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Cydonia oblonga Mill. (Quince) Peel as a Functional Food Ingredient in Gluten-Free Sorghum Muffins: Effects on Nutritional, Technological, and Sensory Properties

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Abstract

The technological limitations of gluten-free flours, including weak structure and low elasticity, negatively impact the sensory quality and consumer acceptance of the final product. Incorporating quince peel, a source of fiber and bioactive compounds, may enhance the nutritional and textural profile while improving key sensory attributes such as flavor and mouthfeel. This study aimed to valorize quince peel powder (QP), a fruit-processing by-product, by incorporating it (0%, 6%, 12%, 18%) into gluten-free sorghum muffins to enhance their nutritional profile and assess its impact on their technological and sensory properties. Phenolic characterization revealed that QP was rich in phenolics (337.1 µg/g), predominantly chlorogenic acid (54.5%). The 18% QP formulation increased the dietary fiber content by 80.8% and improved antioxidant activity by 23.3% relative to the control muffins. Image processing analysis of the crumb structure showed that QP created a uniform texture while moderately reducing air cell volume. Texture profile analysis revealed that increasing QP levels resulted in higher hardness and lower springiness. Quantitative descriptive analysis combined with multivariate analysis indicated that the 6–12% QP formulations were the most acceptable in terms of key sensory attributes. These results demonstrate the successful valorization of quince peel as a functional ingredient in sorghum muffins, enhancing nutritional and textural properties while maintaining structural integrity.

Keywords: quince; sorghum; gluten-free muffin; fruit by-product; valorization; functional ingredient; principle component analysis

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1. Introduction

The industrial processing of fruits and vegetables generates substantial by-products (e.g., peels, cores, pomace), accounting for nearly 50% of the total output [1]. Valorizing these by-products is critical to addressing environmental and economic challenges while enhancing resource efficiency [2]. Their incorporation into food systems offers a sustainable strategy to improve the value of waste streams and mitigate health and ecological concerns [3]. As these by-products are rich in fiber and bioactive compounds, their incorporation may enhance certain nutritional and functional aspects of gluten-free products [4], a growing market driven by rising celiac disease prevalence. However, traditional gluten-free bakery items frequently face challenges such as lower nutritional quality and compromised

physical and sensory attributes, including reduced volume and rapid staling [5–7]. This well-documented nutritional deficit arises from the fundamental composition of the most commonly used gluten-free flours. For instance, staple gluten-free cereal flours like rice and maize contain significantly less dietary fiber (3.6 ± 3.1%) than gluten-containing flours (7.1 ± 3.9%) [8]. Furthermore, the protein content of packaged gluten-free products is more than two times lower across 57% of all food categories compared to their gluten-containing counterparts [9]. This nutritional gap is critical because, unlike whole-grain wheat, the majority of gluten-free flours (such as rice, brown rice, maize, oat, and millet) have starch as their major component [10]. Gluten-free bakery products typically exhibit reduced loaf volume, weaker crumb structure, and faster staling relative to wheat-based products due to the absence of a gluten network, which normally provides gas-holding capacity, dough elasticity, and structural stability. Therefore, these products fail to reach acceptable specific volume and frequently present inferior textural and sensory properties [11].

To address these limitations, research has focused on fortifying gluten-free muffins with nutrient-dense ingredients, including alternative flours (e.g., rice, quinoa, sorghum) [12–14] and fruit/vegetable by-products (e.g., watermelon rind, apple peel) [1,4]. Among these, sorghum (*Sorghum bicolor* (L.) Moench) is a particularly promising option for gluten-free formulations [13]. As a sustainable, cost-effective, and drought-tolerant crop, sorghum serves as an excellent alternative to costly gluten-free options like rice and maize [14,15]. It offers distinct advantages, including higher protein content [9], the absence of maize's characteristic odor [16], and a rich profile of minerals and bioactive compounds [13,17]. However, like all gluten-free flours, sorghum's lack of gluten limits its hydration and dough functionality, creating textural challenges [15]. A formulation based solely on sorghum flour would also be expected to have less dietary fiber and a less diverse profile of specific phenolic compounds than those found in various fruit by-product fortificants used to enhance the nutritional properties of muffins. Therefore, it is crucial to investigate how adding functional ingredients, particularly those with high nutritional value, will impact the final product's texture and overall functional properties.

Quince (*Cydonia oblonga* Mill.) is a species of the genus Cydonia in the Rosaceae family and originates from a broad geographical range that includes Türkiye, Iran, Azerbaijan, the northern Caucasus, and the Caspian Sea region [18–20]. It serves as a valuable source of organic acids, major sugars (fructose, glucose, and sucrose), dietary fiber, and vitamins, in addition to minerals such as phosphorus, potassium, sodium, and calcium [21–24]. Building on this nutritional profile, interest in quince fruit has been increasing among researchers and consumers, not only because of its strong antioxidant and anti-inflammatory activities but also due to its characteristically intense aroma [19,20,25,26]. Quince peel by-products, obtained during processing, are notably rich in dietary fiber (up to 20.2 g/100 g) and polyphenols, highlighting their potential as functional ingredient sources [23,27,28]. Previous research has examined the incorporation of quince and fruit-derived materials into various food matrices, including the utilization of scalding water (a quince-based extract) for yogurt fortification [29], quince flour in muffin formulations [30], quince pomace in wheat-based sponge cake [31], quince peel in cookies [32], and quince pulp in soft candy (lokum) production [20]. Despite these applications, the use of quince peel powder (QP) in gluten-free sorghum muffins has not been investigated to date.

This gap is critical because QP's unique combination of dietary fiber, polyphenols, and distinct taste profile has the potential to directly address the key limitations of sorghum-based gluten-free products. Specifically, its fiber is expected to enhance the structural network and texture. Its bioactive compounds may increase nutritional value, and its flavor may create a more complex and appealing sensory experience for consumers. Yet, the comprehensive effect of QP incorporation on the final quality, microstructure, and

sensory profile of sorghum-based muffins remains unknown, particularly whether these potential benefits can be achieved without compromising product quality. This study aimed to investigate the effects of incorporating different levels of QP on the nutritional, textural, microstructural, and sensory properties of gluten-free sorghum muffins to systematically evaluate its potential as a functional ingredient. The findings demonstrate a dual sustainable solution by valorizing agricultural waste and promoting the use of a resource-efficient grain. This approach addresses the growing demand for nutritious and healthy food options.

2. Materials and Methods

2.1. Quince Peel Powder Production and Phenolic Characterization

Mature quince fruits (*Cydonia oblonga* Mill.) were obtained from local producers (Söz Retail Chain Markets, Afyonkarahisar, Türkiye). Fruits (pH 3.32 ± 0.02, Brix° 13.8 ± 0.2 at 23.0 °C) were washed and peeled. The peels were dried in a convection oven (Binder 9010-0218, GmbH, Tuttlingen, Germany) at 60 °C until constant weight. The final moisture content (10.58%) was determined using AOAC 934.06 [33]. Dried peels were ground for one minute using a laboratory grinder (Demsan, Konya, Türkiye) and sieved through a 300-µm standard test sieve (Miprolab, Ankara, Türkiye). The resulting QP was stored in sealed HDPE bags under dry, light-protected conditions at 23 ± 1 °C until use.

HPLC analysis of phenolic compounds was performed following the method described in [34]. Phenolic compounds were extracted from QP by mixing 10 g of powder with 20 mL of methanol (1:2 w/v). A 20 µL sample was injected into the Shimadzu HPLC system equipped with an SPD-M10Avp DAD detector (λ_{max} = 278 nm), an SIL-10ADvp autosampler, an SCL-10Avp system controller, an LC-10ADvp pump, a DGU-14A degasser, and a CTO-10Avp column oven (Shimadzu Corp., Kyoto, Japan). Separation was achieved on an Agilent Eclipse XDB-C18 column (250 × 4.6 mm, 5 µm) (Agilent Technologies, Santa Clara, CA, USA) with a mobile phase consisting of solvent A (3% acetic acid in water) and solvent B (methanol) at a flow rate of 0.8 mL/min. The column temperature was maintained at 30 °C. HPLC standards of gallic acid, protocatechuic acid, catechin, p-hydroxybenzoic acid, chlorogenic acid, caffeic acid, epicatechin, syringic acid, vanillin, p-coumaric acid, ferulic acid, sinapic acid, benzoic acid, o-coumaric acid, rutin, hesperidin, rosmarinic acid, eriodictyol, cinnamic acid, quercetin, luteolin, and kaempferol were purchased from Sigma-Aldrich (St. Louis, MO, USA). All solvents and reagents were of analytical or HPLC grade.

2.2. Hydration and Particle Size Distribution Analysis of Sorghum Flour

Sorghum flour for gluten-free muffin production was obtained from Tam Tarım Inc. (Gümüşhane, Türkiye). The manufacturer's nutritional analysis indicated the following composition: 10% protein, 6% fiber, 3.1% fat, 69% carbohydrates, 8.1% moisture, and 3.8% ash. To characterize the flour's hydration properties, water binding capacity (WBC), swelling volume (SV), and water holding capacity (WHC) were determined using the method described in [35].

To determine the water binding capacity (WBC), briefly, a 5 g dry sample (W_0) was mixed with 25 mL of water in a Falcon tube. After shaking, the slurry was centrifuged at 2000 rpm for 10 min. The supernatant was discarded, and the weight of the sediment after centrifugation was recorded (W_{sc}). WBC (g water/g sample) was calculated as (Equation (1)):

$$WBC\left(\frac{g}{g}\right) = \frac{W_{sc-}\,W_o}{W_o} \quad (1)$$

Swelling volume (SV) was measured by hydrating 5 g of dry sample (W_0) with 100 mL of water in a graduated cylinder. After standing for 24 h at room temperature, the final total volume of the hydrated sediment (V_f) was recorded. SV was calculated as (Equation (2)):

$$SV\left(\frac{mL}{g}\right) = \frac{V_f}{Wo} \quad (2)$$

This procedure was performed prior to the WHC measurement. The water holding capacity (WHC) was then determined separately using the hydrated sediment from this test, after careful removal of the excess surface water. Water holding capacity (WHC) was determined using the hydrated sediment from the SV test. After carefully removing the excess surface water, the hydrated sediment was weighed ($W_h s$). WHC was expressed as grams of water per gram of dry sample using the formula (Equation (3)):

$$WHC\left(\frac{g}{g}\right) = \frac{W_{hs-}\,W_o}{W_o} \quad (3)$$

Particle size distribution (PSD) analysis of sorghum flour was conducted using a Malvern Mastersizer 2000 Laser Diffraction System (Malvern Instruments Ltd., Malvern, Worcestershire, UK). Samples were dispersed in deionized water using a Hydro 2000MU wet dispersion unit (Malvern Instruments Ltd., Malvern, Worcestershire, UK), followed by 5 min of sonication to ensure complete dispersion and agglomerate breakdown, as described in a previously established method [36]. The particle size distribution was characterized by the percentiles D(0.1), D(0.5), and D(0.9), representing the particle diameters below which 10%, 50%, and 90% of the sample volume lies, respectively.

2.3. Muffin Preparation

The muffin batter ingredients were white sugar (Torku, Türkiye), whole medium eggs (Evrenkaya, Afyonkarahisar, Türkiye), whole cow milk (Torku, Konya, Türkiye), corn oil (Orkide, İzmir, Türkiye), baking powder (Dr. Oetker, İzmir, Türkiye), and sorghum (*Sorghum bicolor* (L.) Moench) flour (Tam Tarım, Gümüşhane, Türkiye). For muffin production, the control gluten-free muffin formulation contained sorghum flour as the sole flour component. Varying proportions of sorghum flour were replaced with QP at 6%, 12%, and 18% substitution levels, selected to align with the range commonly investigated for fruit by-product enrichment in muffins, which typically spans 5% to 20% in previous studies [4,37,38]. The remaining ingredients per 100 g of total flour mass (sorghum flour with QP) were fixed: 60 g sugar, 50 g eggs, 75 g milk, 50 g sunflower oil, and 4 g baking powder. The samples were grouped as QP0 (control), QP6, QP12, and QP18 to reflect their respective compositions. For preparation, whole eggs and sugar were mixed for one minute using a hand-held mixer (Fakir Trinity, Fakir Werke GmbH, Bissendorf, Germany). Subsequently, sunflower oil, milk, and the pre-mixed dry ingredients (sorghum flour, QP, and baking powder) were added and mixed for an additional two minutes. A total of 30 g (±0.2 g) of batter was dispensed into paper-lined muffin molds (4 cm base diameter). The muffins were baked in a preheated conventional oven (Teka HAK 625N, Teka Group, Mönchengladbach, Germany) at 170 °C for 20 min in separate batches. After cooling for 30 min at ambient temperature, they were sealed in plastic bags to retain moisture and stored at room temperature (23 ± 1 °C) until analysis. Each formulation was produced in triplicate, with at least three muffins per production selected for analytical evaluation. Muffins were analyzed within 48 h of preparation, and texture and sensory assessments were conducted within the initial 24 h to preserve product freshness.

2.4. Proximate Composition Analysis

The muffins' proximate composition was determined using official protocols (AOAC) [39]: moisture content (925.09), lipid content (920.39), crude protein (954.01), mineral ash (923.03), and dietary fiber (991.43). The carbohydrate content (CHO) was calculated by subtracting the sum of all other constituents from 100%.

2.5. Baking Loss and Product Height

Muffin height was measured using a digital caliper. After vertically sectioning the muffins, the tallest point from the bottom to the top center was recorded as the height of the sorghum muffins in mm. The percentage of weight lost during baking was derived from Equation (4):

$$Baking\ Loss\ (\%) = \frac{(Batter\ weight - Muffin\ weight)(g)}{Batter\ weight\ (g)} \times 100 \quad (4)$$

2.6. Total Phenolic Content and Antioxidant Activity Analysis

Muffin samples were extracted to determine total phenolic content and antioxidant activity [40]. The extraction was performed for 30 min at room temperature (23 ± 1 °C) under constant magnetic stirring at 600 rpm using an IKA RT 15 magnetic stirrer (IKA-Werke GmbH & Co. KG, Staufen, Germany). The mixture was then centrifuged at 6800× g for 30 min at 4 °C, and the resulting supernatant was filtered. Total phenolic content (TPC, mg GAE/g dry sample) and antioxidant activity (measured as DPPH radical scavenging activity, % inhibition) were determined according to [41] using a spectrophotometer (UV-1800, Shimadzu, Kyoto, Japan). For the DPPH assay, a methanol blank (negative control) was used to set the baseline (0% inhibition). Absorbance was measured against a methanol blank at 765 nm and 517 nm for TPC and antioxidant activity, respectively.

2.7. Color Measurements

The color parameters (L*, a*, b*) of muffin crusts and crumbs were measured using a Chroma Meter CR-400 (Minolta Co., Tokyo, Japan). To evaluate the impact of QP on color change during baking, the overall color change (ΔE) relative to the control sample (QP0) was calculated. Crumb measurements were taken on cross-sectional slices, whereas crust readings were performed on intact surfaces. The color change was derived mathematically using Equation (5):

$$\Delta E = \sqrt{(L^* - {L_o}^*) + (a^* - {a_o}^*) + (b^* - {b_o}^*)} \quad (5)$$

where ${L_o}^*$, ${a_o}^*$, and ${b_o}^*$ represent the color values of the control sample.

2.8. Texture Analysis

The textural properties of muffins were analyzed by Texture Profile Analysis (TPA) using a TA-XT Plus Texture Analyzer (Stable Micro Systems, Godalming, Surrey, UK), following a method adapted from [42]. For TPA, cylindrical crumb samples (approximately 4 cm diameter, 2.5 cm height) were excised from the central top section. A 36 mm cylindrical probe was used for double compression, ensuring the sample diameter exceeded the probe diameter for valid TPA measurements. The pre-test speed, test speed, and post-test speed were 2.0 mm/s, 1.0 mm/s, and 10.0 mm/s, respectively. A 5 s pause was applied between compressions at 25% strain relative to the initial height. Hardness, springiness, cohesiveness, chewiness, and resilience were calculated using Texture Exponent 32 software (version 6.1.11.0, Stable Micro Systems, Godalming, Surrey, UK).

2.9. Image Processing

The crumb cell structure was characterized following an established methodology [43]. Muffin samples were horizontally sectioned at 2.5 cm above the base. High-resolution images (600 dpi) of the crumb structure were then obtained using a scanner (Canon E510, Tokyo, Japan). These images were analyzed with ImageJ software (version 1.54g, NIH, Bethesda, MD, USA). The images were processed by converting them to 8-bit grayscale, followed by binarization. The key structural parameters determined via image analysis were total air cell (pore) area (mm^2), mean air cell diameter (mm), air cell area %, and cell circularity.

2.10. Sensory Analysis

Quantitative Descriptive Analysis (QDA) was utilized to evaluate the sensory profile of the sorghum muffins [44]. The trained sensory panel comprised ten members (n = 10) from the Afyon Kocatepe University's Food Engineering Department, selected based on their experience and availability. Panelists underwent three-hour training sessions focused on identifying and scaling the relevant attributes. Descriptors, definitions, and anchor points were established during two preliminary consensus sessions (detailed in Supplementary Table S1). The study protocol received ethical approval from the Afyon Kocatepe University Scientific Research and Publication Ethics Committee (Approval no.: 2025/20; Date: 8 September 2025), and written informed consent was secured from all participants. Samples were presented in a unique randomized order under three-digit codes, with water used for palate cleansing between samples. Sensory attributes were rated on a 10 cm unstructured scale across five categories: appearance (porosity, color), texture (hardness, springiness), mouthfeel (moistness, oiliness, chewiness), odor, and taste (typical, aromatic, aftertaste). QDA data were converted to numerical values for statistical analysis.

2.11. Statistical Analysis

To elucidate the relationships between sensory attributes and muffin formulations, multivariate analyses, specifically Principal Component Analysis (PCA) and heatmap visualization, were performed using ClustVis (custom BETA edition) [45]. PCA was specifically applied to reduce the dimensionality of the data and identify the dominant latent factors governing sensory variation. Sensory data were row-centered, scaled to unit variance, and constant variables were removed prior to analysis. PCA was computed using singular value decomposition (SVD) with imputation. Heatmaps were generated using a correlation distance metric and average linkage, with dendrograms arranged according to the "tightest cluster first" algorithm without predefining the number of clusters.

All data were analyzed using a one-way ANOVA followed by Duncan's multiple range test for post hoc comparisons using SPSS software (version 23.0, IBM SPSS Statistics, Armonk, NY, USA), and differences were considered statistically significant at $p < 0.05$. All analyses were conducted in triplicate, and the data are presented as the mean ± standard deviation (SD).

3. Results and Discussion

3.1. Characterization of Phenolic Compounds in Quince Peel

To evaluate its potential as a functional ingredient, the phenolic profile of QP was characterized using high-performance liquid chromatography with diode-array detection (HPLC-DAD). The resulting chromatogram (Supplementary Figure S1) confirms the presence of the 14 detected phenolic compounds. The quantitative analysis revealed the following concentrations (μg/g) for each compound: chlorogenic acid (286.5), rutin (166.5), epicatechin (73.2), ferulic acid (46.3), quercetin (15.0), luteolin (7.3), kaempferol (7.9), sy-

ringic acid (6.7), p-coumaric acid (4.3), rosmarinic acid (3.2), cinnamic acid (2.6), o-coumaric acid (1.7), gallic acid (0.4), and eriodictyol (0.5). Compounds were classified into three main groups based on their chemical structure. Hydroxycinnamic acids constituted the dominant group, making up 54.5% of the total phenolics (337.1 μg/g) and comprising five compounds: chlorogenic acid, *p*-coumaric acid, o-coumaric acid, cinnamic acid, and rosmarinic acid. Flavonoids represented the second-largest group, accounting for 43.8% (270.9 μg/g) with six constituents: rutin, epicatechin, quercetin, luteolin, kaempferol, and eriodictyol. Hydroxybenzoic acids, representing 1.7% of total phenolics (11.4 μg/g), were the minor group and included gallic acid, vanillin, and syringic acid.

In line with previous findings, chlorogenic acid was identified as the predominant phenolic acid [46], with a concentration of 286.5 ± 2.9 μg/g in this study. Similarly, rutin (quercetin-3-O-rutinoside) was quantified at 166.5 ± 0.7 μg/g, confirming its role as a major flavonol, as documented in earlier research [47]. Both chlorogenic acid and rutin possess well-documented antioxidant and anti-inflammatory properties, as demonstrated in vitro and in vivo [22,28,46]. The profile also revealed the presence of epicatechin and diverse minor phenolics, which are also commonly reported in quince and contribute to its overall phytochemical complexity [22,28]. Overall, this characterization confirms that QP is a rich source of diverse phenolic compounds, supporting its selection as a promising functional ingredient for muffin enrichment [28].

3.2. Hydration Properties and Particle Size Distribution of Sorghum Flour

The hydration behavior of sorghum flour was quantified through water binding capacity (WBC), water holding capacity (WHC), and swelling volume (SV) measurements, which provide fundamental parameters for its functionality in baked products. The results showed that sorghum flour has a WBC of 2.07 ± 0.04 g/g, WHC of 2.98 ± 0.05 g/g, and SV of 5.06 ± 0.02 mL/g. The observed hydration properties are attributed to the flour's composition, particularly its fiber (6%) and protein (10%) content. This interpretation is supported by a comparative analysis with other flours. The literature suggests that such proteins and fibers promote water retention through hydrophilic fiber–water interactions and protein–water binding, where non-gluten proteins actively compete for water molecules [35]. Consistent with this mechanism, similar hydration characteristics have been reported in other protein and fiber-rich gluten-free flours, such as okara [35] and buckwheat [48]. Furthermore, a direct comparison with wheat flour provides a key reference point. Sorghum flour, as gluten-free flour, exhibits a lower water absorption capacity compared to wheat flour. Studies demonstrate that incorporating 40% sorghum flour into wheat flour blends reduces water absorption from 58.2% to 52.7% [15]. In gluten-free muffin production, water retention properties are essential, as they directly influence batter viscosity, crumb softness, and shelf life [49]. To address sorghum's relatively limited water-binding capacity in this context, high-fiber ingredients like QP can be incorporated to improve the hydration capacity and textural quality of gluten-free muffins. This approach is well-supported in the literature. The partial replacement of flour with dried fruit by-products, such as mango peel and grapefruit powder, has been consistently shown to significantly increase water absorption in dough systems [50,51]. This behavior is primarily attributed to the high content of pectin and dietary fiber in fruit by-products, which are capable of binding large amounts of water through hydrogen bonding [50,52]. Furthermore, quince-derived by-products are specifically reported to possess high hydration-related functional properties; for example, quince processing residues show a water-binding capacity of 6.41 g/g, oil-binding capacity of 2.93 g/g, and swelling capacity of 2.70 mL/g [53]. Although the hydration properties of QP used in the present study were not directly measured, this collective evidence from the literature strongly suggests its potential to modify the

water distribution and availability within the gluten-free batter system, thereby counterbalancing the inherently limited water-binding capacity of the sorghum flour base.

Particle size and surface area are important for flour's functional properties, directly influencing its water binding, swelling, absorption, and solubility. The particle size distribution (PSD) of the sorghum flour sample, measured via laser diffraction, revealed a heterogeneous distribution with three discernible populations (Figure 1), and a median particle size D(0.5) of 30.996 µm. The D(0.1) value of 9.875 µm suggests that 10% of particles fell below this threshold, highlighting the presence of fine starch granules, while the D(0.9) value of 119.732 µm confirms a minor fraction of coarse particles. The broad distribution was quantitatively confirmed by the span value of 3.554, indicating size heterogeneity. This is in good agreement with the literature, which reports that sorghum flour can have a broad particle size distribution due to the coexistence of various components and the milling process, including fine starch granules, protein bodies, and coarse fiber fragments from bran [54,55]. According to studies on gluten-free systems, such a broad particle size distribution can be advantageous for muffin production [14], where the fine fraction enhances water absorption and gelatinization, while the coarse particles may provide structural scaffolding that prevents starch gel collapse and stabilizes pore networks during baking.

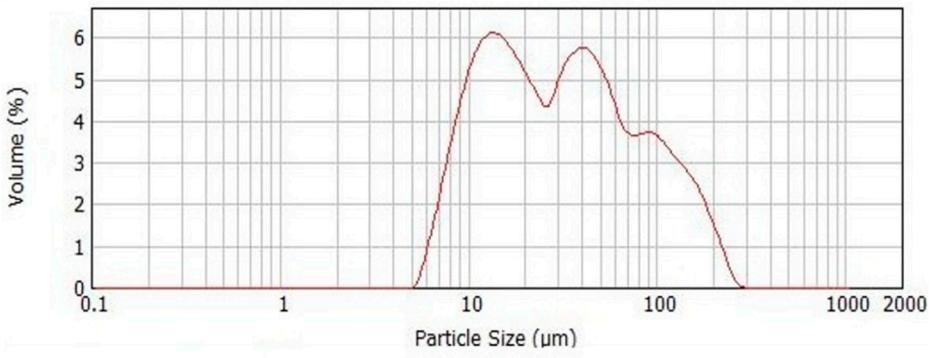


Figure 1. Particle size distribution of sorghum flour.

3.3. Proximate Composition and Bioactive Properties of Sorghum Muffins

The incorporation of QP led to significant changes in the nutritional composition of gluten-free sorghum muffins (Table 1). Moisture content exhibited a significant decrease with increasing QP levels ($p < 0.05$). This observed reduction aligns with the high dietary fiber content of fruit peels, which can alter water distribution in the matrix. While dietary fiber enhances water-binding capacity, its interaction with starch during baking may reduce the availability of free water, as reported in studies on fruit peel-fortified baked goods [4,28,56].

Table 1. Proximate composition (% wet basis), total phenolic content (TPC), and antioxidant activity (AA) of sorghum muffins.

Sample	Moisture	Fat	Protein	Ash	Fiber	CHO	TPC	AA
QP0	20.1 ± 0.3^{c}	21.4 ± 0.3^{a}	7.0 ± 0.2^{a}	2.1 ± 0.08^{a}	2.1 ± 0.1^{a}	47 ± 2^{a}	3.88 ± 0.01^{a}	60.2 ± 0.3^{a}
QP6	19.4 ± 0.3^{bc}	21.3 ± 0.2^{a}	7.0 ± 0.3^{a}	2.2 ± 0.07^{a}	2.7 ± 0.1^{b}	47 ± 2^{a}	4.37 ± 0.07^{b}	63.9 ± 0.1^{b}
QP12	18.9 ± 0.3^{ab}	21.0 ± 0.2^{a}	7.0 ± 0.1^{a}	2.2 ± 0.08^{a}	3.3 ± 0.1^{c}	48 ± 2^{a}	4.80 ± 0.08^{c}	67.7 ± 0.3^{c}
QP18	18.5 ± 0.3^{a}	20.9 ± 0.2^{a}	7.00 ± 0.1^{a}	2.3 ± 0.06^{a}	3.9 ± 0.1^{d}	48 ± 3^{a}	5.45 ± 0.11^{d}	74.2 ± 0.3^{d}

Data represent mean ± SD. Different superscript letters ($^{a–d}$) within the same column indicate significant differences among samples (Duncan's test, $p < 0.05$).

The most notable impact of QP substitution was on dietary fiber content, which increased significantly ($p < 0.05$). The 80.75% increase in total dietary fiber over the control is consistent with quince peel's well-documented status as a fiber-rich by-product [56].

Dietary fiber, a non-starch polysaccharide abundant in fruit and vegetable by-products, possesses a high capacity to bind water, thereby influencing the texture and stability of food products [3,4,56]. This trend is supported by previous research. For instance, the addition of quince fruit flour to gluten-free muffins resulted in a decrease in moisture content, consistent with our observations [30]. Similarly, in muffins fortified with watermelon rind powder, the high dietary fiber content led to increased mix density and a decrease in product volume [4].

No significant differences ($p > 0.05$) were observed in the fat, protein, and ash content across the formulations. The stability in fat content indicates that QP incorporation did not interfere with lipid retention, which is consistent with the naturally low crude fat content of quince peel (approximately 0.57% dry weight) as reported by [28]. Similarly, the consistent protein levels suggest that QP neither contributes substantial protein nor disrupts the existing sorghum protein matrix, which aligns with the low protein content (approx. 1.34% dry weight) of quince peel [28]. It should be noted that the proximate composition values used for this interpretation are based on literature data, as the specific QP sample used in this study was not analyzed for its full proximate composition; direct measurement in future studies would provide a more precise understanding of its contribution. This stability is advantageous for maintaining consistent nutritional quality in gluten-free products [12,14]. The sustained protein levels further suggest that QP incorporation did not adversely impact the structural integrity provided by sorghum proteins, such as kafirins, which are crucial for dough properties and final product texture [13].

QP fortification increased the bioactive profile of the muffins, with effects observed across the tested substitution levels, as reflected in the TPC and AA results (Table 1). The QP18 sample showed the highest increase, with a 40% rise in TPC and a 23% improvement in AA compared to the control (QP0). This enhancement is likely related to its rich phenolic composition, as characterized by HPLC-DAD (Figure S1). In particular, the high levels of chlorogenic acid and rutin—both recognized for their radical scavenging activity [46,47]—appear to contribute to the observed improvements. It is also noteworthy that the control sample (QP0) exhibited substantial baseline AA (60.19%), consistent with previous reports on the intrinsic antioxidant capacity of sorghum flour [57]. This suggests a combined effect of sorghum and QP in enhancing the bioactive properties of the muffins. In addition to the direct contribution of QP phenolics, the observed AA may also involve interactions with Maillard reaction products generated during baking, which have been reported to possess antioxidative properties [58]. This is supported by studies on thermally processed quince, which indicate maintained or increased antioxidant activities after heating [20,59]. Overall, these results are consistent with previous studies on phenolic-rich fruit by-products, such as apple, lemon, and mango pomace, in improving the bioactive content of baked goods [59–61]. A limitation of this study is that a positive control (e.g., Trolox or ascorbic acid) was not included in the DPPH assay protocol. While the results clearly show a relative enhancement of antioxidant activity with QP fortification, the use of a positive control in future work would provide absolute validation of the assay's performance for each run.

The results indicate that QP substitution enhanced both the dietary fiber content and antioxidant profile of gluten-free sorghum muffins without compromising protein or fat levels, while moderately reducing moisture, and the potential effects of these compositional changes on physical and sensory characteristics are further evaluated in the following sections.

3.4. Color Analysis of Sorghum Muffins

The color of muffins is an important quality attribute and serves as a visual indicator for consumers. The results are presented in Table 2. On the crust, QP levels was associated

with a decrease in L*, with QP12 and QP18 significantly lower than QP0 ($p < 0.05$), indicating darkening of the surface. This trend has been linked in the literature to the higher sugar content in fruit by-products, which can promote non-enzymatic browning, including Maillard reactions, during baking [62,63]. The increase in a* value, reflecting enhanced reddish-brown pigmentation, is a phenomenon observed in thermally processed quince [19,20]. The b* value, representing yellowness, reached a maximum at QP12 before slightly decreasing, which may be related to polyphenol polymerization [19].

Table 2. Color parameters of sorghum muffins.

Samples	L*	a*	b*	ΔE
Crust				
QP0	51.1 ± 0.3 ^{c}	18.9 ± 0.3 ^{a}	32.8 ± 0.1 ^{a}	
QP6	50.0 ± 0.1 ^{b}	19.8 ± 0.1 ^{b}	34.0 ± 0.3 ^{b}	2.2 ± 0.2 ^{a}
QP12	48.1 ± 0.1 ^{a}	19.8 ± 0.1 ^{b}	34.1 ± 0.0 ^{b}	3.4 ± 0.1 ^{b}
QP18	47.5 ± 0.3 ^{a}	21.0 ± 0.1 ^{c}	33.0 ± 0.1 ^{a}	4.2 ± 0.2 ^{c}
Crumb				
QP0	65.0 ± 0.1 ^{c}	4.1 ± 0.3 ^{ab}	21.5 ± 0.2 ^{b}	
QP6	63.7 ± 0.2 ^{b}	4.4 ± 0.0 ^{b}	19.7 ± 0.6 ^{a}	2.2 ± 0.3 ^{a}
QP12	62.8 ± 0.3 ^{a}	4.0 ± 0.0 ^{ab}	19.1 ± 0.1 ^{a}	3.2 ± 0.1 ^{b}
QP18	62.4 ± 0.0 ^{a}	3.5 ± 0.3 ^{a}	19.7 ± 0.2 ^{a}	3.2 ± 0.0 ^{b}

Data represent mean ± SD. Different superscript letters ($^{a–c}$) within the same column indicate significant differences among samples within crust or crumb (Duncan's test, $p < 0.05$).

In the crumb, L* values decreased moderately, with QP12 and QP18 significantly lower than QP0 ($p < 0.05$). Similarly, the significant decrease in the b* value (yellowness) in all fortified samples compared to the control is a direct result of incorporating QP, which alters the crumb's color profile by reducing its lightness and yellowness intensity. The changes in a* values were inconsistent and less pronounced. The lower internal baking temperatures of the crumb, which limit non-enzymatic browning, may also have contributed to the observed color profile, but the dominant effect appears to be the direct color contribution from the quince peel.

The smaller ΔE values observed in the crumb compared to the crust further support the reduced effect of surface browning. Overall, these observations are consistent with previous reports on muffins fortified with fruit by-products, where phenolic compounds and dietary fiber have been shown to influence browning and color characteristics [4,64].

3.5. Weight Loss, Height, Textural Properties, and Crumb Cellular Structure

In gluten-free muffin development, evaluation of physical parameters (weight loss, height, texture) is crucial, as the absence of gluten fundamentally alters starch gelatinization and gas retention mechanisms compared to conventional wheat-based systems. Results in Table 3 demonstrate progressive increases in weight loss (17.23% to 18.38%) with QP addition. This is attributable to its high dietary fiber content [56,64], which influences water mobility during baking. The observed increase in weight loss, coupled with the measured decrease in final moisture content (Table 1), suggests a complex role of the fiber. While dietary fiber possesses high water-binding capacity, its incorporation into the gluten-free sorghum matrix likely created a more open and less cohesive structure, as evidenced by the increased hardness (Table 3) and reduced porosity (Table 4). This structural modification is potentially driven by the competition for water between the fiber and starch, which may limit optimal starch gelatinization. The resulting less continuous matrix could facilitate moisture release during baking, leading to greater weight loss. The observed height reduction is attributed to the impact of QP's dietary fiber on batter rheology. The fiber,

known for its high water-binding capacity as shown in quince by-products [53], competes with starch for available water, thereby affecting gelatinization [4,64] and compromising the structural integrity of the continuous starch-based matrix. The statistically significant decrease ($p < 0.05$) in muffin height was achieved with increasing substitution at QP12 levels. The reduction in muffin height observed at higher QP concentrations is consistent with reports showing that increased levels of fiber-or peel-based ingredients can be accompanied by decreases in specific volume or height in cake and muffin systems, particularly at higher substitution levels [65,66].

Table 3. Weight loss, height, and textural properties of sorghum muffins.

Sample	Weight Loss (%)	Height (cm)	Hardness	Springiness	Cohesiveness	Chewiness	Resilience
QP0	17.2 ± 0.1^{a}	4.23 ± 0.04^{b}	309 ± 4^{a}	0.71 ± 0.01^{c}	0.85 ± 0.01^{b}	186 ± 5^{a}	0.56 ± 0.01^{b}
QP6	17.7 ± 0.1^{b}	4.20 ± 0.14^{b}	344 ± 5^{b}	0.66 ± 0.02^{b}	0.83 ± 0.02^{ab}	188 ± 1^{b}	0.53 ± 0.03^{ab}
QP12	17.9 ± 0.1^{b}	3.90 ± 0.07^{a}	382 ± 5^{c}	0.64 ± 0.03^{b}	0.80 ± 0.01^{ab}	190 ± 2^{c}	0.50 ± 0.01^{ab}
QP18	18.4 ± 0.1^{c}	3.73 ± 0.04^{a}	431 ± 4^{d}	0.57 ± 0.01^{a}	0.77 ± 0.03^{a}	192 ± 5^{d}	0.46 ± 0.03^{a}

Data represent mean ± SD. Different superscript letters ($^{a–d}$) within the same column indicate significant differences among samples (Duncan's test, $p < 0.05$).

Table 4. Quantitative microstructural properties of sorghum muffins obtained by image processing.

Sample	Total Air Cell Area	Average Air Cell Size	Air Cell Area (%)	Circularity
QP0	51.7 ± 1.3^{c}	0.33 ± 0.17^{a}	32.1 ± 0.8^{c}	0.79 ± 0.04^{a}
QP6	48.1 ± 1.1^{b}	0.25 ± 0.10^{a}	29.8 ± 0.7^{b}	0.82 ± 0.01^{a}
QP12	45.6 ± 0.7^{b}	0.20 ± 0.04^{a}	28.3 ± 0.4^{b}	0.79 ± 0.03^{a}
QP18	42.6 ± 0.4^{a}	0.26 ± 0.08^{a}	26.4 ± 0.3^{a}	0.78 ± 0.05^{a}

Data represent mean ± SD. Different superscript letters ($^{a–c}$) within the same column indicate significant differences among samples (Duncan's test, $p < 0.05$).

Texture profile analysis revealed notable changes, as hardness significantly increased with higher QP substitution levels, indicating a firmer structure ($p < 0.05$). This increase is a common effect of fiber addition in gluten-free matrices [4,65,66]. It is linked to the disruptive or dilution effect of dietary fiber on the starch–protein network and its water-binding capacity, which results in a more compact, less aerated crumb [4,13,67]. Chewiness also showed a slight but significant increase ($p < 0.05$). These modifications suggest that QP incorporation leads to a denser, less springy crumb structure, consistent with other studies on fiber-enriched baked goods [64–66]. However, it should be noted that certain dietary fibers, such as soluble cocoa fiber used as a fat replacer, have been reported to decrease hardness and improve moisture retention in muffins [44], highlighting that the technological functionality of a fiber is highly dependent on its specific properties and other ingredients in the formulation. This highlights the need for careful formulation when valorizing fruit and vegetable by-products in gluten-free muffin applications, balancing functional benefits with consumer acceptance, which was the primary focus of our subsequent sensory analysis.

In gluten-free formulations, image analysis is crucial for quantifying pore formation and structural changes induced by ingredient modifications, as these parameters are direct determinants of perceived texture and quality in baked products like muffins. Using ImageJ software, four structural parameters were evaluated (Figure 2, Table 4). Comparative analysis revealed that QP substitution altered the cellular structure of the muffin crumb. A dose-dependent decrease in both the total air cell area (porosity) and relative air cell area percentage was observed, with the QP18 formulation being statistically distinct from all others. Most notably, the reduction in porosity occurred without significant changes in average air cell size or circularity ($p > 0.05$) at any QP substitution level. This indicates that QP incorporation

primarily reduces the number of air cells in the crumb structure, rather than altering the morphology of individual cells. For muffins, these structural modifications correspond to a denser and potentially less spongy texture. This textural change is further supported by the observed reduction in muffin height and aligns with established mechanisms where fiber-rich ingredients increase batter viscosity [64] and density [4]. This restricts bubble expansion and weakens gas retention capacity. The findings also align with literature demonstrating fiber's disruptive effects through water competition and protein matrix interference, ultimately yielding denser crumb structures [1,67]. Collectively, these internal structural changes are characterized by a progressive, dose-dependent reduction in air cell area (porosity), resulting in a denser crumb. They provide both a visual and quantitative explanation for the textural modifications induced by QP fortification, highlighting how fiber-rich ingredients systematically alter the crumb's pore network.

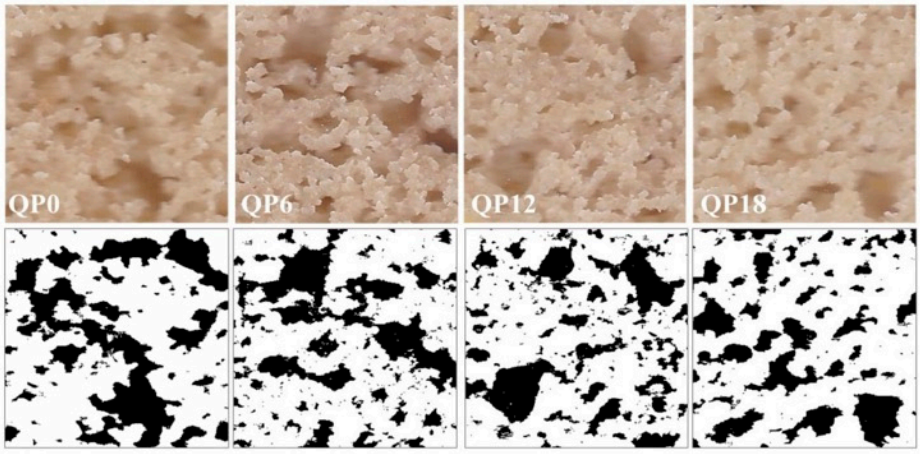


Figure 2. Cellular structure of crumbs analyzed by ImageJ. Color images: Scanned images of cross-sections showing the muffin groups tested (0%: control, 6%, 12%, and 18% QP substituted samples) Binarized images: Corresponding images processed using ImageJ.

3.6. Sensory Analysis of Sorghum Muffins

The substitution of QP resulted in a significant and systematic alteration of the sensory profile of sorghum muffins compared to the control (QP0) (Figure 3), with the majority of attributes (10 out of 13) being significantly affected ($p < 0.05$). The sensory evaluation revealed that this transformation was characterized by a fundamental trade-off between enhanced aroma and deteriorated texture, a finding strongly supported by multivariate and statistical analyses.

Multivariate analysis confirmed that QP concentration was the dominant factor driving this change. Principal Component Analysis (PCA) revealed that the primary direction of variation in the sensory data (PC1) was driven by the gradient of QP addition, explaining a powerful 83% of the total variance (Figure 4). The PCA biplot maps this dominant sensory pattern. It shows a clear separation of the samples along PC1: the control (QP0) and low-QP (QP6) samples on the positive side, characterized by Springiness and Moistness, versus the high-QP samples (QP12 and QP18) on the negative side, associated with Hardness and Aromatic Taste. Furthermore, the second component (PC2) revealed a nuanced distinction between the high-QP samples; QP12 was positioned higher on PC2 than QP18, indicating a sensory profile that achieved a notable Aromatic Taste while being less dominated by Hardness, supporting its identification as a balanced formulation.

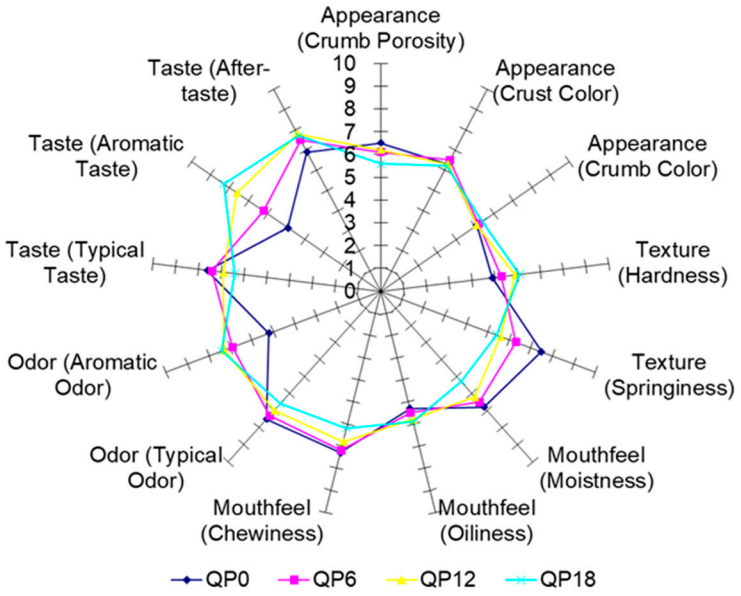


Figure 3. Radar plot of QDA sensory profiles for the sorghum muffins (0%: control, 6%, 12%, and 18% QP substituted samples).

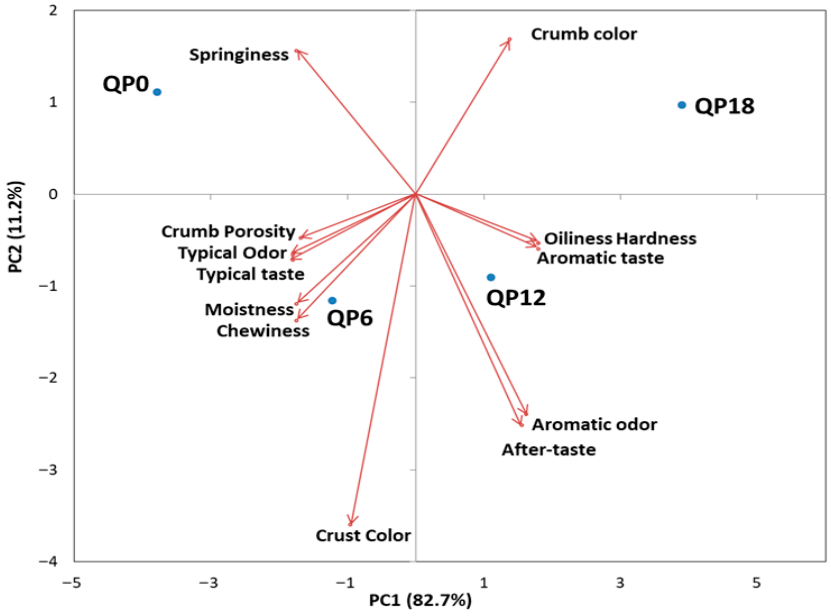


Figure 4. Principal Component Analysis (PCA) biplot illustrating the relationship between the sorghum muffin groups (0%: control, 6%, 12%, and 18% QP substituted samples) and their sensory attributes (vectors).

This pattern was visually confirmed by the Hierarchical Cluster Analysis (HCA) heatmap and its accompanying dendrograms (Figure 5). The HCA dendrograms clearly demonstrated that the sensory profiles clustered into two distinct groups: one cluster composed of the control (QP0) and low-substitution (QP6) samples, and another cluster containing the higher-substitution levels (QP12 and QP18). The horizontal dendrogram further provided critical insight by revealing a strong inverse correlation between the original positive textural attributes (e.g., springiness and moistness) and the traits driven by QPP inclusion (e.g., hardness and aromatic taste). This categorical clustering and the systematic separation of samples confirm that QPP concentration is the single primary driver dictating the overall sensory quality of the final product.

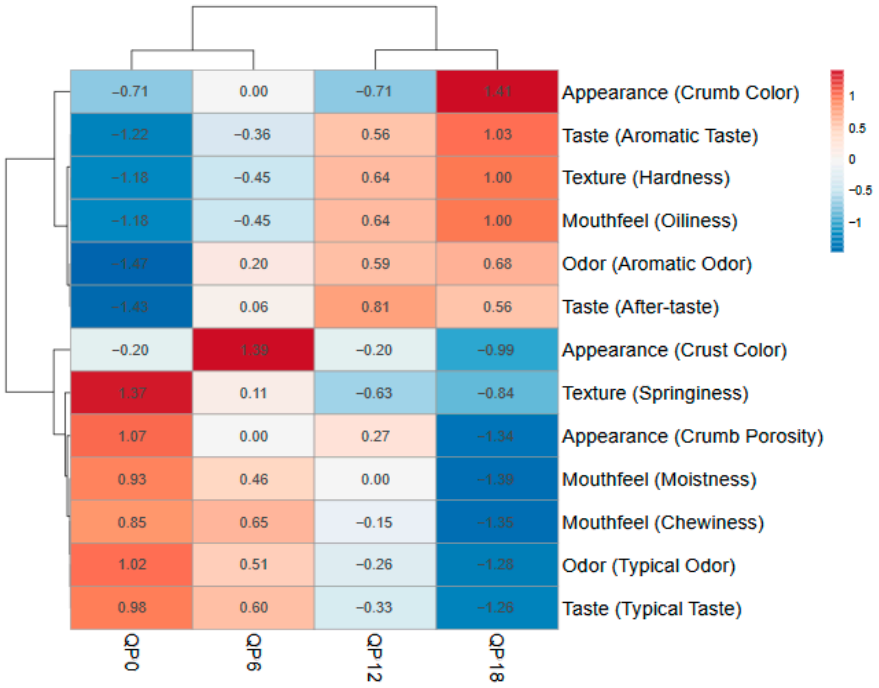


Figure 5. Heatmap with hierarchical clustering of sensory attributes for the sorghum muffin groups (0%: control, 6%, 12%, and 18% QP substituted samples).

The sensory results clarify the nature of this split in PCA and the heatmap. The QP0 and QP6 clusters were characterized by high intensities of desirable textural attributes, such as springiness (with a score of 7.5 in QP0). Conversely, the QP12 and QP18 cluster exhibited high intensity in attributes detrimental to mouthfeel, most notably hardness, which increased significantly from QP6 to QP18. This textural deterioration is a direct consequence of incorporating dietary fiber into a gluten-free matrix. Sorghum flour inherently lacks the gluten network essential for viscoelasticity and gas retention [14,15], and the addition of QP fiber further disrupts the fragile starch–protein matrix. This leads to a denser internal structure with fewer air pockets, as confirmed by image analysis (e.g., total air cell area decreased from 51.71 mm^2 to 42.56 mm^2), resulting in the observed increases in hardness and reductions in springiness and moistness—a phenomenon consistent with studies on fiber-enriched baked goods [4,64].

The reduction in moistness aligns with the challenges of sorghum-based systems. The kafirin proteins in sorghum are hydrophobic, inhibiting starch moisture absorption and contributing to a drier final product [13]. Although fibers have a high water-holding capacity, they may compete for the available water in the gluten-free system, increasing dough viscosity [35], thereby ultimately contributing to a drier mouthfeel.

In stark contrast to the textural drawbacks, QP acted as a powerful natural flavor enhancer. Duncan analysis confirmed that aromatic taste showed a continuous, statistically distinct increase across all four groups, a trend strongly associated with the QP12/QP18 cluster in the multivariate analysis. This profound aromatic enhancement can be attributed to the intense aroma of quince, which is rich in volatile compounds like aldehydes and terpenes that impart fruity-citrus notes [20,68]. Thermal processing during baking likely further amplified this profile through Maillard reactions [59,64]. It is noteworthy that, unlike the results for other sensory attributes, the panelists' scores for color appearance did not show significant differences with QP inclusion ($p = 0.241$ for crumb, $p = 0.398$ for crust). The discrepancy between the instrumental color measurements and the sensory evaluation may be attributed to the complex and heterogeneous visual matrix of the muffin

crumb, which can mask subtle color variations, as well as the simultaneous influence of other sensory cues during evaluation.

The clear sensory trade-off enables a strategic approach to product development. Among the QP-enriched formulations, three distinct consumer profiles emerged: The QP6 sample is ideal for those seeking a noticeable aromatic lift with minimal textural compromise, closely mirroring the control's profile. The QP18 sample caters to a niche market that prioritizes a potent, novel aromatic experience and tolerates a substantially firmer texture. Crucially, the QP12 sample exhibits a balanced combination of aromatic and textural characteristics, offering a noticeable aroma while maintaining acceptable textural properties, making it a practical choice among the QP-enriched formulations.

4. Conclusions

This study successfully demonstrates the valorization of quince peel powder (QP) as a multi-functional ingredient for gluten-free sorghum muffins, directly addressing the previously unexplored potential of this by-product. The research confirms that QP's unique composition, rich in dietary fiber and bioactive phenolics like chlorogenic acid, effectively tackles key technological and nutritional limitations of sorghum-based matrices while introducing specific modifications to its technological properties. The incorporation of QP significantly enhanced the nutritional profile, increasing dietary fiber by up to 80.8% and antioxidant activity by 23.3%. Image processing results revealed that QP fortification resulted in a structural modification characterized by a denser crumb with reduced air cell volume, providing a clear explanation for the corresponding increase in hardness. A key outcome, revealed by quantitative descriptive analysis and multivariate statistics (PCA, HCA), was the fundamental sensory trade-off driven by QP concentration. Higher substitution levels (QP12, QP18) provided a potent, dose-dependent enhancement in "aromatic taste", imparting a distinct fruity character. However, this aromatic benefit was counterbalanced by a systematic increase in hardness and a decrease in springiness and moistness, creating a denser texture compared to the control.

In conclusion, this study provides a complete and practical strategy for utilizing an agricultural by-product. It proves that QP can simultaneously enhance nutritional value, significantly increasing the antioxidant capacity. At 6–12% optimal substitution levels, these functional benefits were achieved while forming a denser crumb structure that remained sensorially acceptable, which exemplifies the successful management of the fundamental trade-off between nutritional enhancement and textural alterations. These findings emphasize a clear trade-off between nutritional and sensory enhancements and textural changes, providing insight for future studies aimed at modulating texture while retaining the functional benefits of QP in gluten-free sorghum muffins.

The findings offer the food industry a viable, dual-purpose solution for developing healthier, sustainable baked goods, with the 6–12% QP substitution level identified as the most suitable for achieving a balance between nutritional enhancement, aromatic improvement, and textural acceptability. To facilitate the commercial adoption of this valorization strategy, future studies should focus on the product's shelf-life, specifically investigating its staling behavior and microbial stability under controlled storage conditions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr13123915/s1, Figure S1: Phenolic profile of quince peel characterized by HPLC-DAD. Peaks: (1) gallic acid, (5) chlorogenic acid, (7) epicatechin, (8) syringic acid, (10) p-coumaric acid, (11) ferulic acid, (14) o-coumaric acid, (15) rutin, (17) rosmarinic acid, (18) eriodictyol, (19) cinnamic acid, (20) quercetin, (21) luteolin, and (22) kaempferol; Table S1: Descriptors, scale anchors and descriptor definitions used in the quantitative descriptive analysis.

Author Contributions: Conceptualization, D.D.K. and B.A.; methodology, D.D.K., B.A. and B.A.Y.; software, D.D.K.; formal analysis, D.D.K., B.A. and B.A.Y.; data curation, D.D.K. and B.A.; writing—original draft preparation, D.D.K. and B.A.; writing—review and editing, D.D.K.; visualization, D.D.K.; supervision, D.D.K.; project administration, D.D.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Gómez, M.; Martinez, M.M. Fruit and Vegetable By-Products as Novel Ingredients to Improve the Nutritional Quality of Baked Goods. *Crit. Rev. Food Sci. Nutr.* **2018**, *58*, 2119–2135. [CrossRef]
2. Pathak, P.D.; Mandavgane, S.A.; Kulkarni, B.D. Fruit Peel Waste: Characterization and Its Potential Uses. *Curr. Sci.* **2017**, *113*, 444–454. [CrossRef]
3. Taheri, S.; Hosseini, S.S. Waste Not, Want Not: Comprehensive Valorization of Fruit and Vegetable Waste from Single-Product Recovery to Zero-Waste Strategies. *Clean. Waste Syst.* **2025**, *11*, 100300. [CrossRef]
4. Çelik, C.; Işık, F. Quality Characteristics of Gluten-Free Muffins Fortified with Watermelon Rind Powder. *Food Sci. Technol.* **2023**, *43*, e113822. [CrossRef]
5. Matos Segura, M.E.; Rosell, C.M. Chemical Composition and Starch Digestibility of Different Gluten-Free Breads. *Plant Foods Hum. Nutr.* **2011**, *66*, 224–230. [CrossRef] [PubMed]
6. Marta, H.; Rahayu, A.K.; Yarlina, V.P.; Fetriyuna, F.; Cahyana, Y.; Arifin, H.R.; Sondari, D. Physicochemical, Pasting, and Functional Properties of Tuber-Based Composite Flours and Their Application in Gluten-Free Muffins. *CyTA—J. Food* **2025**, *23*, 2541891.
7. Roman, L.; Reguilon, M.P.; Martinez, M.M.; Gomez, M. The Effects of Starch Cross-Linking, Stabilization and Pre-Gelatinization at Reducing Gluten-Free Bread Staling. *LWT—Food Sci. Technol.* **2020**, *132*, 109908. [CrossRef]
8. González, M.P.; López-Laiz, P.; Achón, M.; de la Iglesia, R.; Fajardo, V.; García-González, Á.; Úbeda, N.; Alonso-Aperte, E. Determination and Comparison of Fat and Fibre Contents in Gluten-Free and Gluten Containing Flours and Breads: Nutritional Implications. *Foods* **2025**, *14*, 894. [CrossRef]
9. Missbach, B.; Schwingshackl, L.; Billmann, A.; Mystek, A.; Hickelsberger, M.; Bauer, G.; König, J. Gluten-Free Food Database: The Nutritional Quality and Cost of Packaged Gluten-Free Foods. *PeerJ* **2015**, *3*, e1337. [CrossRef]
10. Culetu, A.; Susman, I.E.; Duta, D.E.; Belc, N. Nutritional and Functional Properties of Gluten-Free Flours. *Appl. Sci.* **2021**, *11*, 6283. [CrossRef]
11. Torbica, A.; Hadnadev, M.; Dapčević, T. Rheological, Textural and Sensory Properties of Gluten-Free Bread Formulations Based on Rice and Buckwheat Flour. *Food Hydrocoll.* **2010**, *24*, 626–632. [CrossRef]
12. Bhaduri, S. A Comprehensive Study on Physical Properties of Two Gluten-Free Flour Fortified Muffins. *J. Food Process. Technol.* **2013**, *4*, 251. [CrossRef]
13. de Oliveira, L.L.; de Oliveira, G.T.; de Alencar, E.R.; Queiroz, V.A.V.; de Alencar Figueiredo, L.F. Physical, Chemical, and Antioxidant Analysis of Sorghum Grain and Flour from Five Hybrids to Determine the Drivers of Liking of Gluten-Free Sorghum Breads. *LWT* **2022**, *153*, 112407. [CrossRef]
14. Suarni, A.; Sulistyaningrum, A. Modified Sorghum Flour as a Wheat Substitute in Functional Food Muffin Products. *BIO Web Conf.* **2023**, *69*, 03010. [CrossRef]
15. Apostol, L.; Belc, N.; Gaceu, L.; Oprea, O.B.; Popa, M.E. Sorghum Flour: A Valuable Ingredient for Bakery Industry? *Appl. Sci.* **2020**, *10*, 8597. [CrossRef]
16. Ciacci, C.; Maiuri, L.; Caporaso, N.; Bucci, C.; Del Giudice, L.; Massardo, D.R.; Londei, M. Celiac Disease: In Vitro and In Vivo Safety and Palatability of Wheat-Free Sorghum Food Products. *Clin. Nutr.* **2007**, *26*, 799–805. [CrossRef] [PubMed]

17. Cardoso, L.M.; Pinheiro, S.S.; Martino, H.S.D.; Pinheiro-Sant'Ana, H.M. Sorghum (*Sorghum bicolor* L.): Nutrients, Bioactive Compounds, and Potential Impact on Human Health. *Crit. Rev. Food Sci. Nutr.* **2017**, *57*, 372–390. [CrossRef]
18. Kavak, D.D. Optimization of Extraction Time, Temperature and Solvent Concentration for the Antioxidant Activity and Total Phenolic Content of the *Cydonia oblonga* Mill. Leaves. *Am.-Eurasian J. Sustain. Agric.* **2017**, *11*, 1–6.
19. Najman, K.; Adrian, S.; Sadowska, A.; Świder, K.; Hallmann, E.; Buczak, K.; Waszkiewicz-Robak, B.; Szterk, A. Changes in Physicochemical and Bioactive Properties of Quince (*Cydonia oblonga* Mill.) and Its Products. *Molecules* **2023**, *28*, 3066. [CrossRef]
20. Kavak, D.D.; Ogun, S. Use of Quince (*Cydonia oblonga* Mill.) as Artificial Coloring and Flavoring Substitute in Functional Soft Candy (Lokum) Production. *LWT* **2025**, *225*, 117831. [CrossRef]
21. Elmizadeh, A.; Shahedi, M.; Hamdami, N. Quality Assessment of Electrohydrodynamic and Hot-Air Drying of Quince Slice. *Ind. Crops Prod.* **2018**, *116*, 35–40. [CrossRef]
22. Al-Zughbi, I.; Krayem, M. Quince Fruit Cydonia oblonga Mill Nutritional Composition, Antioxidative Properties, Health Benefits and Consumers Preferences Towards Some Industrial Quince Products: A Review. *Food Chem.* **2022**, *393*, 133362. [CrossRef]
23. Romero, J.; Díez Méndez, A.; Castro-Alija, M.J.; Poveda, J.; Albertos, I. Quince (*Cydonia oblonga* Mill.) Waste By-Product Characterization as a Potential Functional Ingredient. *Sustainability* **2024**, *16*, 8596. [CrossRef]
24. Berktas, S.; Cam, M. Effects of Acid, Alkaline, and Enzymatic Extraction Methods on Functional, Structural, and Antioxidant Properties of Dietary Fiber Fractions from Quince (*Cydonia oblonga* Miller). *Food Chem.* **2025**, *464*, 141596. [CrossRef] [PubMed]
25. Essafi-Benkhadir, K.; Refai, A.; Riahi, I.; Fattouch, S.; Karoui, H.; Essafi, M. Quince (*Cydonia oblonga* Miller) Peel Polyphenols Modulate LPS-Induced Inflammation in Human THP-1-Derived Macrophages through NF-κB, p38MAPK and Akt Inhibition. *Biochem. Biophys. Res. Commun.* **2012**, *418*, 180–185. [CrossRef] [PubMed]
26. Herrera-Rocha, K.M.; Rocha-Guzman, N.E.; Gallegos-Infante, J.A.; Gonzalez-Laredo, R.F.; Larrosa-Perez, M.; Moreno-Jimenez, M.R. Phenolic Acids and Flavonoids in Acetonic Extract from Quince (*Cydonia oblonga* Mill.): Nutraceuticals with Antioxidant and Anti-Inflammatory Potential. *Molecules* **2022**, *27*, 2462. [CrossRef] [PubMed]
27. Babashpour-Asl, M.; Piryaei, M. Free Radical Scavenging and Phenolic Compounds of Peel and Pulp of Quince. *Int. J. Hortic. Sci. Technol.* **2021**, *8*, 91–101.
28. Othman, S.; Anibarro-Ortega, M.; Dias, M.I.; Ćirić, A.; Mandim, F.; Soković, M.; Ferreira, I.C.F.R.; Pinela, J.; Barros, L. Valorization of Quince Peel into Functional Food Ingredients: A Path Towards "Zero Waste" and Sustainable Food Systems. *Heliyon* **2022**, *8*, e11042. [CrossRef]
29. Trigueros, L.; Pérez-Alvarez, J.A.; Viuda-Martos, M.; Sendra, E. Production of Low-Fat Yogurt with Quince (*Cydonia oblonga* Mill.) Scalding Water. *LWT* **2011**, *44*, 1388–1395. [CrossRef]
30. Păucan, A.; Man, S.; Chiș, S.; Suciu, R.; Mureșan, C. Impact of Quince Flour on Gluten-Free Muffins Production. *Bull. Univ. Agric. Sci. Vet. Med. Cluj-Napoca Food Sci. Technol.* **2017**, *74*, 1–10.
31. Anvar, A.; Nasehi, B.; Noshad, M.; Barzegar, H. Improvement of Physicochemical and Nutritional Quality of Sponge Cake Fortified with Microwave-Air Dried Quince Pomace. *Iran. Food Sci. Technol. Res. J.* **2019**, *15*, 69–79.
32. Kavak, D.D.; Akdeniz, B. Use of Quince Peel for the Production of Cookie Enriched with Dietary Fibre. *AKU J. Sci. Eng.* **2023**, *23*, 1481–1487.
33. AOAC International. *Official Methods of Analysis of AOAC International*, 22nd ed.; Method 934.06, Loss on Drying (Moisture) in Dried Fruits; Oxford University Press: Oxford, UK, 2023.
34. Kavak, D.D.; Kececi, S. Extraction of Phenolic Antioxidants from *Pyrus elaeagrifolia* Pallas: Process Optimization, Investigation of the Bioactivity and β-Glucuronidase Inhibitory Potential. *J. Food Meas. Charact.* **2019**, *13*, 2894–2902. [CrossRef]
35. Ostermann-Porcel, M.V.; Rinaldoni, A.N.; Campderrós, M.E.; Gómez, M. Evaluation of Gluten-Free Layer Cake Quality Made with Okara Flour. *J. Food Meas. Charact.* **2020**, *14*, 1614–1622. [CrossRef]
36. Aprianita, A.; Purwandari, U.; Watson, B.; Vasiljevic, T. Physico-Chemical Properties of Flours and Starches from Selected Commercial Tubers Available in Australia. *Int. Food Res. J.* **2009**, *16*, 507–520.
37. Baldán, Y.; Riveros, M.; Fabani, M.P.; Rodriguez, R. Grape Pomace Powder Valorization: A Novel Ingredient to Improve the Nutritional Quality of Gluten-Free Muffins. *Biomass Convers. Biorefin.* **2021**, *13*, 9997–10009. [CrossRef]
38. Dos Santos, B.B.; Fernandes, L.C.; Burak, N.M.; Isaka, G.V.; Pimentel, T.C.; Rosset, M. Valorization of Melon (*Cucumis melo* L.) Peels as Flour for Vegan and Gluten-Free Muffins. *Appl. Sci.* **2025**, *15*, 9680. [CrossRef]
39. AOAC International. *Official Methods of Analysis of AOAC International*, 18th ed.; AOAC International: Gaithersburg, MD, USA, 2005.
40. Sung, W.C.; Chai, P.-S. Effect of flaxseed flour and xanthan gum on gluten-free cake properties. *J. Food Nutr. Res.* **2017**, *5*, 717–728. [CrossRef]
41. Kumar, V.; Sharma, H.K. Process Optimization for Extraction of Bioactive Compounds from Taro (*Colocasia esculenta*), Using RSM and ANFIS Modeling. *J. Food Meas. Charact.* **2017**, *11*, 704–718. [CrossRef]
42. Lončar, B.; Pezo, L.; Filipović, V.; Nićetin, M.; Filipović, J.; Pezo, M.; Šuput, D.; Aćimović, M. Physico-Chemical, Textural and Sensory Evaluation of Spelt Muffins Supplemented with Apple Powder Enriched with Sugar Beet Molasses. *Foods* **2022**, *11*, 1750. [CrossRef]

43. Rodríguez-García, J.; Salvador, A.; Hernando, I. Replacing Fat and Sugar with Inulin in Cakes: Bubble Size Distribution, Physical and Sensory Properties. *Food Bioprocess Technol.* **2014**, *7*, 964–974. [CrossRef]
44. Martínez-Cervera, S.; Salvador, A.; Muguerza, B.; Moulay, L.; Fiszman, S.M. Cocoa Fibre and Its Application as a Fat Replacer in Chocolate Muffins. *LWT* **2011**, *44*, 729–736. [CrossRef]
45. Metsalu, T.; Vilo, J. ClustVis: A web tool for visualizing clustering of multivariate data using Principal Component Analysis and heatmap. *Nucleic Acids Res.* **2015**, *43*, W566–W570. [CrossRef]
46. Athanasiadis, V.; Chatzimitakos, T.; Bozinou, E.; Kotsou, K.; Palaiogiannis, D.; Lalas, S.I. Optimization of Extraction Parameters for Enhanced Recovery of Bioactive Compounds from Quince Peels Using Response Surface Methodology. *Foods* **2023**, *12*, 2099. [CrossRef]
47. Sonmez, F.; Sahin, Z. Comparative Study of Total Phenolic Content, Antioxidant Activities, and Polyphenol Oxidase Enzyme Inhibition of Quince Leaf, Peel, and Seed Extracts. *Erwerbs-Obstbau* **2023**, *65*, 745–750. [CrossRef]
48. Inglett, G.E.; Xu, J.; Stevenson, D.G.; Chen, D. Rheological and Pasting Properties of Buckwheat (*Fagopyrum esculentum* Moench) Flours with and without Jet-Cooking. *Cereal Chem.* **2009**, *86*, 1–6. [CrossRef]
49. Palavecino, P.M.; Penci, M.C.; Calderón-Domínguez, G.; Ribotta, P.D. Chemical Composition and Physical Properties of Sorghum Flour Prepared from Different Sorghum Hybrids Grown in Argentina. *Starch* **2016**, *68*, 1055–1064. [CrossRef]
50. Ajila, C.M.; Leelavathi, K.; Prasada Rao, U.J.S. Improvement of Dietary Fiber Content and Antioxidant Properties in Soft Dough Biscuits with the Incorporation of Mango Peel Powder. *J. Cereal Sci.* **2008**, *48*, 319–326. [CrossRef]
51. Kohajdová, Z.; Karovičová, J.; Jurasová, M. Influence of Grapefruit Dietary Fibre Rich Powder on the Rheological Characteristics of Wheat Flour Dough and on Biscuit Quality. *Acta Aliment.* **2013**, *42*, 91–101. [CrossRef]
52. Rosell, C.M.; Rojas, J.A.; Benedito de Barber, C. Influence of Hydrocolloids on Dough Rheology and Bread Quality. *Food Hydrocoll.* **2001**, *15*, 75–81. [CrossRef]
53. Aksit, Z.; Genccelep, H. Investigation of Tomato, Quince and Grapefruit Waste: Compositions and Functional Properties. *Hittite J. Sci. Eng.* **2021**, *8*, 19–26. [CrossRef]
54. Winger, M.; Khouryieh, H.; Aramouni, F.; Herald, T. Sorghum Flour Characterization and Evaluation in Gluten-Free Flour Tortilla. *J. Food Qual.* **2014**, *37*, 95–106. [CrossRef]
55. Palavecino, P.M.; Penci, M.C.; Ribotta, P.D. Effect of Planetary Ball Milling on Physicochemical and Morphological Properties of Sorghum Flour. *J. Food Eng.* **2019**, *262*, 22–28. [CrossRef]
56. Pereira, A.; Añibarro-Ortega, M.; Nogueira, A.; Barros, L.; Pinela, J. Optimization of Dietary Fiber Extraction from Quince Peel. *Eng. Proc.* **2023**, *37*, 78.
57. Shen, S.; Huang, R.; Li, C.; Wu, W.; Chen, H.; Shi, J.; Chen, S.; Ye, X. Phenolic Compositions and Antioxidant Activities Differ Significantly among Sorghum Grains with Different Applications. *Molecules* **2018**, *23*, 1203. [CrossRef] [PubMed]
58. Antoniewska, A.; Rutkowska, J.; Martinez Pineda, M.; Adamska, A. Antioxidative, Nutritional and Sensory Properties of Muffins with Buckwheat Flakes and Amaranth Flour Blend Partially Substituting for Wheat Flour. *LWT* **2018**, *89*, 217–223. [CrossRef]
59. Mateus, A.R.S.; Pena, A.; Silva, A.S. Development of Functional Muffins Enriched with Lemon By-Products as Sources of Bioactive Compounds. *Food Chem. Adv.* **2025**, *7*, 100972. [CrossRef]
60. Sudha, M.L.; Dharmesh, S.M.; Pynam, H.; Bhimangouder, S.V.; Eipson, S.W.; Somasundaram, R.; Nanjarajurs, S.M. Antioxidant and Cyto/DNA Protective Properties of Apple Pomace Enriched Bakery Products. *J. Food Sci. Technol.* **2016**, *53*, 1909–1918. [CrossRef]
61. Aziah, A.A.N.; Min, W.L.; Bhat, R. Nutritional and Sensory Quality Evaluation of Sponge Cake Prepared by Incorporation of High Dietary Fiber Containing Mango (*Mangifera indica* var. Chokanan) Pulp and Peel Flours. *Int. J. Food Sci. Nutr.* **2011**, *62*, 559–567. [CrossRef]
62. Rocha Parra, A.F.; Belorio, M.; Ribotta, P.D.; Ferrero, C.; Gómez Pallarés, M. Effect of the particle size of pear pomace on the quality of enriched layer and sponge cakes. *Int. J. Food Sci. Technol.* **2019**, *54*, 1265–1275. [CrossRef]
63. Kallel, F.; Chaieb, Z.; Fendri, L.B.; Chaabouni, S.E.; Neifar, M. By-product of prickly pear juice industry: A novel ingredient to improve the physicochemical, texture and sensory properties of cake. *J. Food Meas. Charact.* **2024**, *18*, 7656–7668. [CrossRef]
64. Struck, S.; Gundel, L.; Zahn, S.; Rohm, H. Fiber Enriched Reduced Sugar Muffins Made from Iso-Viscous Batters. *LWT* **2016**, *65*, 32–38. [CrossRef]
65. Kumar, P.S.; Birundha, M.K.; Pushpavalli, S.; Arthee, R.; Shuprajhaa, T.; Wakchaure, G.C. Enhancing the Dietary Fibre in Muffins with Banana Peel Powder and Evaluating Its Effect on Physicochemical Characteristics, Textural Quality and Storage Life. *Discov. Food* **2025**, *5*, 231. [CrossRef]
66. Aydogdu, A.; Sumnu, G.; Sahin, S. Effects of Addition of Different Fibers on Rheological Characteristics of Cake Batter and Quality of Cakes. *J. Food Sci. Technol.* **2018**, *55*, 667–677. [CrossRef] [PubMed]

67. Gao, J.; Han, F.; Guo, X.; Zeng, X.; Mason, S.L.; Brennan, M.A.; Brennan, C.S. Image Analysis of the Sugar-Reduced Muffin Formulated with Stevianna® or Inulin as a Sugar Replacer. *Grain Oil Sci. Technol.* **2018**, *1*, 63–71. [CrossRef]
68. Griñán, I.; Galindo, A.; Rodríguez, P.; Morales, D.; Corell, M.; Centeno, A.; Collado-González, J.; Torrecillas, A.; Carbonell-Barrachina, A.A.; Hernández, F. Volatile Composition and Sensory and Quality Attributes of Quince (*Cydonia oblonga* Mill.) Fruits as Affected by Water Stress. *Sci. Hortic.* **2019**, *244*, 68–74. [CrossRef]

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