manganese, phosphorus, potassium, and zinc. It also provides beneficial fatty acids, high dietary fiber, and lysine-rich proteins. Owing to its nutritional richness and functional properties, quinoa holds significant potential for use in a wide range of food formulations (Ogungbenle, 2003; Vejdanivahid & Salehi, 2025b). Quinoa has a superior nutritional profile compared to common grains, due to its high levels of essential amino acids (lysine, methionine, cysteine), protein (14–18%), fiber, and bioavailable minerals like calcium, magnesium, and potassium. It also contains more folic acid and riboflavin than grains such as rice, wheat, and corn, highlighting its high nutritional value (Casalvara et al., 2024). The findings of Pooja et al. (2021) demonstrated that the incorporation of rice and quinoa powder in gluten-free bread formulations significantly enhanced the nutritional profile of the final product. Bozdogan et al. (2019) examined the effects of incorporating quinoa powder into gluten-free cake formulations and reported that the replacement of rice flour and potato starch with quinoa powder led to an increase in batter density.

The development and enhancement of gluten-free food products for individuals with celiac disease represents a significant area of research within the food industry (Jnawali et al., 2016; Karami et al., 2025). Sarmasti et al. (2023) investigated the preparation and quality characteristics of gluten-free sponge cakes formulated with alfalfa seed flour. Their findings indicated that substitution with alfalfa seed flour significantly reduced the specific volume and porosity of the cakes, while increasing their hardness. However, the incorporation of alfalfa seed flour also resulted in higher moisture, protein, and ash contents, demonstrating its potential to enhance the nutritional value of gluten-free baked products despite some changes in texture.

The present study aims to systematically investigate the effects of substituting rice flour with varying levels of quinoa powder (0–100%) on the physicochemical, textural, and sensory properties of gluten-free sponge cakes. Specifically, the study evaluates how quinoa substitution influences batter rheology, cake volume, density, moisture, ash content, pH, acidity, protein content, color, textural attributes, and antioxidant-related parameters, including total phenolic content and antioxidant capacity. In addition, the study seeks to identify the optimal level of quinoa powder that maximizes nutritional and functional benefits while maintaining desirable sensory qualities, thereby providing a comprehensive understanding of quinoa's potential as a functional ingredient in gluten-free baked products.

2. Materials and Methods

2.1. Materials

White quinoa seeds (OAB, Iran), Rice flour (Tarkhineh, Iran), sugar (Mojeze, Iran), fresh eggs (Telavang, Iran), oil (Famila, Iran), milk powder (Kalleh, Iran), baking powder (Golestan, Iran), and vanilla (Golha, Iran) used in cake preparation were procured from local markets in Hamedan, Iran. The quinoa seeds were milled using an industrial grinder produced by Best Company (China). The chemical reagents used in this study included Folin–Ciocalteu reagent (Sigma-Aldrich, USA), sodium carbonate (Merck, Germany), gallic acid (Merck, Germany), 2,2-diphenyl-1-picrylhydrazyl (DPPH, Sigma-Aldrich, USA), and ethanol (Kimia Alcohol Zanjan Co., Iran).

2.2. Cake preparation

A suitable cake formulation was prepared based on the method of Salehi et al. (2017) with some modifications, consisting of 100 g rice flour, 0.5 g vanilla, 2 g baking powder, 57 g oil, 72 g sugar, 6 g milk powder, 102 g egg, and 30 g water. In the initial stage of cake preparation, egg whites were separated from the yolks. The egg whites were then whipped using an electric mixer for 5 minutes until stable white foam was formed. Subsequently, half of the sugar was added, and mixing continued for an additional minute. In a separate bowl, the egg yolks were blended with oil, vanilla, water, milk powder, and baking powder. Following this, flour was incorporated gradually, with varying substitution levels of quinoa powder at 0% (100% rice flour), 25%, 50%, 75%, and 100% (0% rice flour). In the final step, the previously whipped egg whites were gently folded into the yolk-flour mixture along with the remaining sugar, using a circular folding motion to maintain the aerated structure. The resulting batter was poured into round paper cake pans.

Cakes were baked in a Tulips oven toaster (model OT-4506 BD, P.R.C.) at 180 °C for 45 minutes. After baking, the cakes were removed from the oven and allowed to cool at room temperature. The cooled cakes were then stored in moisture- and oxygen-resistant polyethylene containers to preserve their quality.

2.3. Evaluation of cake batter viscosity

The apparent viscosity of the cake batter was measured as a function of spindle rotation speed (5, 10, and 15 RPM) and time (0–120 s) using a rotational viscometer (Brookfield DV2T, RV model, USA) equipped with spindle RV-05. All measurements were conducted at a temperature of 25 °C.

2.4. Baking loss determination

Baking loss was determined according to the method described by Shao et al. (2015), using the following formula (Eq. (1)).

$$\text{Baking loss (\%)} = \left[\frac{(\text{mass of cake batter before baking} - \text{mass of baked cake})}{\text{mass of cake batter before baking}}\right] \times 100 \quad (1)$$

2.5. Volume and density determination

The volume of the baked cakes was determined using the canola seed displacement method, in which the volume of canola seeds displaced by the cake sample was measured in a graduated container. The density of the baked cakes was determined following the method described by Amin Ekhlas et al. (2023).

2.6. Moisture and ash contents determination

Moisture content of rice flour, quinoa powder, and cake samples was measured using a digital moisture analyzer (DBS60-3, Kern, Germany), with results reported as the percentage of weight loss after heating. Ash content was determined by weighing 3 g of each sample, initially combusting it over a gas flame, and then incinerating in a muffle furnace (Pars-Azma-Co., Iran) at 600 °C until constant weight (Samary et al., 2025).

2.7. pH and acidity determination

The pH and acidity of the rice flour, quinoa powder, and cake samples were assessed following the protocol described by Vejdanivahid and Salehi (2025b).

2.8. TPC and AC determination

The TPC of rice flour, quinoa powder, and cake samples was assessed following the method described by Samary et al. (2025). Sample extract was prepared by mixing 2 g of sample with 20 mL of 80% methanol and stirring for 30 min, followed by centrifugation at 4000 rpm for 5 min. The supernatant was collected for analysis. TPC was determined using the Folin–Ciocalteu method. Briefly, 0.5 mL of extract was mixed with 0.5 mL of Folin–Ciocalteu reagent and, after 5 min, 2 mL of 20% sodium carbonate was added. The mixture was kept at 25 °C for 15 min, then diluted with distilled water and centrifuged again at 4000 rpm for 5 min. Absorbance was measured at 725 nm using a spectrophotometer (XD-7500, Lovibond, Germany), and results were expressed as micrograms of gallic acid equivalents per gram (µg GAE/g) of dry sample, based on a standard calibration curve prepared with gallic acid.

The AC of rice flour, quinoa powder, and cake samples was evaluated using the DPPH radical scavenging method described by Vejdanivahid and Salehi (2025b). Briefly, 2 g of sample was extracted with 20 mL of 80% methanol, stirred for 30 min, and centrifuged at 4000 rpm for 5 min. Then, 2 mL of the extract was mixed with 2 mL of 0.1 mM DPPH solution and incubated at 25 °C for 30 min in the dark. The absorbance was measured at 517 nm using a spectrophotometer (XD-7500, Lovibond, Germany).

2.9. Color parameters determination

Image processing techniques were employed to evaluate the color parameters of the cake crust (outer layer) and crumb (inner portion). Photographs of the cake samples were taken using a 48-megapixel camera (iPhone 15 Pro Max, Apple Co., China) under consistent lighting conditions, while images of the rice flour and quinoa powder were acquired using a scanner (HP Scanjet-300). The captured images were then analyzed by converting the RGB color space to L^* (lightness), a^* (green to red spectrum), and b^* (blue to yellow spectrum) indices using ImageJ software (version 1.42e, USA) with a specialized color analysis plugin (Pourghasemian et al., 2025).

2.10. Protein determination

The protein content of the samples was determined using the Kjeldahl technique (Bordbar Lomer & Ghannadiasl, 2025).

2.11. Puncture and TPA tests

The crust hardness of the cake samples was measured using a puncture test conducted with a texture analyzer (Santam, STM-5, Iran). A cylindrical probe with a diameter of 5 mm was employed, operating at a constant speed of 0.1 cm/s to a penetration depth of 1 cm.

Texture Profile Analysis (TPA) was conducted using a cylindrical probe with a diameter of 50 mm, operating at a speed of 1 mm/s and applying a deformation of 50%, in order to assess the overall textural properties of the cake samples with dimensions of $2 \times 2 \times 2$ cm^3. The parameters evaluated included firmness, cohesiveness, springiness, and chewiness.

2.12. Sensorial evaluation of cake

The sensory analysis was conducted in the Laboratory of New Technologies at Bu-Ali Sina University. The sensory evaluation procedures performed in this study were reviewed and approved by the Biomedical Research Ethics Committee of Bu-Ali Sina University, Iran. The approval was granted on July 2025 under the ethical approval code 6084. In this study, 20 panelists (10 men and 10 women) from various age groups including children (5-12 years), adolescents and young adults (14-23 years), adults (25-43 years), and older adults (48-73 years) were recruited to evaluate the cakes. All participants were informed about the purpose and procedures of the study and gave their informed consent prior to participation. The study was carried out in compliance with the ethical standards for research involving human subjects. The evaluation criteria included appearance, aroma, flavor, texture, and overall acceptability.

2.13. Statistical analysis

All experiments were performed in triplicate, and the results are presented as mean ± standard deviation. Data were analyzed using one-way analysis of variance (ANOVA) in SPSS (version 21, SPSS Inc., Chicago, IL, USA). Post hoc comparisons were conducted using Duncan's multiple range test, and differences were considered statistically significant at $p < 0.05$.

3. Results and Discussion

3.1. Viscosity of cake batter

Viscosity measurement is a critical parameter in food science, as it provides valuable insights into the flow behavior, texture, stability, and overall quality of food products during processing, formulation, and consumption (Salehi et al., 2024; Firoozi et al., 2025). Fig. 1 illustrates the effect of spindle rotation speed (ranging from 5 to 15 RPM) and mixing time (in seconds) on the apparent viscosity of gluten-free cakes batter. As the spindle speed increased, corresponding to a higher shear rate, a noticeable decrease in apparent viscosity was observed. This shear-thinning behavior is indicative of the batter's pseudoplastic nature, a common characteristic in non-Newtonian food systems. A similar trend was consistently observed across all levels of quinoa powder substitution, suggesting that the incorporation of quinoa powder does not alter the fundamental rheological behavior of the batter. Consistent with the findings of the present study, Vejdanivahid and Salehi (2025b) observed that increasing spindle rotation speed and shear rate led to a decrease in the viscosity of pancake batters containing sprouted quinoa powder, confirming their pseudoplastic flow behavior. They also reported that batters prepared with sprouted quinoa powder exhibited lower flowability and higher viscosity compared to other samples, whereas the lowest viscosity was recorded in batters made with unsprouted quinoa powder.

Furthermore, during the duration of spindle rotation, the viscosity of the batter remained relatively stable, with minimal reduction over time. This indicates that the viscosity was not significantly affected by prolonged shear, and thus, the batter did not

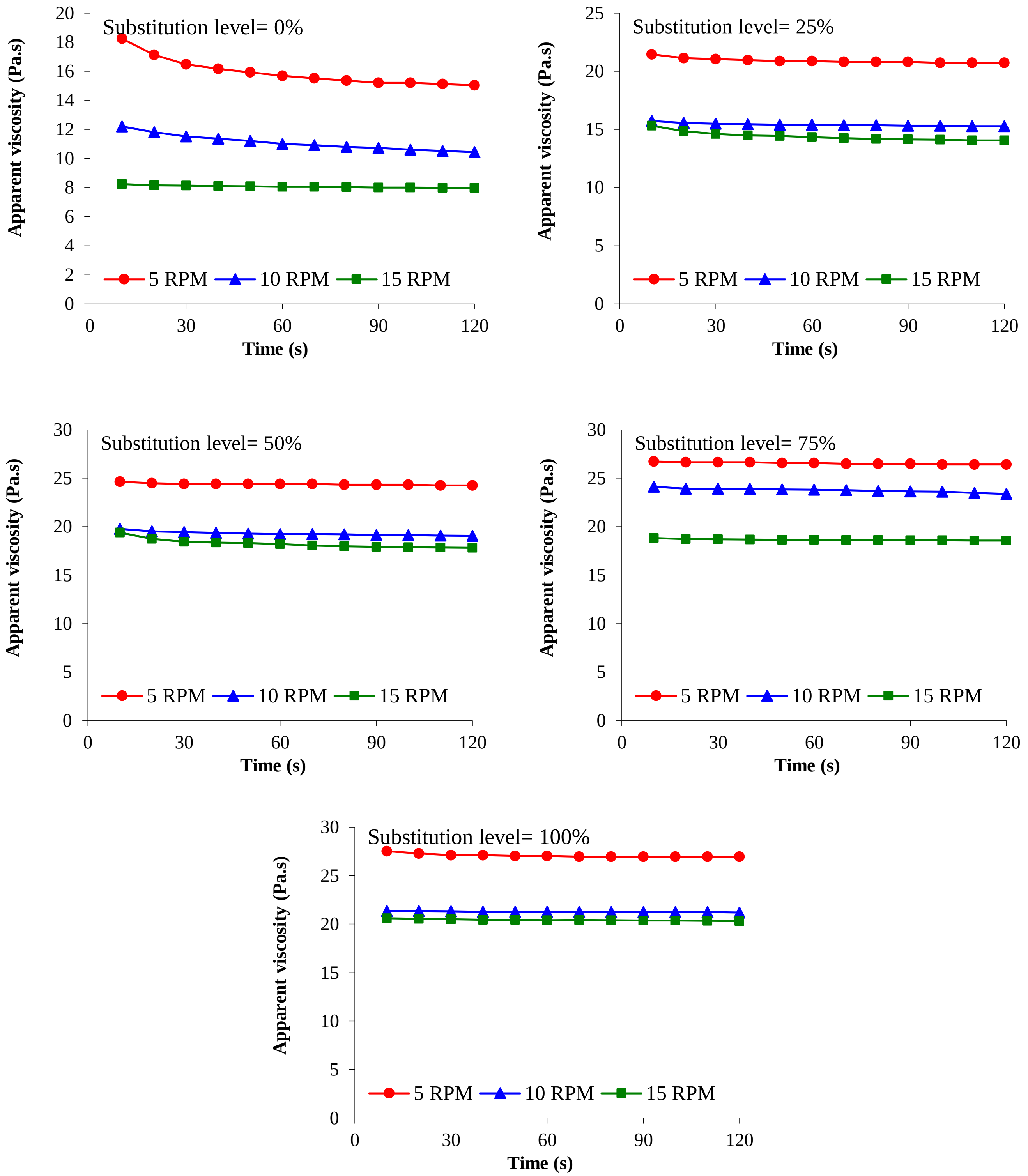

Fig. 1. Influence of spindle rotation speed and time on the apparent viscosity of gluten-free cake batter containing quinoa powder .

exhibit time-dependent rheological behavior such as thixotropy. These findings suggest that the batter maintains its structural stability under shear, an important property for ensuring consistency during processing and handling in gluten-free cake production.

Fig. 2 presents the effect of varying levels of quinoa powder substitution on the apparent viscosity of gluten-free cake batter as a function of spindle rotation speed. An increase in the proportion of quinoa powder in the formulation led to a corresponding increase in the batter's apparent viscosity. This suggests that quinoa powder contributes to a thicker batter consistency. Moreover, across all substitution levels, a decrease in viscosity was observed with increasing spindle speed, reflecting the batter's pseudoplastic behavior. This shear-thinning property is typical of many starch- and hydrocolloid-containing systems, where molecular alignment under shear leads to reduced flow resistance. These results indicate that while the quinoa powder increases the overall viscosity, it does not alter the non-Newtonian flow behavior of the cake batter. Turkut et al. (2016) reported that the incorporation of quinoa powder significantly influenced the consistency index and viscosity of the gluten-free bread batter. This effect was attributed to the higher water absorption capacity associated with the increased levels of quinoa powder, likely due to its substantial soluble dietary fiber content.

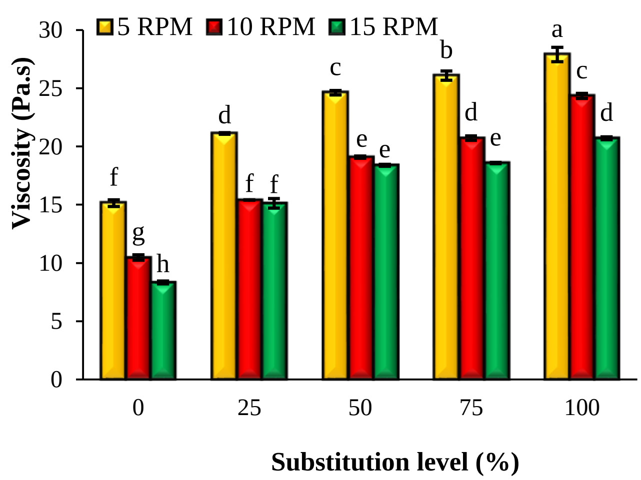

Fig. 2. Effect of quinoa powder substitution level on the apparent viscosity of gluten-free cake batter as a function of spindle rotation speed. Distinct letters above the columns denote statistically significant differences at the $p < 0.05$ level.

3.2. Baked cake weight and Baking loss

Fig. 3 presents the influence of quinoa powder substitution levels on the weight and baking loss of rice cakes. As the proportion of quinoa powder increased, the final weight of the baked cakes also increased (Fig. 3a). Consequently, a corresponding decrease in baking loss percentage was observed (Fig. 3b). The cake made with 100% rice flour exhibited the minimum post-baking weight and the maximum baking loss, while the sample formulated with 100% quinoa powder showed the maximum weight and the minimum baking loss. The differences between these two formulations were statistically significant ($p < 0.05$) for both weight and baking loss parameters. The observed increase in cake weight and reduction in baking loss with higher levels of quinoa powder may be attributed to the superior water absorption and retention capacity of quinoas, likely due to their higher protein content. The reduced baking loss is a desirable trait, as it contributes to improved yield and product consistency in baked goods. Nazari and Gharekhani (2021) reported that increasing the level of sprouted mung bean flour in bread dough up to 15% resulted in a non-significant reduction in baking loss, indicating that moderate substitution levels may slightly improve moisture retention during baking without significantly altering water loss dynamics.

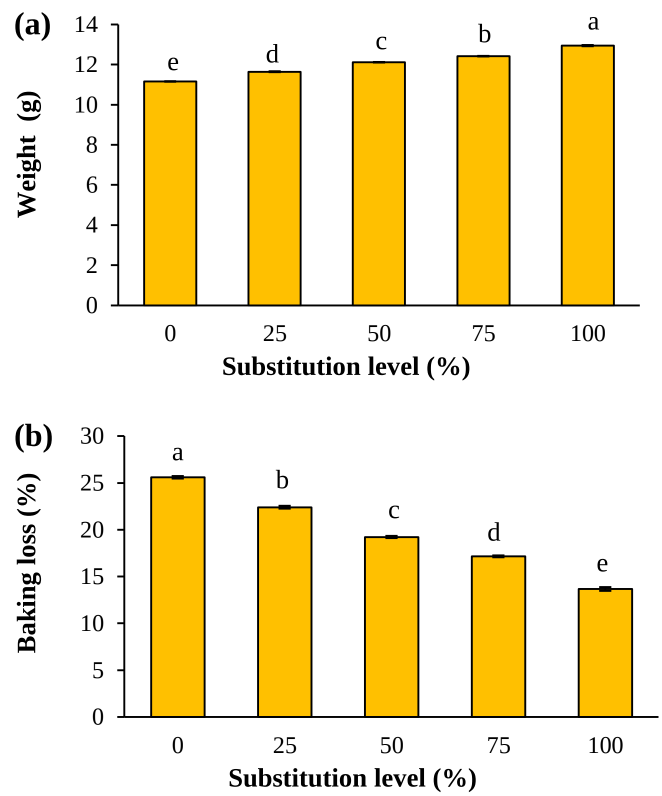

Fig. 3. Effect of replacing rice flour with quinoa powder on the weight (a) and baking loss (b) of gluten-free cake. Distinct letters above the columns denote statistically significant differences at the $p < 0.05$ level.

3.3. Volume and density

Fig. 4 displays the effect of different substitution levels of quinoa powder on the volume and density of gluten-free cakes. Substituting rice flour with quinoa powder significantly influenced the volume of gluten-free cakes ($p < 0.05$). As the substitution level increased from 0% to 100%, the cake volume exhibited a progressive and statistically significant rise (Fig. 4a). The control sample (0% quinoa) had the lowest volume, whereas the highest volume (approximately 20.26 cm³) was recorded at 100% quinoa powder. This increase in volume may be attributed to the enhanced water-binding capacity and protein content of quinoa, which can improve gas retention and batter structure during baking. In accordance with the results of the present study, Bozdogan et al. (2019) demonstrated that the substitution of rice flour with quinoa powder significantly enhanced the physical and chemical properties, as well as the overall quality attributes of gluten-free cakes. Specifically, increasing the proportion of quinoa powder led to higher cake volume and a reduction in crumb hardness, indicating improved textural characteristics. In addition, Aslan Türker et al. (2023) developed gluten-free cakes with quinoa powder, potato, and tapioca starch, reporting that quinoa addition increased cake volume due to its three-dimensional protein structure, which retained air during mixing. An inverse relationship between cake hardness and volume was also observed.

Conversely, increasing the quinoa powder substitution level resulted in a statistically significant decrease in cake density ($p < 0.05$) (Fig. 4b). The density dropped from approximately 975.93 kg/m³ in the control sample to about 639.33 kg/m³ in the fully substituted (100% quinoa) cake. This inverse relationship between substitution level and density supports the volume data and suggests that quinoa powder incorporation contributes to a lighter and more aerated cake structure. These results highlight the functional benefits of quinoa powder in gluten-free cake formulations, particularly in improving volume and reducing product density, both of which are desirable attributes in baked goods.

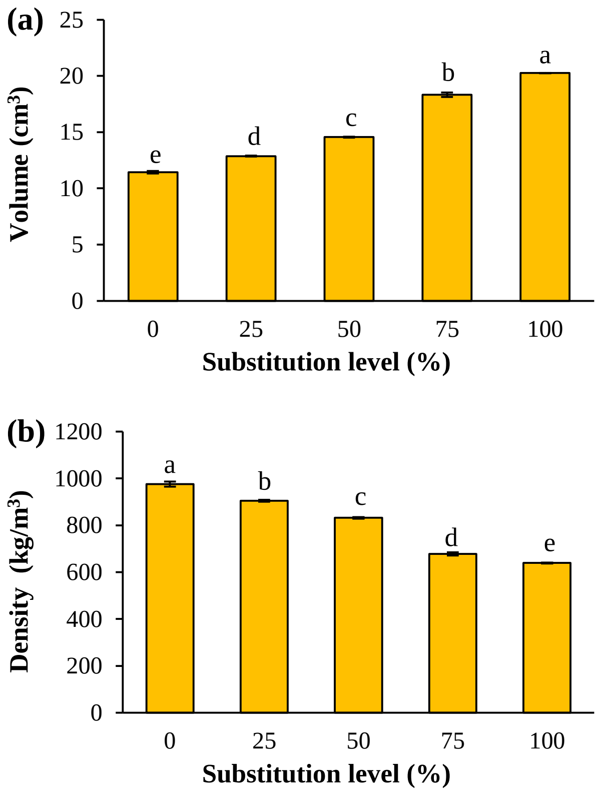

Fig. 4. Effect of replacing rice flour with quinoa powder on the volume (a) and density (b) of gluten-free cake. Distinct letters above the columns denote statistically significant differences at the $p < 0.05$ level.

3.4. Moisture and ash contents

The average moisture content of the rice flour and quinoa powder used in this study was 9.72% and 9.50%, respectively. Fig. 5a illustrates the influence of quinoa powder substitution level on the moisture content of cakes. Despite the slightly lower initial moisture content of quinoa powder, its incorporation into rice cake formulations had a notable impact on the final moisture content of the baked products. As the proportion of quinoa powder increased, the moisture content of the baked cakes increased. The sample made entirely with rice flour (0% substitution) exhibited the lowest moisture content (13.83%), while the highest value (17.25%) was recorded for the cake made with 100% quinoa powder. The difference between these two formulations was statistically significant ($p < 0.05$). This increase in moisture retention may be attributed to the higher protein content of quinoa powder, which likely enhances the water-holding capacity of the baked cake. Ghasemzadeh et al. (2017) demonstrated that the addition of quinoa powder and xanthan gum to bread formulations significantly enhanced moisture content, specific volume, and ash content, while also improving the product's texture and color characteristics.

Compared to commonly consumed cereals, quinoa is distinguished by its higher content of essential amino acids (lysine, methionine, cysteine), as well as greater levels of starch, fiber, protein, and ash. Its elevated ash content reflects a rich supply of bioavailable minerals such as calcium, magnesium, and potassium (Casalvara et al., 2024; Vejdanivahid & Salehi, 2025a). The average ash content of the rice flour and quinoa powder used in this study was 0.74% and 1.93%, respectively. Fig. 5b illustrates the effect of quinoa powder substitution level on the ash content of gluten-free sponge cakes. As the proportion of quinoa powder increased in the formulation, a corresponding increase in ash content was observed. The sample made with 100% rice flour exhibited the lowest ash content (0.86%), while the highest ash content (1.51%) was recorded for the cake containing 100% quinoa powder. This finding is consistent with the higher intrinsic mineral content of quinoa powder compared to rice flour. Levent (2018) reported that the incorporation of chia and quinoa powders into rice flour- and starch-based cakes led to a statistically significant enhancement in mineral content, including calcium, phosphorus, potassium, magnesium, iron, and zinc.

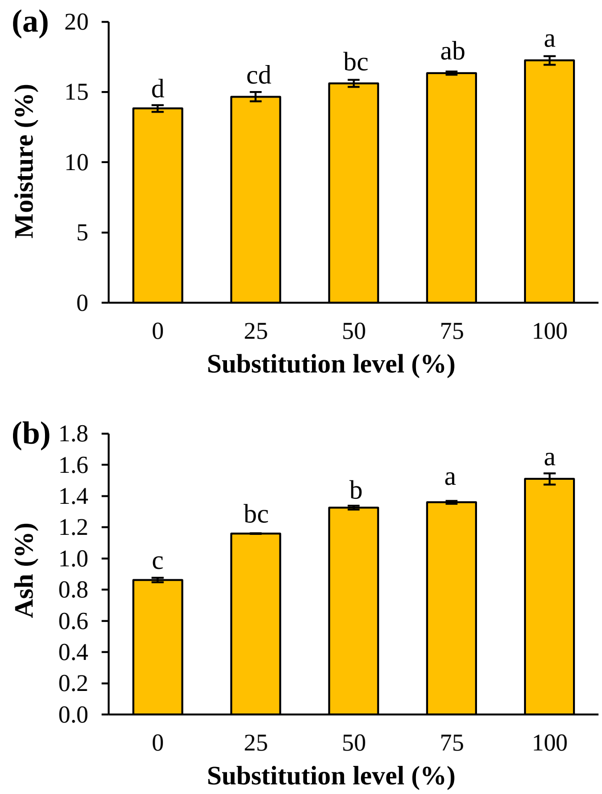

Fig. 5. Effect of replacing rice flour with quinoa powder on the moisture (a) and ash (b) contents of gluten-free cake. Distinct letters above the columns denote statistically significant differences at the $p < 0.05$ level.

3.5. pH and acidity of cake

The average pH values of the rice flour and quinoa powder used in this study were 6.83 and 6.66, respectively, while their corresponding average titratable acidity values were 0.47% and 0.66%. Fig. 6 illustrates the influence of quinoa powder substitution level on the pH and acidity of rice cakes. As the proportion of quinoa powder increased, the acidity of the baked cakes also increased, while the pH values showed a corresponding decrease. The lowest acidity (0.54%) and highest pH (6.93) were observed in the sample containing 100% rice flour. In contrast, the highest acidity (0.92%) and lowest pH (6.62) were recorded in the sample made with 100% quinoa powder. These differences were statistically significant ($p < 0.05$). The observed trends can be attributed to the acidic nature of quinoa powder, which introduces a greater concentration of organic acids into the batter.

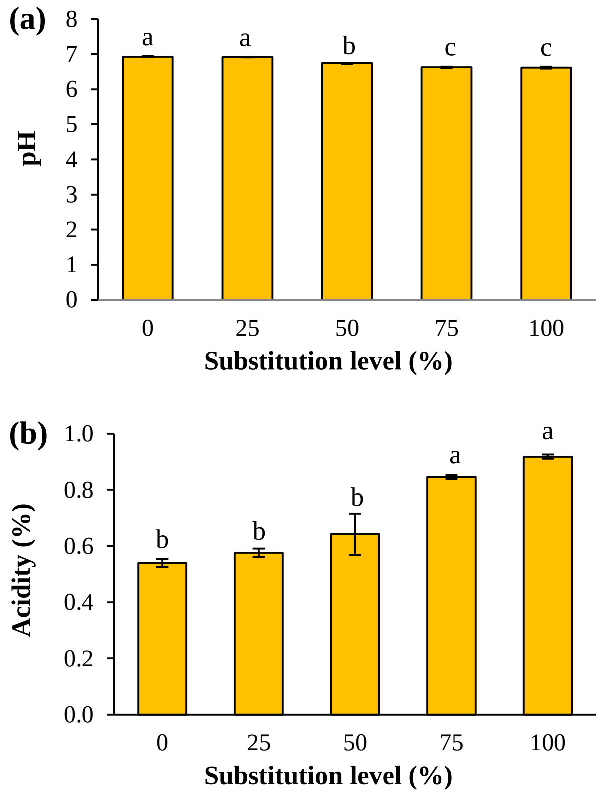

Fig. 6. Effect of replacing rice flour with quinoa powder on the pH (a) and acidity (b) of gluten-free cake. Distinct letters above the columns denote statistically significant differences at the $p < 0.05$ level.

3.6. TPC and AC

Quinoa seeds possess a high concentration of bioactive compounds such as saponins, phenolics, phytosterols, phytoecdysteroids, betalains, and functional peptides, contributing to their nutritional and health-promoting properties (Martínez-Villaluenga et al., 2020; Casalvara et al., 2024). In the current study, the TPC and AC of the rice flour and quinoa powder were 382.0 µg GAE/g and 1065.3 µg GAE/g, and 64.4% and 93.5%, respectively. These data highlight the significantly higher nutritional values of quinoa powder compared to rice flour. Fig. 7 demonstrates the influence of quinoa powder substitution on the TPC and AC of gluten-free cakes. As the substitution level of quinoa powder increased, both the TPC and AC of the cakes rose correspondingly. The lowest TPC and AC values were observed in the control sample containing 100% rice flour, while the highest were found in the sample made entirely with quinoa powder. The differences between these two extremes were statistically significant ($p < 0.05$). These findings collectively highlight the potential of quinoa powder as a functional ingredient for the development of more nutritious, antioxidant-rich, and health-promoting gluten-free baked products.

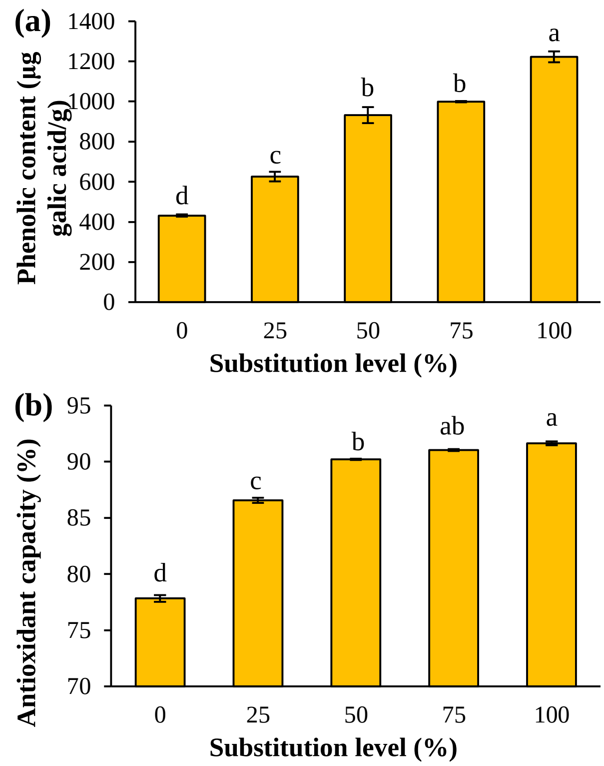

Fig. 7. Effect of replacing rice flour with quinoa powder on the total phenolic content (a) and antioxidant capacity (b) of gluten-free cake. Distinct letters above the columns denote statistically significant differences at the $p < 0.05$ level.

3.7. Crust and crumb color indices of cake

In this study, the color parameters of the rice flour and quinoa powder used in the formulations were notably different. The rice flour exhibited a lightness value of 97.31, a redness value of 0.01, and a yellowness (b*) value of 3.54, indicating its bright and neutral color profile. In contrast, the quinoa powder showed a lower lightness value of 89.21, along with higher redness ($a^* = 2.03$) and yellowness ($b^* = 12.41$) values, reflecting its darker and more intensely pigmented appearance. Fig. 8 illustrates the effect of replacing rice flour with quinoa powder on the color attributes of gluten-free cakes. The figure comprises six distinct graphs, each representing changes in a specific color parameter. The results corresponding to each graph are discussed individually below.

Fig. 8a – Crust lightness (L*): The substitution of rice flour with quinoa powder led to a gradual and statistically significant decrease in crust lightness (L*) values ($p < 0.05$). The control sample (0% substitution) exhibited the highest lightness, which progressively declined with increasing levels of quinoa powder, reaching the lowest value at 100% substitution. The observed reduction in crust lightness may be attributed to the elevated levels of phenolic compounds present in quinoa, as well as the formation of enzymatic

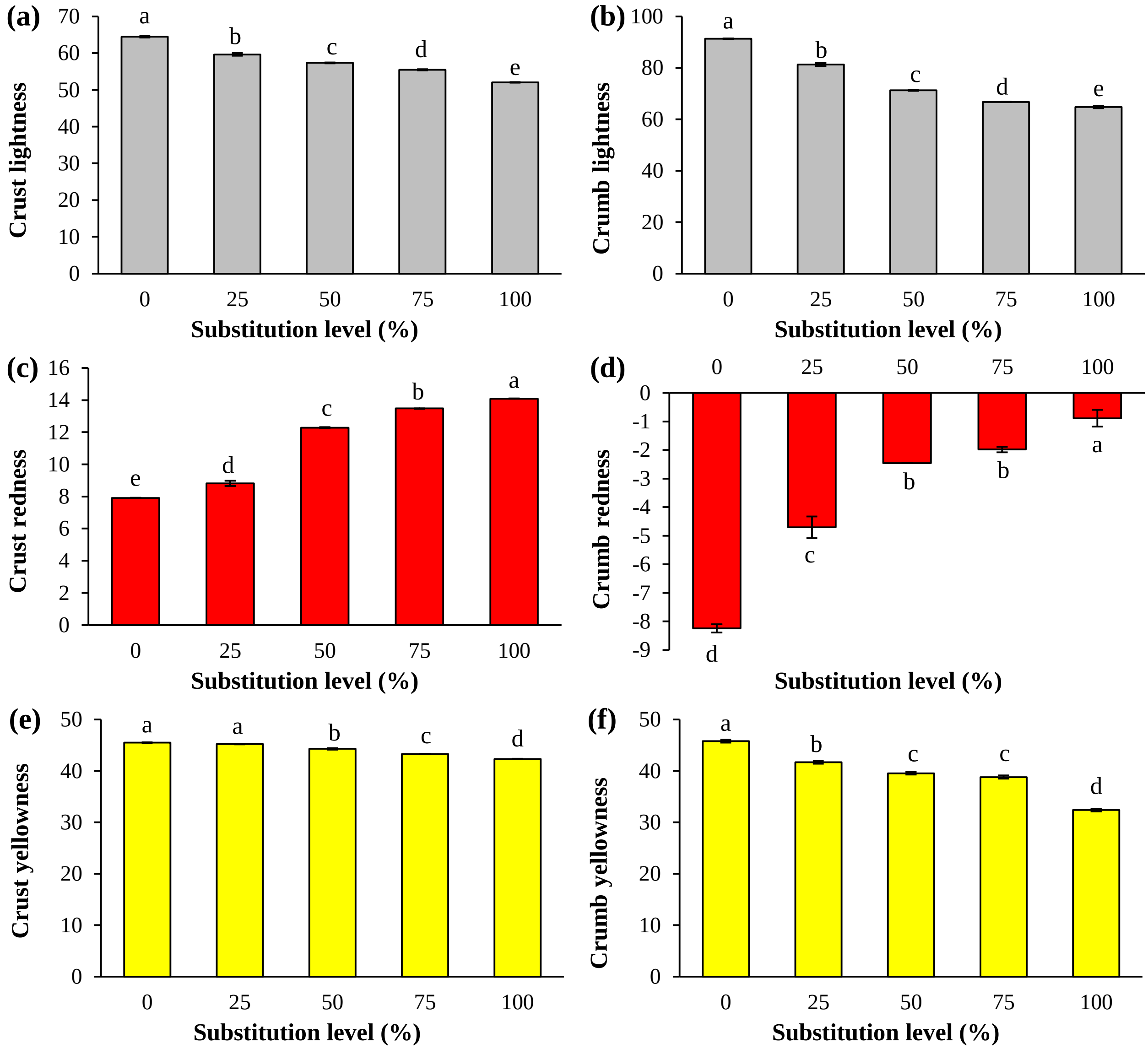

Fig. 8. Effect of replacing rice flour with quinoa powder on the lightness (crust (a) and crumb (b)), redness (crust (c) and crumb (d)), and yellowness (crust (e) and crumb (f)) of gluten-free cake. Distinct letters above the columns denote statistically significant differences at the p < 0.05 level.

browning products during the baking process. Sarmasti et al. (2023) examined the preparation and quality characteristics of gluten-free sponge cakes made with alfalfa seed flour. They reported that the incorporation of alfalfa seed flour significantly decreased the lightness values while increasing the redness and yellowness values of both the crumb and crust, indicating a darker overall color due to the natural pigments present in the flour.

Fig. 8b – **Crumb lightness (L*)**: Similar to the crust, crumb lightness significantly decreased as the proportion of quinoa powder increased ($p < 0.05$). The highest crumb lightness was observed in the control sample, while the lowest value was recorded in the 100% quinoa formulation. This decline suggests that quinoa's natural pigmentation and increased enzymatic browning reactions during baking contribute to darker crumb coloration. In this study, crust lightness values ranged from 52.08 to 64.50, and crumb lightness ranged from 64.80 to 91.30.

Fig. 8c – **Crust redness (a*)**: The redness index (a*) of the cake crust increased significantly with higher levels of quinoa powder substitution ($p < 0.05$). The lowest redness value was found in the control sample, while the 100% quinoa powder sample exhibited the highest redness. This trend may result from intensified enzymatic and Maillard browning reactions enhanced by the nutrient composition of quinoa. Consistent with the findings of the present study, Ghasemzadeh et al. (2017) reported that the incorporation of quinoa powder into bread formulations led to a significant decrease in lightness and an increase in redness values, indicating a darker coloration of the bread with increasing quinoa powder content.

Fig. 8d – **Crumb redness (a*)**: Crumb redness followed a similar increasing trend with quinoa substitution, showing statistically considerable differences between treatments ($p < 0.05$). The redness values shifted from negative to positive with increasing substitution, indicating a transition from greenish to reddish hues in the crumb. The highest redness index was recorded in the 100% quinoa powder sample. In the present study, the redness index of the crust ranged from 7.91 to 14.09, while the crumb ranged from -8.24 to -0.89.

Fig. 8e – Crust yellowness (b*): The crust yellowness decreased significantly as the quinoa powder level increased ($p < 0.05$). The control sample showed the highest yellowness value, while the sample with 100% quinoa powder had the lowest.

Fig. 8f – Crumb yellowness (b*): Crumb yellowness also decreased significantly with higher levels of quinoa powder ($p < 0.05$). The control sample exhibited the most intense yellow color, which diminished with increasing substitution. The lowest crumb yellowness was associated with the 100% quinoa sample, indicating the cumulative effect of darker quinoa pigments and intensified browning on crumb coloration. In the present study, the yellowness index of the crust ranged from 42.32 (100% substitution) to 45.49 (0% substitution), while the crumb ranged from 32.39 (100% substitution) to 45.80 (0% substitution).

3.8. Protein content

The protein content of the rice flour and quinoa powder used in this study was 9.8% and 14.4%, respectively. This difference reflects the naturally higher protein content of quinoa. Fig. 9 illustrates the effect of quinoa powder substitution level on the protein content of gluten-free cakes. As the proportion of quinoa powder increased in the formulation, a corresponding increase in protein content was observed. The maximum protein content (9.45%) was recorded in the cake made with 100% quinoa powder. This trend demonstrates that quinoa powder can serve as an effective protein enhancer in gluten-free baked products. The increase in protein content is particularly relevant for improving the nutritional quality of gluten-free formulations, which often lack sufficient protein. Incorporating quinoa powder may therefore contribute to the development of more balanced and nutritionally adequate gluten-free products. Levent (2018) reported that substituting rice flour and starch with chia and quinoa powders in gluten-free cakes significantly enhanced their nutritional profile, increasing ash, protein, fat, TPC and AC by 1.5-, 1.8-, 1.3-, 3.5-, and 2.9-fold, respectively, compared to the control.

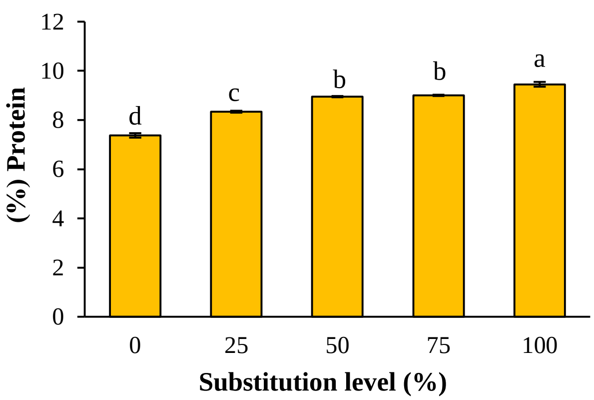

Fig. 9. Effect of replacing rice flour with quinoa powder on the protein content of gluten-free cake. Distinct letters above the columns denote statistically significant differences at the $p < 0.05$ level.

3.9. Puncture and TPA tests results

Texture is one of the most critical quality attributes of food products, particularly in baked goods such as cake, and plays a significant role in consumer acceptance. Among the various textural parameters, crust hardness is especially important as it influences the initial mouthfeel and overall eating experience. Fig. 10 illustrates the effect of quinoa powder substitution level on the crust hardness of gluten-free cakes. The sample made with 100% rice flour exhibited the highest crust hardness (0.54 N), while the formulation containing 100% quinoa powder showed the lowest value (0.28 N). These values were significantly different ($p < 0.05$). Consistent with the findings of the present study, Turkut et al. (2016) demonstrated that the incorporation of quinoa powder at a 25% substitution level in gluten-free bread formulations led to improved textural softness and enhanced sensory acceptance.

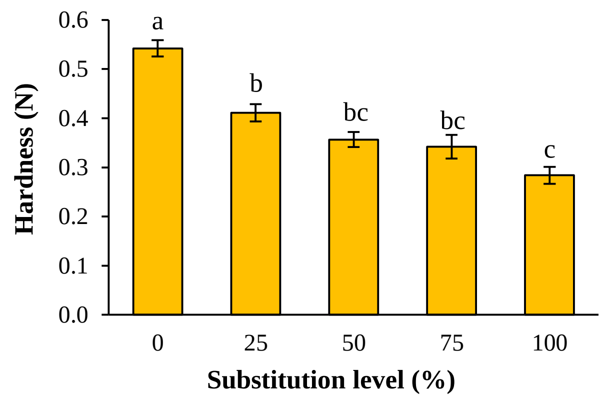

Fig. 10. Effect of replacing rice flour with quinoa powder on the crust hardness (puncture test) of gluten-free cake. Distinct letters above the columns denote statistically significant differences at the $p < 0.05$ level.

Table 1 illustrates the impact of substituting rice flour with quinoa powder at different levels (0–100%) on the textural properties of gluten-free cakes, as determined by Texture Profile Analysis (TPA). A considerable reduction in firmness was observed with increasing levels of quinoa powder ($p < 0.05$), declining from 3.29 N in the control to 1.38 N in the 100% quinoa-substituted sample. This reduction in firmness may also be associated with the increased cake volume, which results in a more aerated and less compact crumb structure.

Cohesiveness values increased progressively with higher substitution levels, ranging from 0.44 in the control to 0.62 in the 100% quinoa sample, indicating improved internal bonding within the cake structure. A similar trend was observed in springiness, which rose from 0.75 to 0.91, suggesting enhanced elasticity and structural recovery after deformation due to quinoa's functional properties.

Chewiness decreased from 1.06 N in the control to 0.78 N at 100% substitution, reflecting the softer and less resistant texture of cakes with higher quinoa content. These textural modifications collectively indicate that quinoa powder contributes positively to the mouthfeel and softness of gluten-free cakes, making it a suitable alternative to rice flour in improving product quality without compromising structural integrity.

3.10. Sensory evaluation

The data presented in Table 2 highlight the impact of substituting rice flour with quinoa powder on the sensorial attributes of gluten-free cakes. As observed, all substitution levels were generally well

Table 1. Effect of replacing rice flour with quinoa powder on the textural attributes of gluten-free cake.

Substitution level	Firmness (N)	Cohesiveness	Springiness	Chewiness (N)
0%	3.29 ± 0.48 [a]	0.44 ± 0.06 [c]	0.75 ± 0.04 [d]	1.06 ± 0.08 [a]
25%	2.39 ± 0.40 [b]	0.52 ± 0.01 [b]	0.81 ± 0.00 [c]	1.02 ± 0.15 [ab]
50%	1.88 ± 0.07 [bc]	0.55 ± 0.00 [ab]	0.83 ± 0.01 [bc]	0.86 ± 0.04 [bc]
75%	1.60 ± 0.02 [c]	0.58 ± 0.02 [ab]	0.88 ± 0.03 [ab]	0.82 ± 0.04 [bc]
100%	1.38 ± 0.10 [c]	0.62 ± 0.01 [a]	0.91 ± 0.01 [a]	0.78 ± 0.06 [c]

Data are shown as mean ± standard deviation (N = 3). Distinct letters within the columns denote statistically significant differences at the $p < 0.05$ level.

Table 2. Effect of replacing rice flour with quinoa powder on the sensorial attributes of gluten-free cake.

Substitution level	Appearance acceptance	Aroma acceptance	Flavor acceptance	Texture acceptance	Overall acceptance
0%	8.80 ± 0.40 [abc]	8.95 ± 0.22 [a]	8.75 ± 0.43 [a]	8.40 ± 0.49 [c]	8.50 ± 0.50 [b]
25%	8.85 ± 0.36 [ab]	8.90 ± 0.30 [ab]	8.65 ± 0.48 [ab]	8.45 ± 0.50 [bc]	8.35 ± 0.48 [b]
50%	8.95 ± 0.22 [a]	8.95 ± 0.22 [a]	8.85 ± 0.36 [a]	8.95 ± 0.22 [a]	8.90 ± 0.30 [a]
75%	8.55 ± 0.50 [c]	8.75 ± 0.43 [ab]	8.35 ± 0.48 [b]	8.70 ± 0.46 [ab]	8.25 ± 0.43 [b]
100%	8.60 ± 0.49 [bc]	8.70 ± 0.46 [b]	8.40 ± 0.66 [b]	8.90 ± 0.30 [a]	8.40 ± 0.49 [b]

Data are shown as mean ± standard deviation (N = 20). Distinct letters within the columns denote statistically significant differences at the $p < 0.05$ level.

accepted, with scores above 8.0 on a 9-point hedonic scale across all evaluated attributes, indicating favorable sensory perceptions. In terms of appearance, no statistically significant differences were found between samples containing 0–50% quinoa powder. However, the 50% substitution level yielded the highest score (8.95 ± 0.22), indicating enhanced visual appeal. Similarly, aroma acceptance showed no significant variation across most treatments, except for the 100% quinoa sample, which had a significantly lower score (8.70 ± 0.46). Flavor acceptance remained high in all formulations, but a slight decline was observed at 75% and 100% substitution levels, with the lowest score (8.35 ± 0.48) at 75%. Nonetheless, no significant differences were found between 0%, 25%, and 50% substitution levels, suggesting that moderate quinoa inclusion maintains palatability.

Regarding texture, the cake made with 50% quinoa powder received the highest score (8.95 ± 0.22), which was significantly superior to the control (8.40 ± 0.49), indicating a more favorable mouthfeel and crumb structure. This aligns with the objective textural improvements observed in firmness and cohesiveness. Overall acceptance followed a similar trend, with the 50% substitution level achieving the highest rating (8.90 ± 0.30), significantly outperforming the control (8.50 ± 0.50). Although samples with 0.25%, 75%, and 100% quinoa substitution received lower scores, they remained within the acceptable range. Overall, these results indicate that quinoa powder can be incorporated into gluten-free cake formulations up to a 50% substitution level without negatively impacting consumer acceptability, while enhancing both nutritional value and sensory quality. In agreement with the findings of the present study, Bozdogan et al. (2019) reported that cakes formulated with 50% quinoa powder achieved the highest sensory scores for taste and overall acceptability. Levent (2018) demonstrated that incorporating chia and quinoa powders into rice flour- and starch-based gluten-free cakes improved texture and taste–odor scores compared to the control. Sensory analysis indicated that both flours can be effectively used at substitution levels of up to 20% without compromising sensory quality. Rothschild et al. (2015) investigated the influence of quinoa roasting on the sensory and physicochemical characteristics of allergen-free, gluten-free cakes, reporting that cakes prepared with non-roasted quinoa achieved the highest sensory scores in terms of appearance, color, and texture.

4. Conclusion

The present study demonstrated that replacing rice flour with quinoa powder in gluten-free cake formulations significantly improved their nutritional, functional, and sensory properties. Incorporation of quinoa enhanced protein content, AC, TPC, and moisture retention, while rheological analysis confirmed increased batter viscosity without altering its pseudoplastic behavior. Physically, quinoa addition led to higher cake volume, lower density, and softer texture, alongside darker coloration resulting from its natural pigments and phenolic compounds. Sensory evaluation indicated that up to 50% quinoa substitution achieved optimal acceptability, balancing improved nutrition with desirable sensory qualities. Overall, quinoa powder shows strong potential as a functional ingredient for developing healthier, antioxidant-rich, and texturally improved gluten-free baked products. Future studies are recommended to explore the application of quinoa powder in the formulation of various types of bread and pastries, aiming to assess its functional, nutritional, and sensory impacts across a broader range of gluten-free baked products.

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Ethics statement

The study received ethical approval from the Biomedical Research Ethics Committee of Bu-Ali Sina University, Iran (Approval No. 6084).

Conflict of interest

The authors declare that there is no conflict of interest.

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