

ORIGINAL ARTICLE

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Effect of Amaranth and Corn Flour Ratios in Batter and Breader on the Physicochemical and Technological Properties of Gluten-Free Turkey Nuggets

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The present research investigates the development of gluten-free turkey nuggets using various concentrations of amaranth flour in the coating material, aiming to address the growing demand of individuals with celiac disease and those seeking healthier, high-quality gluten-free meat products. In this context, the batter and breader were prepared by replacing corn flour with amaranth flour at three different concentrations (30%, 40%, and 50%), while the control group was coated with 100% corn flour. After the formed turkey nugget dough was enrobed with four different formulations of coating formulations, the nuggets were fried at $180^{\circ}\text{C} \pm 5^{\circ}\text{C}$ for 4 min. Coating pick-up and adhesion degree decreased, whereas cooking loss increased, with higher amounts of amaranth flour ($p < 0.05$). Oil content in the crust region increased as the proportion of amaranth flour rose, likely due to its high fat-holding capacity ($p < 0.05$). The use of amaranth flour also promoted moisture retention in the core region of nuggets, resulting in juicier products. The color of nuggets shifted from yellow to yellowish-green with increasing amounts of amaranth flour. The increase in amaranth flour content led to a decrease in gumminess, chewiness, and resilience values of the nuggets ($p < 0.05$), while enhancing moisture retention and resulting in a softer product. Overall, the findings of the study suggest that incorporating up to 30% amaranth flour into batter and breader formulations could be a viable approach for producing healthier gluten-free turkey nuggets as an alternative product for health-conscious and gluten-intolerant consumers.

1 | Introduction

Recognized as an autoimmune disorder, celiac disease influences an estimated 48 to 300 million people worldwide and has been increasingly acknowledged as a major public health challenge (Dochat et al. 2024; Singh et al. 2018). It is characterized by chronic inflammation of the mucosa and submucosa of the small intestine, along with various systemic symptoms (Kaur et al. 2024; Mazzola et al. 2024). In individuals with celiac disease, gluten intake results in injury to the small intestinal tissue and may trigger complaints including abdominal discomfort, tiredness,

dermatological findings, and neurological disturbances (Sahin 2021; Zoghi et al. 2024). The primary cause of the disease is the immune system's reaction to gliadin, a subfraction of gluten found in wheat, and to prolamins present in other grains (Raiteri et al. 2022). Effective management of celiac disease depends on maintaining a strict gluten-free diet, which usually supports intestinal recovery and reduces symptoms.

The main components of gluten, gliadin, and glutenin proteins form a network structure in foods, providing elasticity and viscoelastic properties to the dough (Biesiekierski 2017; Wieser

2007). The ratio of these two proteins influences the handling properties of the dough and, in turn, the quality of baked goods like bread, pasta, and cakes (Salari et al. 2024). The absence or limited presence of gluten poses substantial technological challenges in the formulation of gluten-free products. Common problems include reduced dough stickiness, decreased elasticity, poor texture, undesirable color, off-flavors, and a shorter shelf life (Ren et al. 2020; Singla et al. 2024; Šmidová and Rysová 2022). Accordingly, recent research has focused on improving the quality, nutritional value, and technological characteristics of gluten-free products (Kaur et al. 2024; Singla et al. 2024). To address these challenges, alternative raw materials and formulation strategies that mimic the viscoelastic and other functional properties of gluten are needed for gluten-free product development.

Researchers have explored the production of gluten-free products using various cereals, pseudo-cereals, seeds, legume flours, and other raw materials (Alvarez-Jubete et al. 2009; Culetu et al. 2021; Das and Bhattacharya 2019; De Meo et al. 2011; Dedebas and Cebi 2024; Xu et al. 2020). Pseudocereals, which are not members of the wheat family, often have a superior nutritional profile compared to commonly used gluten-free grains such as rice and maize (Cappelli et al. 2020). Amaranth, a pseudocereal that has gained popularity in recent years, is characterized by higher levels of essential nutrients relative to those found in buckwheat, wild rice, corn, millet, oats, and quinoa. It is rich in vitamins and minerals, and is an excellent source of lysine, an amino acid found in low amounts in most cereals (Janssen et al. 2017; Mătiș et al. 2024; Thakur and Kumar 2019). Several studies have reported that substituting wheat and other grains with amaranth improves the viscoelastic properties, water retention capacity, and micronutrient content of gluten-free products (de la Barca et al. 2010; Liu et al. 2019; Singh et al. 2019; Tang and Tsao 2017).

In addition to a gluten-free diet, supplementation with vitamins and other nutrients is important to ensure dietary balance and adequate nutrition in patients with celiac disease. Meat and meat products play a significant role in this regard. Previous studies have developed a range of gluten-free products—such as bread, beverages, noodles, cookies, and cakes—for individuals with celiac disease or those who choose a gluten-free diet (Demirkesen et al. 2010; Gómez et al. 2013; Kreiszi et al. 2008; Levent 2017; Rai et al. 2014; Sabanis et al. 2009; Salehi 2019; Xu et al. 2020). However, the literature on gluten-free meat products is limited, with most research focusing on gluten-free chicken nuggets (Davarcioglu and Kolsarici 2019; Devatkal et al. 2011; Pinkaew and Naivikul 2019). In this context, incorporating amaranth flour, which has been previously identified in the literature (Alvarez-Jubete et al. 2010; Klimczak et al. 2002; Mir et al. 2018) as a promising alternative for gluten-free formulations, together with turkey meat, which is low in fat and rich in essential minerals such as sodium, potassium, and iron, may provide a valuable approach for producing advanced processed products for individuals with celiac disease. Therefore, the main objective of this study was to evaluate the potential use of amaranth flour at different ratios (0%, 30%, 40%, and 50%) in the coating material of turkey nuggets and to determine its effects on the quality properties of gluten-free turkey nuggets (GFTNs).

2 | Materials and Methods

2.1 | Materials

Raw turkey thigh and breast meats were obtained from a local poultry company (Bolca Hindi Co., Bolu, Turkey). Cornstarch, onion powder, garlic powder, sugar, black pepper, salt, and corn flour were obtained in commercially sealed packages from Bağdat Baharat Co. Amaranth flour was obtained from the Ingro company (İngro Ltd., Turkey). The composition of corn flour was 2.3% fat, 77% carbohydrate, and 6.5% protein, whereas amaranth flour contained 5.5% fat, 59% carbohydrate, and 16.1% protein. All solvents and reagents used in the study were of analytical grade and purchased from Sigma-Aldrich (Steinheim, Germany). The Ridascreen Gliadin Kit (R-Biopharm AG, Darmstadt, Germany) was used for gluten analysis.

2.2 | Manufacture of GFTNs

The formulations for turkey nuggets were determined based on the sensory panel results from preliminary trials and literature data. The production of GFTNs was carried out in the pilot kitchen of the Department of Gastronomy and Culinary Arts at Hasan Kalyoncu University. Turkey meat, after removal of visible fat and skin, was ground using a meat grinder equipped with a 5 mm perforated plate (Bosch Multi Power, MFWS440B). The nugget dough was prepared by mixing the following ingredients: turkey thigh meat (15%), turkey breast meat (67%), cornstarch (5%), onion powder (5%), water (3%), garlic powder (2%), sugar (1%), black pepper (1%), and salt (1%). The dough mixture was kneaded for 2 min and rested at 4°C for 1 h. It was then manually shaped into square pieces (4 × 4 × 1.5 cm), and rested again at 4°C for 1 h.

A mixture of corn flour and amaranth flour was used as a coating material. Four different breader formulations were prepared, consisting of amaranth flour to corn flour ratios of 0:100, 30:70, 40:60, and 50:50, respectively. Each dry flour mixture was diluted with water at a ratio of 1:2 (flour:water, w/w) and homogenized using a mixer (Tefal Masterchop Powelix Maxi, MB470B) to prepare the batter. After resting for an hour, each nugget was dipped into the batter twice to ensure sufficient adhesion to the meat dough. For the final step, nuggets were covered with breader and deep-fried in sunflower oil at 180°C ± 5°C for 4 min. The effects of gluten-free coatings on the texture, color, and physicochemical quality parameters of fried turkey nuggets were determined by specific analyses. In addition, batter viscosity was measured, and coating performance was assessed through the calculation of coating pick-up, adhesion degree, cooking loss, moisture retention, and fat uptake. The experimental design was replicated two times, and parallel analyses were performed for each replication.

2.3 | Coating Performance Parameters of GFTNs

Coating pick-up, adhesion degree, and cooking loss in GFTNs were calculated by using weights before (W_1) and after (W_2) coating according to the equations reported by researchers (Devatkal

et al. 2011; Martin Xavier et al. 2017). Coating thickness was measured on the coated side of the nuggets using calipers.

$$\text{Coating pick - up (\%)} = [(W_2 - W_1) / W_1] \times 100$$

$$\text{Adhesion degree (\%)} = ((W_2 - W_1) / W_2) \times 100$$

$$\text{Cooking loss (\%)} = (\text{initial [unfried] nugget weight} \\ - \text{fried nugget weight}) / \text{initial weight}) \times 100$$

Additionally, fat uptake and moisture retention of the nuggets were calculated in the present study. Fat uptake was determined based on the fat content before frying (W_{f1}) and after frying (W_{f2}). Moisture retention was calculated according to the following formula, in which moisture content before frying (W_{m1}) and after frying (W_{m2}) was used.

$$\text{Fat uptake (\%)} = ([W_{f2} - W_{f1}] / W_{f1}) \times 100$$

$$\text{Moisture retention (\%)} = ([W_{m2} - W_{m1}] / W_{m1}) \times 100$$

2.4 | Viscosity of Batter

The apparent viscosity of the batters was measured at $25^\circ\text{C} \pm 1^\circ\text{C}$ using a rotational viscometer (RVDV-II, Brookfield). Measurements were performed with a cylindrical No. 27 spindle (SC4-27 Spindle, Brookfield AMETEK, Middleboro, MA, USA) at a speed of 100 rpm. The samples were evaluated at a constant shear rate of 120/s for 300 s. For the Brookfield SC4 series spindle, an 11 mL chamber was used, with 8 mL of sample placed in the chamber for measurement.

2.5 | Diffusion Coefficient Calculation for Moisture Loss

To evaluate the moisture transfer process in gluten-free nuggets, the diffusion coefficient was determined using Fick's Second Law (Boucheham et al. 2019). The moisture loss diffusion coefficient was calculated based on the formula stated by previous researchers (Vélez-Ruiz et al. 2002).

2.6 | Chemical Properties of GFTN Samples

The analyses for moisture (950.46), ash (920.153), fat (991.36), and protein (955.04) were conducted according to the methods specified by AOAC (2010), and the results were expressed as percentages. In this study, the moisture and oil contents of the core (meat portion) and crust (coating material) of GFTNs were determined separately. The carbohydrate content was determined indirectly by deducting the total percentages of moisture, protein, ash, and fat from 100. The fat, protein, ash, and carbohydrate

values were calculated on a dry matter (DM) basis. The pH values of the samples were measured using a pH meter (Hanna HI 221, Ann Arbor, MI, USA). The caloric value of one nugget was calculated based on its macronutrient composition. The thiobarbituric acid reactive substances (TBARS) assay was used to determine the extent of lipid oxidation in the samples, and the results were expressed as mg malondialdehyde/kg. The TBARS values of the cooked GFTNs on day 0 were determined according to the method described by Mielnik et al. (2006).

2.7 | Gluten Contents of GFTN Samples

Gluten analysis was performed using the RIDASCREEN Gliadin ELISA Test Kit (R-Biopharm AG) based on the R5 monoclonal antibody method (AOAC, 2012). A 0.25 g sample was treated with 2.5 mL of the kit's proprietary extraction buffer (Cocktail solution, R-Biopharm AG), incubated at 50°C for 40 min, cooled, and then mixed with 7.5 mL of 80% ethanol. The mixture was shaken for 1 h and centrifuged at 2500 rpm for 10 min. The resulting supernatant was diluted 1:12.5. The wells were prepared, washed, treated with diluted conjugate, and incubated. Substrate and chromogen solutions were added, and after a final incubation, absorbance was measured at 450 nm. Gluten levels were calculated using RIDASOFT software and expressed in mg/kg.

2.8 | Instrumental Analysis Performed on GFTNs

2.8.1 | Crust Color Values

The L^* (lightness/darkness), a^* (red/green), and b^* (yellow/blue) color values on the crust surface of the gluten-free nugget samples were measured at multiple points on five different nuggets using a Konica Minolta CR-300 colorimeter (Japan). In addition to these parameters, chroma (C^*), and hue angle (h^*) values were determined, and the whiteness index was calculated using the following equation.

$$\text{Whiteness index} = 100 - \sqrt{[(100 - L^*)^2 + a^{*2} + b^{*2}]}$$

2.8.2 | Texture Profile Analysis in GFTNs

The hardness, springiness, cohesiveness, gumminess, and chewiness values for each GFTN sample were measured using a texture profile analysis (TPA) device (TA Plus, Stable Micro Systems Ltd., Surrey, UK). The device was set to apply 75% compression to the samples, with a pre-test speed of 1 mm/s, a test speed of 5 mm/s, a post-test speed of 5 mm/s, and a trigger force of 0.04903 N (Ulu 2006). The time interval between the two compression cycles was set to 5 s. From the TPA curves, mechanical parameters such as hardness, cohesiveness, and springiness were obtained directly, while secondary parameters such as gumminess and chewiness were calculated using the device software. All tests were conducted at room temperature using a 50 mm cylindrical probe (model P/50R). Texture measurements were performed on the surface of five different nugget samples for each replication.

TABLE 1 | Results for coating parameters of GFTNs.

Parameters	Treatments			
	A0C100	A30C70	A40C60	A50C50
Coating pick-up (%)	28.16 ± 0.17 ^a	24.67 ± 1.45 ^{ab}	23.77 ± 0.75 ^{ab}	21.26 ± 0.30 ^b
Adhesion degree (%)	21.95 ± 0.10 ^a	19.78 ± 0.94 ^{ab}	19.16 ± 0.46 ^{ab}	17.53 ± 0.20 ^b
Cooking loss (%)	16.28 ± 0.25 ^b	17.36 ± 0.06 ^b	17.10 ± 0.11 ^{ab}	18.28 ± 0.01 ^a
Fat uptake (%)	10.35 ± 0.34 ^b	10.59 ± 0.40 ^b	11.04 ± 0.02 ^b	12.90 ± 0.12 ^a
Moisture retention (%)	8.75 ± 0.30 ^a	8.48 ± 0.30 ^b	8.16 ± 0.25 ^c	7.81 ± 0.25 ^d
Coating thickness (mm)	1.31 ± 0.05 ^c	1.57 ± 0.02 ^b	1.72 ± 0.03 ^a	1.96 ± 0.01 ^a

a–d: Different letters within a row indicate significant differences among treatments ($p < 0.05$).

A0C100: A mixture of 0% amaranth flour and 100% corn flour, **A30C70:** A mixture of 30% amaranth flour and 70% corn flour, **A40C60:** A mixture of 40% amaranth flour and 60% corn flour, and **A50C50:** A mixture of 50% amaranth flour and 50% corn flour.

2.9 | Statistical Analysis

The experimental results were analyzed using the Minitab 22 statistical software package (Minitab Inc., Enterprise Drive, State College, PA, USA). A one-way randomized block design was employed to determine differences between treatments, and Tukey's post-hoc test was applied to assess the significance of differences among samples ($p < 0.05$). Replication was considered as the block (random effect), and treatments (nugget samples with different formulations) were defined as the independent variable influencing the dependent variables (analysis results). Data are presented as mean ± SEM (standard error of the mean).

3 | Results and Discussion

3.1 | Coating Performance Parameters of GFTN

Coating parameters are critical factors in evaluating the final quality of coated products. Table 1 presents the coating parameters of turkey nuggets coated with batters and breaders containing different levels of amaranth and corn flour. As the amaranth flour content increased, coating pick-up and adhesion degree gradually decreased ($p < 0.05$), indicating that less coating material adhered to the nugget surface. The highest values were recorded in the A0C100 group, in which the coating contained only corn flour ($p < 0.05$). Similar pick-up values have been reported for fish nuggets coated with tapioca and coconut (Silva et al. 2021). However, our results differ from those of chicken nuggets coated with other flour types (Albert et al. 2009; Gökçe et al. 2016; Uyarcan et al. 2022), which could be related to differences in the compositional (e.g., protein, starch, and fiber content) and functional properties (e.g., water- and oil-holding capacity, amylose/amylopectin ratio) of the different types of flours used in the batter formulations, as stated in the literature (El-Adawy and Taha 2001; Joshi et al. 2015).

Lower pick up and adhesion degree values may be explained by the lower viscosity of amaranth-based batters and their reduced ability to adhere to the nugget surface. It has been reported that amaranth flour generally exhibits lower viscosity than other flours due to its low amylose content (Coşovanu and Mironeasa 2021; Olawoye and Gbadamosi 2020). In the present study, at a constant shear rate of 25°C, the apparent viscosity of batters was measured to be 3.65, 3.52, 3.45, and 3.36 Pa.s for A0C100,

A30C70, A40C60, and A50C50, respectively, confirming a gradual decrease with higher amaranth flour content. In a similar study, increasing the proportion of corn flour from 30% to 70% in wheat–corn mixtures reduced viscosity from 4.26 to 1.87 Pa.s, which was attributed to differences in amylose/amylopectin ratio and viscosity-building capacity of the flours used (Xue and Ngadi 2006).

Batter viscosity is a critical factor affecting coating pick-up, product quality, appearance, texture, and handling characteristics of coated products (Pinkaw and Naivikul 2019). Lower viscosity leads to less adherence of the coating material to the nugget surface; therefore, in the present study, the reduced viscosity of amaranth flour batters likely impacted the pick-up rate and overall adhesion, ultimately affecting the final coating quality.

Cooking loss refers to the reduction in weight during the frying. In the current study, nuggets without amaranth flour had the lowest cooking loss, while higher values were observed as the proportion of amaranth flour increased in the batter and breaders ($p < 0.05$). The low viscosity of amaranth flour limits batter penetration into the meat, which may increase cooking loss. This finding highlights the importance of batter adherence to the product surface in reducing cooking loss during frying.

Increasing the amaranth flour concentration significantly affected both moisture retention and fat uptake during frying ($p < 0.05$). Fat uptake values increased significantly with higher amaranth flour content. Previous studies have suggested that this effect may be associated with high oil-binding capacity (Bhatt et al. 2021; Olawoye and Gbadamosi 2020). In contrast, moisture retention values decreased significantly as the proportion of amaranth flour increased. The literature suggests that the formation of a more porous structure in the presence of amaranth flour facilitates moisture evaporation during frying (Coşovanu and Mironeasa 2021), which may also explain the higher cooking loss observed.

In terms of coating thickness, the thinnest layer was found in the control group containing 100% corn flour, while a gradual increase was observed with higher levels of amaranth flour ($p < 0.05$). Previous frying studies have shown that water evaporation plays a crucial role in increasing coating porosity and thickness (Dogan et al. 2005; Ziaifar et al. 2010). Flours such as amaranth

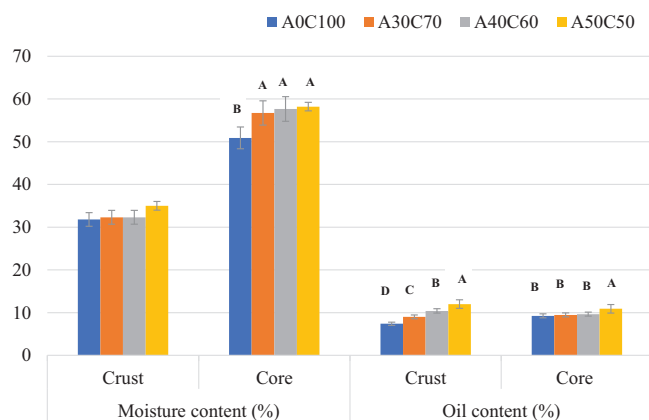


FIGURE 1 | Moisture and oil content in core and crust part of GFTNs **A0C100**: A mixture of 0% amaranth flour and 100% corn flour, **A30C70**: A mixture of 30% amaranth flour and 70% corn flour, **A40C60**: A mixture of 40% amaranth flour and 60% corn flour, **A50C50**: A mixture of 50% amaranth flour and 50% corn flour.

can enhance coating porosity, leading to the formation of air pockets, which cause the coating to expand and thicken further (Xu, Leong, et al. 2020). Overall, these findings indicate that amaranth flour can significantly modify coating parameters due to its unique macro composition. Consequently, incorporating amaranth flour into batter and breader formulations may result in notable changes in the texture, crispness, and overall sensory profile of the final product (Kumar et al. 2013; Alvarez-Jubete et al. 2010).

3.2 | Moisture and Oil Contents of GFTNs

The moisture and oil contents of the crust and core of GFTNs were measured separately, and the results are shown in Figure 1. Increasing the proportion of amaranth flour in the coating formulation resulted in higher moisture and oil contents in both the crust and core ($p < 0.05$). A0C100 had the lowest moisture content in both the crust (31.80%) and core region (50.89%), whereas A50C50 had the highest values, with 35.00% in the crust and 58.21% in the core. While differences in core moisture content were statistically significant ($p < 0.05$), no significant differences were observed in the crust ($p > 0.05$). This could be attributed to the small granule size of amaranth flour, which has a higher water absorption and retention capacity (Machado Alencar et al. 2015), as well as its higher pH, which promotes water retention. In other words, the moisture contents of both crust and core were also influenced by the functional properties of the corn and amaranth flours used in the coatings (Bringas-González et al. 2022; Shevkani and Singh 2014). In all samples, the crust moisture content was lower than that of the core, likely because water vaporization occurs first at the surface during frying, followed by the interior. Additionally, the higher moisture content in the core suggests a juicier texture in the GFTNs.

To better understand how flour affected moisture permeability and water migration within the nuggets, diffusion coefficients were calculated using Fick's Second Law. The values were 2.51×10^{-8} m²/s for A0C100, 2.44×10^{-8} m²/s for A30C70, 2.42×10^{-8} m²/s for A40C60, and 2.40×10^{-8} m²/s for A50C50. The

highest value was observed in nuggets coated with only corn flour, and the lowest in those coated with an equal mixture of corn and amaranth flour. These results indicate that the higher water-holding capacity of amaranth flour may slow down moisture transfer in the crust. The higher diffusion coefficient in A0C100 suggests more rapid moisture loss during frying and more efficient moisture transfer dynamics.

Regarding oil content, the lowest values were found in the crust (7.4%) and core (9.24%) of A0C100, whereas the highest were in A50C50, with 12.00% in the crust and 10.90% in the core. The significant increase in crust oil content with higher amaranth flour levels ($p < 0.05$) was likely due to the higher oil absorption capacity of amaranth flour, while differences in the core were smaller but still significant ($p < 0.05$). Oil content was consistently higher in the crust than in the core. During deep-fat frying, increasing internal temperature leads to moisture evaporation and the formation of a porous structure in the crust, which facilitates oil penetration and accumulation in the outer layer (Feng et al. 2025). Based on our findings, increasing amaranth flour content in the coating material enhanced fat absorption, resulting in higher fat content in the GFTNs. Moreover, crust formation restricts moisture loss from the core by creating a moisture barrier, which supports moisture retention inside the product and the formation of softer, gummier, chewier, and more elastic texture, as explained in the sub-section of the TPA analysis results.

In a similar study conducted by Pinkaew and Naivikul (2019), it was found that rice flour-based coatings for deep-fat-fried chicken nuggets provided better oil resistance and reduced oil content compared to wheat flour. The relationship between moisture and oil contents in gluten-free chicken nuggets prepared with different cereal flours was examined in another study, and results were found to be similar to our findings (Uyarcin et al. 2022). Other studies have shown that cereal protein type, polarity, hydrophobicity, and amino acid composition can significantly affect moisture and oil contents in gluten-free products (Chandra et al. 2015). Changes in the amylose/amylopectin ratio have also been reported to influence the water-oil-absorption capacities of flours and, consequently, the final product (Culetu et al. 2021).

3.3 | Proximate Composition and pH Value of GFTNs

The proximate composition parameters of turkey nuggets containing different concentrations of amaranth and corn flours are presented in Table 2. The pH values of GFTNs ranged from 6.30 to 6.38, while their moisture, fat, protein, and ash contents varied from 50.13% DM to 53.39% DM, from 35.63% DM to 44.08% DM, from 32.28% DM to 33.23% DM and from 4.17% DM to 4.25% DM, respectively. Specifically, the A50C50 group had the highest pH value, fat content, and energy value, whereas the lowest moisture, protein, and carbohydrate results were measured in the same group. The fat content of the GFTNs was statistically increased with increasing amounts of amaranth flour ($p < 0.05$) due to the possible impact of the fat absorption ability of amaranth flour. The same trend was seen in energy values resulting from the increase in fat content. The proportional

TABLE 2 | Proximate composition and pH value of GFTNs.

Parameters	Treatments			
	A0C100	A30C70	A40C60	A50C50
pH	6.30 ± 0.16 ^c	6.34 ± 0.05 ^b	6.36 ± 0.16 ^{ab}	6.38 ± 0.01 ^a
Moisture (%)	53.39 ± 0.50	52.19 ± 0.30	51.68 ± 0.51	50.13 ± 0.80
Fat (%DM)	35.63 ± 0.14 ^c	38.66 ± 0.68 ^{bc}	41.40 ± 0.98 ^{ab}	44.08 ± 0.70 ^a
Protein (%DM)	33.23 ± 0.28	32.86 ± 0.25	32.79 ± 0.29	32.28 ± 0.35
Ash (%DM)	4.17 ± 0.12	4.10 ± 0.17	4.35 ± 0.03	4.25 ± 0.09
Carbohydrate (%DM)	26.97 ± 0.54 ^a	24.38 ± 1.10 ^{ab}	21.46 ± 1.29 ^{ab}	19.39 ± 1.13 ^b
Energy (kcal/100g)	261.69 ± 2.72 ^c	275.80 ± 0.42 ^{bc}	284.27 ± 0.71 ^{ab}	300.88 ± 3.27 ^a
TBARS (mg MA/kg)	0.160 ± 0.03 ^a	0.182 ± 0.03 ^a	0.176 ± 0.02 ^a	0.189 ± 0.05 ^a
Gluten values (mg/kg)	15.15 ± 0.18 ^a	15.69 ± 1.20 ^a	15.06 ± 0.29 ^a	15.02 ± 1.18 ^a

a–c: Different letters within a row indicate significant differences among treatments ($p < 0.05$).

A0C100: A mixture of 0% amaranth flour and 100% corn flour, **A30C70**: A mixture of 30% amaranth flour and 70% corn flour, **A40C60**: A mixture of 40% amaranth flour and 60% corn flour, and **A50C50**: A mixture of 50% amaranth flour and 50% corn flour.

DM: The values were calculated on dry matter basis.

change was also found to be impressive on carbohydrate values, in which statistically decreases were calculated with increasing percentages of amaranth flour. As for moisture, protein, and ash contents, no significant differences were determined ($p > 0.05$). Similar results were also reported by Mătieș et al. (2024). The carbohydrate content of nuggets decreased as the proportion of amaranth flour in the coating increased. In contrast to our results, in a study where amaranth flour was used as a substitute for wheat flour in the coating of chicken nuggets, it was found that amaranth flour significantly increased the pH, fat, protein, and ash contents (Tamsen et al. 2018).

Additionally, gluten analysis was performed in this study. The European Union defines gluten-free foods as those containing no more than 20 mg/kg of gluten (Zerbini et al. 2024). The gluten content of turkey nuggets coated with different concentrations of amaranth and corn flours ranged from 15.02 mg/kg to 15.69 mg/kg. These values comply with the EU regulation for gluten-free products, indicating that the use of amaranth flour together with corn flour in the nugget formulation provides an option to produce GFTNs with different characteristics for individuals with celiac disease.

In this study, TBARS analysis, a quality criterion for cooked meat and meat products used to determine lipid oxidation rate, was also conducted. Generally, products with TBARS values below 3 mg MA/kg are considered to be of good quality. In this study, TBARS values for GFTNs ranged from 0.160 to 0.189 mg MA/kg, and no significant differences were observed among samples ($p > 0.05$). This finding indicates that an increase in the concentration of amaranth flour had no effect on TBARS values. In a study comparing the TBARS data of fish nuggets coated with tapioca, corn, and coconut flours, it was observed that the samples coated with corn flour had lower TBARS values (da Silva et al. 2021). Similar to our study, chicken nuggets containing different amounts of amaranth flour in various layers showed no difference in TBARS values on day 0 (Tamsen et al. 2018).

3.4 | Instrumental Crust Color Properties of GFTNs

Color is a critical factor that enhances consumer satisfaction and acceptance in gluten-free products. In this study, the instrumental color measurement results of turkey nuggets prepared with different concentrations of amaranth and corn flour are presented in Table 3. The lightness (L^*) value of the nugget crust decreased with increasing amounts of amaranth flour ($p < 0.05$). The L^* value of the group containing 0% amaranth flour (A0C100) was significantly higher than those of the groups containing 40% and 50% amaranth flour ($p < 0.05$). This difference was attributed to the bran and betacyanin pigments present in amaranth flour (Alencar et al. 2015), which resulted in a darker color in nuggets produced with a mixture of corn and amaranth flour.

The a^* value of the A0C100 group was statistically higher compared to the other groups ($p < 0.05$), whereas similar results were obtained among groups for the b^* value ($p > 0.05$). Increasing the amaranth flour content in both the batter and breader resulted in a decrease in both redness and yellowness parameters. This finding was directly related to the inherent color of the amaranth flour used in the coating formulation.

The Chroma (C^*) value, which indicates the degree of color saturation, decreased as the amaranth flour content increased ($p > 0.05$). Conversely, the Hue value significantly increased with increasing amounts of amaranth flour, indicating a shift in the nugget color from yellow toward a more yellowish-green tone. The whiteness index, which determines the overall whiteness level, was highest in the A0C100 group, indicating a brighter and lighter surface ($p < 0.05$). This value gradually decreased with increasing amaranth flour content ($p < 0.05$), showing that amaranth flour darkened the nugget surface. Overall, the color results indicate that the A50C50 group, containing a 50:50 mixture of amaranth and corn flours, exhibited a dark, dull appearance with less red and less yellow tones, shifting toward

TABLE 3 | Instrumental color results of GFTNs on crust surface.

Parameters	Treatments			
	A0C100	A30C70	A40C60	A50C50
L* value	60.70 ± 0.17 ^a	56.64 ± 0.97 ^{ab}	53.76 ± 0.92 ^b	52.69 ± 0.05 ^b
a* value	6.33 ± 0.05 ^a	4.99 ± 0.13 ^b	2.85 ± 0.37 ^c	2.54 ± 0.09 ^c
b* value	34.41 ± 0.12 ^a	32.68 ± 0.37 ^a	32.15 ± 1.16 ^a	32.34 ± 0.49 ^a
Chroma value	34.98 ± 1.00 ^a	33.06 ± 0.50 ^a	32.28 ± 0.17 ^a	32.44 ± 0.11 ^a
Hue value	79.58 ± 1.00 ^b	81.32 ± 0.34 ^b	84.93 ± 2.70 ^{ab}	85.51 ± 1.11 ^a
Whiteness index	47.38 ± 0.12 ^a	45.48 ± 0.87 ^{ab}	43.61 ± 0.49 ^b	42.64 ± 1.13 ^c

a–c: Different letters within a row indicate significant differences among treatments ($p < 0.05$).

A0C100: A mixture of 0% amarant flour and 100% corn flour, **A30C70**: A mixture of 30% amarant flour and 70% corn flour, **A40C60**: A mixture of 40% amarant flour and 60% corn flour, and **A50C50**: A mixture of 50% amarant flour and 50% corn flour.

TABLE 4 | Instrumental texture properties of GFTNs.

Parameters	Treatments			
	A0C100	A30C70	A40C60	A50C50
Hardness (N)	16577 ± 42.10 ^a	15000 ± 35.50 ^a	14920 ± 55.21 ^a	14658 ± 5.97 ^a
Cohesiveness (N mm)	0.79 ± 0.01 ^a	0.76 ± 0.02 ^a	0.74 ± 0.01 ^a	0.73 ± 0.01 ^a
Springiness (mm)	0.788 ± 0.05 ^b	0.794 ± 0.05 ^{ab}	0.840 ± 0.02 ^{ab}	0.888 ± 0.03 ^a
Gumminess (N)	17457 ± 5.05 ^a	11502 ± 31.12 ^b	11081 ± 54.00 ^b	10249 ± 6.18 ^b
Chewiness (N mm)	12055 ± 2.65 ^a	9065 ± 3.86 ^b	8811 ± 5.57 ^b	8608 ± 8.06 ^b
Resilience	0.48 ± 0.01 ^a	0.40 ± 0.01 ^b	0.39 ± 0.01 ^b	0.38 ± 0.01 ^b

a–b: Different letters within a row indicate significant differences among treatments ($p < 0.05$).

A0C100: A mixture of 0% amarant flour and 100% corn flour, **A30C70**: A mixture of 30% amarant flour and 70% corn flour, **A40C60**: A mixture of 40% amarant flour and 60% corn flour, and **A50C50**: A mixture of 50% amarant flour and 50% corn flour.

a yellowish-green hue due to the natural pigments in amarant flour.

3.5 | Instrumental Texture Properties of GFTNs

The TPA results of GFTNs are shown in Table 4. As the percentage of amarant flour increased, all TPA parameters, except for springiness, decreased. The reduction in gumminess, chewiness, and resilience was significant in nuggets coated with a mixture of amarant and corn flours compared to those coated with only corn flour ($p < 0.05$), whereas the decrease in hardness and cohesiveness was not significant ($p > 0.05$). This finding was directly attributed to the higher moisture content in the core part of the nuggets (Figure 1) and in the whole nuggets (Table 2) with the increasing amount of amarant flour in the coating material. It is well known that retaining moisture inside the product during deep-fat frying results in nuggets that are chewier, gummier, and softer. In the present study, the replacement of corn flour with amarant flour in the coating material enhanced moisture retention; consequently, lower values were obtained in the TPA analysis.

On the contrary to these TPA parameters, higher springiness values were measured in nuggets with increasing amounts of amarant flour ($p < 0.05$). In a similar study, researchers found that the springiness parameter increased with the use of

amarant flour in chicken nuggets (Tamsen et al. 2018). This increase was also explained by higher moisture retention in nuggets, which could support the formation of a more elastic structure. Additionally, as stated by previous researchers, the higher fat content of nuggets containing amarant flour led to the entrapment of air bubbles, thereby increasing the porosity of the nuggets and enhancing the springiness of the GFTNs (Alvarez-Jubete et al. 2010).

4 | Conclusions

The current study revealed that substitution of corn flour with different concentrations of amarant flour in the production of GFTNs significantly affected various quality parameters. Increasing the amount of amarant flour in batter and breadier led to notable changes in coating pick-up, coating thickness, viscosity, moisture loss, oil absorption, and product color. Specifically, higher concentrations of amarant flour resulted in darker color tones and higher oil content, while reduced viscosity negatively impacted coating performance. Considering all parameters obtained in this study, it can be concluded that incorporating amarant flour into the coating formulation had positive effects on product quality, with formulations containing up to 30% amarant flour offering a balanced option in terms of both technological properties and nutritional value. These findings contribute to the development of alternative, high-quality, and

nutritious meat products for individuals with celiac disease and those following a gluten-free diet.

Author Contributions

Betül Karşlıoğlu: supervision, conceptualization, methodology, validation, formal analysis, investigation, writing – original draft, writing – review and editing, software, project administration. **Eda Demirok Soncu:** writing – original draft, formal analysis, writing – review and editing, software. **İkra Meşhur:** investigation, visualization, resources, project administration. **Aliye Ümran Baştemir:** investigation, visualization. **Afranur Aktaş:** investigation, visualization.

Conflicts of Interest

The authors declare no conflicts of interest.

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