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Sensory Profiling of Vegan Muffins with Plant-Based Egg and Milk Replacers: A Quantitative Descriptive Analysis Approach

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Abstract

The development of plant-based bakery products requires a better understanding of how ingredient substitution influences sensory quality. This study characterized the sensory profiles of vegan muffins prepared with six plant-based egg replacers (aquafaba, banana purée, flaxseed gel, psyllium gel, soapwort extract, and chia gel) and eight plant-based milk alternatives (soy, hazelnut, walnut, quinoa, flaxseed, coconut, oat, and almond milk) using quantitative descriptive analysis (QDA). Two formulation series were evaluated separately by 12 trained assessors using 15 cm intensity scales for appearance, aroma, taste, and texture attributes. Each formulation series included a conventional muffin containing eggs and cow's milk as a reference control. The results revealed distinct ingredient-associated sensory profiles. Pearson correlation analysis, principal component analysis (PCA), and hierarchical cluster analysis (HCA) were used to examine relationships among sensory attributes and similarities between formulations. Banana-based muffins were characterized by intense banana and baked-product aromas and were sweeter. Aquafaba-based muffins were characterized by sensory notes related to legumes. Psyllium-based muffins were rated harder, chewier, more bitter and more intense in aftertaste. For the milk substitutes, a typical cereal-like taste sensory property was found for the oat-milk muffin and a nutty one for the hazelnut-milk muffin, respectively. PCA and HCA further differentiated the formulations according to their combined sensory profiles. These results provide detailed attribute-level sensory information that complements previously reported hedonic acceptability assessments and may support ingredient selection and sensory optimization in plant-based bakery product development.

Keywords: vegan muffins; plant-based egg replacers and milk alternatives; quantitative descriptive analysis; principal component analysis

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1. Introduction

The increasing demand for plant-based foods has led to a growing interest in reformulating traditional bakery products without animal-derived ingredients. Muffins pose specific challenges as their quality depends on the composition of ingredients, properties of the batter and structural changes during baking. Eggs and milk perform several functional roles in cake volume, crumb structure, texture, color and flavor [1–4]. The replacement of these ingredients with plant-based alternatives requires consideration

of their technological performance and the sensory characteristics of the final product [1,2,4].

Eggs serve a number of functions in cake systems, including foam stabilization, emulsification and heat-induced structure formation [3,4]. Some of these functions can be performed by plant-based ingredients, but their functionality is dependent on their composition and behavior in the batter. Flaxseed, chia and psyllium contain polysaccharides that can affect the viscosity of the batter and its water retention, and aquafaba and soapwort extract may have foaming properties. Banana purée can also be a source of sugars, pigments and characteristic flavor compounds [1]. Studies on egg replacement in muffins and similar bakery products indicate that the volume, texture and product acceptability depend on the substitute used [5–7].

Replacing dairy milk with plant-based alternatives also presents formulation challenges. Milk components contribute to the development of structure, browning reactions and flavor formation during baking [8]. The protein, fat and carbohydrate contents of plant-based milk alternatives are dependent on their botanical origin and processing conditions, which may affect their functionality in food systems [9,10]. Soy, hazelnut, walnut, quinoa, flaxseed, coconut, oat and almond milks are derived from different plant sources and differ in composition and sensory properties [10–12]. Therefore, their inclusion in muffin formulations may lead to differences in batter behavior and sensory properties of the final products [2,9].

Sensory evaluation methods provide different information. Hedonic tests measure the level of product liking and acceptance, while descriptive sensory approaches are used to characterize the perceived sensory attributes of products [13,14]. Quantitative descriptive analysis (QDA) employs trained assessors to systematically evaluate the intensity of predefined sensory attributes, enabling comparisons of sensory profiles across formulations [15]. Unlike hedonic evaluations, which assess consumer liking and preference, QDA focuses on the perceived intensity of specific sensory attributes rather than subjective acceptability.

The reformulation of ingredients has been studied in muffins with chickpea flour and added biopolymers, paying particular attention to batter properties and product characteristics [16]. Other researchers have worked on alternative ingredients, such as defatted sunflower seed flour and inulin, and have reported changes in texture and product quality [17,18]. In recent times, pear pomace and quince peel have been added to gluten-free muffins to investigate their technological and sensory properties [19,20]. These studies, although showing the value of assessing other ingredients in muffin formulations, are concerned with other ingredient systems than the plant-based egg replacers and milk alternatives investigated in the present study.

In our previous studies, we investigated six plant-based egg replacers and eight plant-based milk alternatives in vegan muffin formulations, in terms of their technological, nutritional and hedonic properties [1,2]. Nine-point hedonic ratings of crust color, crumb color, flavor, taste, appearance, softness and overall acceptability were recorded in both studies. These assessments provided information on product liking but did not quantify the intensities of individual sensory descriptors such as ingredient-specific aromas, tastes and texture attributes. Therefore, detailed sensory descriptive profiles of these formulations were yet to be characterized.

The aim of the present study was to describe and compare the sensory profiles of vegan muffins prepared with different plant-based egg replacers and milk alternatives using quantitative descriptive analysis (QDA). Two series of formulations were studied separately: six egg replacers (aquafaba, banana purée, flaxseed gel, psyllium gel, soapwort extract and chia gel) and eight plant-based milk alternatives (soy, hazelnut, walnut, quinoa, flaxseed, coconut, oat and almond milk). A panel of 12 trained assessors evaluated

intensities of defined appearance, aroma, taste and texture attributes on 15 cm linear scales. Pearson correlation analysis was employed to examine relationships among sensory attributes, while principal component analysis (PCA) and hierarchical cluster analysis (HCA) were used to explore similarities and differences among formulations based on their sensory profiles. The objective of the study was to determine the sensory characteristics that differentiate individual formulations and to provide detailed descriptive information in addition to the hedonic evaluations published in our previous studies [1,2].

2. Materials and Methods

2.1. Materials and Experimental Design

Two formulation series were evaluated separately to characterize the sensory profiles of muffins prepared with plant-based egg replacers and milk alternatives. The egg-replacement series comprised six formulations containing aquafaba, banana purée, flaxseed gel, psyllium gel, soapwort extract, or chia gel, with almond milk used as a common ingredient in all plant-based formulations. The milk-replacement series comprised eight formulations prepared with soy, hazelnut, walnut, quinoa, flaxseed, coconut, oat, or almond milk, with aquafaba used as the common egg replacer. Each series included a conventional control formulation containing whole eggs and cow's milk.

Commercial soy, hazelnut, coconut, oat, and almond milks (Alpro, Ghent, Belgium) were used. Walnut, quinoa, and flaxseed milks were prepared in the laboratory using walnuts (Tadım, Istanbul, Türkiye), quinoa (Yayla, Istanbul, Türkiye), and flaxseeds (Yayla, Ankara, Türkiye). Chia seeds (Yayla, Ankara, Türkiye) and psyllium powder (Wefood, Istanbul, Türkiye) were used for the preparation of the corresponding egg replacers. The complete ingredient quantities for the egg- and milk-replacement series are provided in Table 1 of our previous studies [1] and [2], respectively. Preparation procedures for the plant-based alternatives, including ingredient-to-water ratios and hydration conditions for the gels where applicable, are described in Section 2.1 of our previous studies [1,2], while muffin preparation procedures are detailed in Section 2.3.1 of the same studies. The present study focuses on the quantitative descriptive sensory analysis of these formulations. The two formulation series were evaluated independently, and comparisons were performed within each series. Throughout the manuscript, the prefixes E- and M- identify formulations in the egg- and milk-replacement series, respectively.

Table 1. Sensory attributes, definitions, reference materials, and intensity levels used for quantitative descriptive analysis of muffin formulations prepared with plant-based egg and milk substitutes.

Sensory Attribute	⚜perational Definition	Reference Materials and Intensity Levels (0–15 cm)	Formulation Series
Appearance			
Crust color	Intensity of browning on the muffin crust	0: Very light crust; 15: Dark brown crust	Both
Crumb color	Darkness of the muffin crumb	E: 0 = very light crumb; 15 = dark yellow–brown crumb. M: 0 = very light crumb; 15 = dark crumb.	Both
Pore size	Size of pores visible in the crumb cross-section	0: Very small pores; 15: Large, distinct pores	Both

Pore homogeneity	Uniformity of pore size and distribution	0: Heterogeneous, irregular; 15: Homogeneous, uniform	Both
Aroma			
Baked-product aroma	Intensity of the characteristic aroma of baked muffins	0: Not perceptible; 15: Very intense	Both
Legume aroma	Aroma associated with aquafaba or legumes, including cooked notes	Aquafaba solution (% *v*/*v*): 0 = water; ~7.5 = 25%; 15 = 100%	Both
Banana aroma	Fruity, sweet aroma characteristic of ripe banana	Banana purée in water (% *w*/*v*): 0 = water; ~7.5 = 10%; 15 = 20%	E
Cereal aroma	Aroma associated with cereals, bran, or oats	Oat flour suspension (% *w*/*v*): 0 = 0%; ~7.5 = 5%; 15 = 10%	Both
Nutty aroma	Characteristic aroma associated with roasted nuts	Hazelnut paste emulsion (% *w*/*v*): 0 = 0%; ~7.5 = 2%; 15 = 5%	M
Vegetal aroma	Green or grassy aroma	Green tea infusion: 0 = water; ~7.5 = 5 min infusion; 15 = 15 min infusion	M
Taste			
Sweetness	Intensity of sweet taste	Sucrose solution (% *w*/*v*): 0 = 0%; ~7.5 = 5%; 15 = 15%	Both
Raw-legume note (taste/flavor)	Perception of a raw or green legume-associated note during tasting	Aquafaba solution (% *v*/*v*): 0 = water; ~7.5 = 25%; 15 = 100%	E
Cereal-like taste	Intensity of cereal-like taste	Oat flour suspension (% *w*/*v*): 0 = 0%; ~7.5 = 5%; 15 = 10%	M
Nutty taste	Intensity of nut-like taste	Hazelnut paste emulsion (% *w*/*v*): 0 = 0%; ~7.5 = 2%; 15 = 5%	M
Bitterness	Intensity of bitter taste perceived on the tongue	Caffeine solution (% *w*/*v*): 0 = 0%; ~7.5 = 0.05%; 15 = 0.10%	Both
Aftertaste	Persistence of taste or flavor after swallowing	0: No persistence; 15: Long-lasting persistence	Both
Texture			
Hardness	Force perceived during the first bite	0: Very soft; 15: Very hard	Both
Moistness	Perception of moisture in the mouth	0: Dry; 15: Very moist	Both
Adhesiveness	Tendency to adhere to the teeth or oral surfaces	0: No adhesion; 15: Pronounced adhesion	Both
Chewiness	Energy required to chew the sample before swallowing	0: Easy to chew; 15: Requires prolonged chewing	Both
Cohesiveness	Ability of the sample to maintain structural integrity	0: Easily disintegrates; 15: High structural integrity	Both
Crumbliness	Tendency of the sample to crumble or break apart	0: No crumbling; 15: Extremely crumbly	Both

Note. E = egg-replacement series; M = milk-replacement series; Both = both series. Reference materials were used during panel training to illustrate different sensory intensity levels. The egg and milk-replacement series were evaluated separately using their respective sensory lexicons.

2.2. Muffin Making

Muffins were prepared by procedures and formulas described in our prior studies [1,2] with the same base recipe and standardized baking conditions. Briefly, each formulation consisted of 200 g wheat flour (Sinangil, Tekirdağ, Türkiye), 150 g granulated sugar (Balküpü, İstanbul, Türkiye), 100 g sunflower oil (Yudum, İstanbul, Türkiye), 5 g baking powder and 3 g vanillin (Dr. Oetker, İzmir, Türkiye). Whole egg or equivalent plant-based egg replacer was added at 90 g, and cow's milk or selected plant-based milk alternative was added at 32 g.

The egg or egg-replacement ingredient was whipped with sugar using a stand mixer (KitchenAid, Classic, 4.3 L, St. Joseph, MI, USA) at 220 rpm for 4 min. Sunflower oil and designated milk were then added at 135 rpm for 1 min, followed by dry ingredients at 95 rpm for 1 min. For each muffin mold (Zenker, Aichach, Germany), approx. 40 g of batter was poured and baked in a preheated fan-assisted convection oven (Inoksan, INO-FKE010, Bursa, Türkiye) at 170 ± 2 °C for 16 min. The muffins were cooled in their molds for 30 min at 25 ± 2 °C before removal.

More details on ingredient preparation, formulation composition and processing conditions are available in the original publications [1,2]. Each muffin formulation was prepared in three independent production batches under standardized processing conditions.

2.3. Descriptive Quantitative Analysis

The quantitative descriptive analysis (QDA) was carried out by a panel of 12 trained assessors selected according to the ISO 8586:2012 [21] standard. The assessors were non-smokers, regularly ate cake products, had normal sensory perception and had no food allergies. Before the evaluations, the panelists attended six training sessions of about 1 h each (6 h in total). Training consisted of principles of QDA, identification and definition of sensory attributes, use of the 15 cm linear intensity scale and familiarization with reference materials. Muffin samples were also used in practice evaluations to familiarize panelists with product characteristics and sensory terminology.

The sensory terminology was developed through panel discussions and preliminary evaluations of the muffin samples, taking into account the general guidance for sensory profiling as set out in ISO 13299:2016 [22]. Descriptor selection was based on sensory characteristics of the formulations, including ingredient-specific aroma and flavor notes and relevant appearance and texture attributes, in line with established descriptive sensory profiling practices [23]. Sensory lexicons were developed separately for the egg and milk replacement series. Both lexicons included appearance, aroma, taste/flavor and texture attributes, with additional descriptors reflecting specific sensory characteristics of ingredients used in each series. Common attributes were collated and presented in Table 1, and series-specific descriptors and scale endpoint definitions were maintained. The sensory attributes, operational definitions, reference materials and the intensity levels are presented in Table 1.

The sensory evaluations were performed on 15-cm linear intensity scales with verbal endpoints appropriate to each attribute. Assessors rated the perceived intensity of each attribute on the respective scale, and we measured the distances from the scale origin to obtain numerical intensity scores. The egg and milk-replacement series were evaluated on different days using their own sensory lexicons. All 12 assessors evaluated each formulation in both series. Samples were coded with randomly assigned three-digit codes

and presented in a randomized complete block design, with the order of presentation randomized among assessors. Standardized muffin portions (20–25 g) were served at 22 ± 1 °C. Water at room temperature and unsalted crackers were provided for palate cleansing between samples. Samples for sensory evaluation were randomly drawn from three independent production batches of each formulation. Each of the 12 trained assessors provided one intensity rating for each sensory attribute for each formulation in the respective series. The sensory results were expressed as the mean and standard deviation of the 12 assessor ratings. Thus, the standard deviations presented in Tables 2 and 3 describe the variability between assessor ratings, not the variability between three independent batch means. Ethical approval for the sensory study was obtained from the Maltepe University Ethics Committee, dated 28 November 2024 (Approval No. 2024/22-09).

2.4. Statistical Analysis

Quantitative descriptive analysis (QDA) data were presented as mean ± standard deviation (SD). SPSS software (version 21.0; SPSS Inc., Chicago, IL, USA) was used for statistical analyses. For each sensory attribute, formulations were compared using one-way analysis of variance (ANOVA) with formulation as the factor and the 12 individual assessor ratings per formulation entered as observations. We did not model assessor and production-batch effects explicitly, and did not estimate between-batch variability separately. The analysis did not account for within-assessor dependence, as the same assessors scored multiple formulations, which is a limitation of the statistical approach. Separate analyses were conducted on the egg and milk-replacement series. The means of the formulations were compared by Tukey's post hoc test, and the differences were considered significant at $p < 0.05$.

Pearson correlation analysis, principal component analysis (PCA) and hierarchical cluster analysis (HCA) were also used to investigate relationships among sensory attributes and to characterize the sensory profiles of the muffin formulations. Pearson correlation analysis was performed to evaluate associations between QDA attributes using formulation mean scores calculated from the evaluations of 12 trained assessors for each sensory attribute (n = 7 for the egg-replacement series and n = 9 for the milk-replacement series). Given the limited number of formulations, these correlations were interpreted as exploratory associations among sensory attributes. PCA and HCA were performed separately for the egg and milk replacement series using formulation mean scores obtained from evaluations by 12 trained assessors. For the egg-replacement series, analyses were conducted on 7 formulations and 18 sensory attributes, and for the milk-replacement series, 9 formulations and 20 sensory attributes were analyzed. PCA was performed using the correlation matrix without rotation. Principal components with eigenvalues greater than 1 were reported in Tables S1 and S2, and the first two components were used for two-dimensional visualization. The HCA of z-score standardized sensory attribute means was performed using Ward's linkage method and squared Euclidean distance.

3. Results and Discussion

3.1. Quantitative Descriptive Sensory Profiles of Egg-Replacement Muffins

Quantitative descriptive analysis (QDA) revealed distinct sensory profiles among muffin formulations prepared with different plant-based egg replacers (Table 2 and Figure 1). Differences among formulations were observed across appearance, aroma, taste, and texture attributes, demonstrating that egg replacement influenced multiple dimensions of the sensory profile. Whereas our previous study primarily evaluated

hedonic responses and instrumental quality characteristics [1], the present QDA provides attribute-specific intensity measurements that enable a more detailed characterization of formulation-dependent sensory differences.

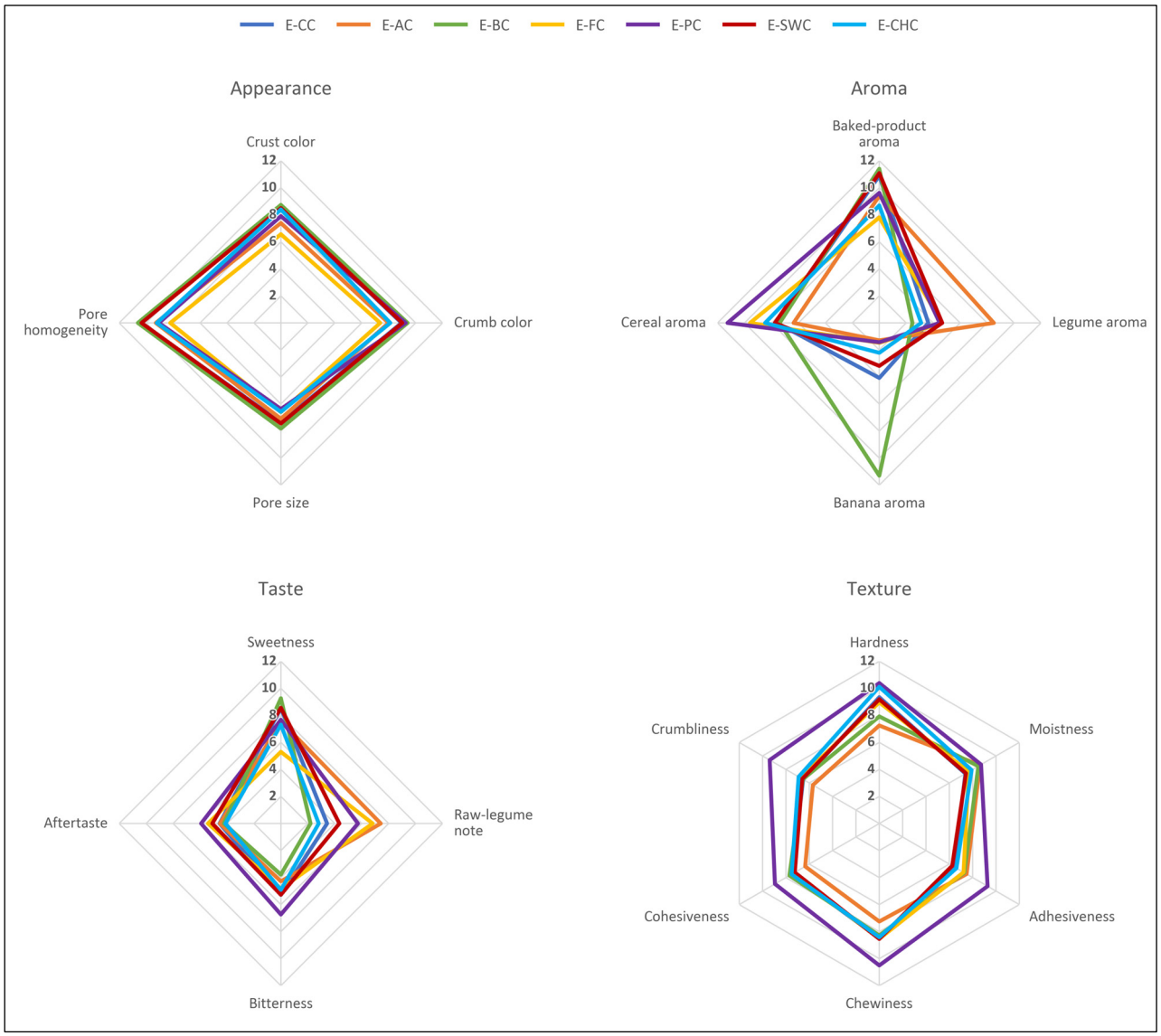


Figure 1. Radar plots of quantitative descriptive analysis (QDA) profiles for the egg-replacement muffin series. Values represent mean sensory intensity scores from 12 trained assessors on 15-cm scales (0–15) for appearance, aroma, taste, and texture attributes. The prefix E- denotes the egg-replacement series. E-CC, conventional control containing whole eggs and cow's milk; E-AC, aquafaba; E-BC, banana purée; E-FC, flaxseed gel; E-PC, psyllium gel; E-SWC, soapwort extract; E-CHC, chia gel. Statistical comparisons among formulations are reported in Table 2.

3.1.1. Appearance

Significant differences (p <0.05) were observed among muffin formulations in crust color, crumb color, pore size, and pore homogeneity (Table 2). Banana-based muffins (E-BC) exhibited the highest crust color intensity and the largest perceived pore size, together with high pore homogeneity. E-BC also showed the numerically highest crumb color intensity, although it did not differ significantly from E-PC. The pronounced coloration of E-BC may be partly associated with the natural sugars present in banana purée, which could contribute to nonenzymatic browning during baking. However, color development is influenced by multiple factors, including ingredient composition, moisture, and

processing conditions [3,8]. Although E-BC exhibited distinctive color characteristics, the conventional control (E-CC) received the highest overall appearance preference in our previous hedonic study [1]. This comparison illustrates that the intensity of a sensory attribute does not necessarily correspond to its degree of liking.

Table 2. Quantitative descriptive analysis (QDA) scores of muffins prepared with different egg replacers [1].

Sensory Attribute	E-CC	E-AC	E-BC	E-FC	E-PC	E-SWC	E-CHC
Appearance							
Crust color	8.50 ± 0.22 ^{b}	7.39 ± 0.17 ^{d}	8.73 ± 0.12 ^{a}	6.56 ± 0.23 ^{e}	7.90 ± 0.21 ^{c}	8.49 ± 0.14 ^{b}	8.39 ± 0.11 ^{b}
Crumb color	8.95 ± 0.31 ^{c}	7.99 ± 0.22 ^{d}	9.40 ± 0.12 ^{a}	7.37 ± 0.22 ^{e}	9.26 ± 0.18 ^{ab}	9.01 ± 0.21 ^{bc}	8.12 ± 0.09 ^{d}
Pore size	7.37 ± 0.18 ^{b}	7.09 ± 0.14 ^{c}	7.81 ± 0.14 ^{a}	6.60 ± 0.36 ^{d}	6.37 ± 0.18 ^{d}	7.44 ± 0.16 ^{b}	6.58 ± 0.12 ^{d}
Pore homogeneity	10.39 ± 0.17 ^{ab}	9.28 ± 0.14 ^{c}	10.61 ± 0.13 ^{a}	8.21 ± 0.24 ^{d}	9.05 ± 0.25 ^{c}	10.34 ± 0.24 ^{b}	9.21 ± 0.09 ^{c}
Aroma							
Baked-product aroma	10.89 ± 0.38 ^{b}	9.40 ± 0.18 ^{c}	11.40 ± 0.12 ^{a}	7.80 ± 0.34 ^{e}	9.62 ± 0.19 ^{c}	11.08 ± 0.24 ^{b}	8.69 ± 0.11 ^{d}
Legume aroma	3.64 ± 0.16 ^{c}	8.50 ± 0.16 ^{a}	2.46 ± 0.10 ^{e}	4.66 ± 0.33 ^{b}	4.48 ± 0.18 ^{b}	4.67 ± 0.20 ^{b}	3.11 ± 0.09 ^{d}
Banana aroma	4.07 ± 0.25 ^{b}	1.29 ± 0.14 ^{e}	11.30 ± 0.13 ^{a}	1.47 ± 0.23 ^{e}	1.43 ± 0.14 ^{e}	3.18 ± 0.13 ^{c}	2.21 ± 0.09 ^{d}
Cereal aroma	7.60 ± 0.20 ^{de}	6.36 ± 0.18 ^{f}	7.39 ± 0.11 ^{e}	9.59 ± 0.31 ^{b}	11.26 ± 0.17 ^{a}	7.75 ± 0.16 ^{d}	8.47 ± 0.14 ^{c}
Taste							
Sweetness	8.53 ± 0.22 ^{b}	7.57 ± 0.17 ^{c}	9.26 ± 0.12 ^{a}	5.30 ± 0.25 ^{e}	7.67 ± 0.20 ^{c}	8.56 ± 0.14 ^{b}	7.31 ± 0.09 ^{d}
Raw-legume note	3.43 ± 0.18 ^{e}	7.41 ± 0.13 ^{a}	2.20 ± 0.10 ^{g}	6.81 ± 0.27 ^{b}	5.72 ± 0.16 ^{c}	4.34 ± 0.18 ^{d}	2.81 ± 0.09 ^{f}
Bitterness	5.28 ± 0.12 ^{b}	4.28 ± 0.13 ^{d}	3.78 ± 0.09 ^{e}	4.82 ± 0.27 ^{c}	6.73 ± 0.19 ^{a}	5.27 ± 0.18 ^{b}	4.91 ± 0.09 ^{c}
Aftertaste	4.55 ± 0.17 ^{d}	4.52 ± 0.13 ^{d}	4.23 ± 0.08 ^{e}	5.41 ± 0.25 ^{b}	5.92 ± 0.17 ^{a}	5.09 ± 0.18 ^{c}	4.11 ± 0.09 ^{e}
Texture							
Hardness	9.34 ± 0.18 ^{c}	7.25 ± 0.11 ^{f}	7.92 ± 0.14 ^{e}	8.96 ± 0.29 ^{d}	10.39 ± 0.16 ^{a}	9.19 ± 0.20 ^{c}	10.11 ± 0.10 ^{b}
Moistness	7.38 ± 0.18 ^{d}	8.63 ± 0.11 ^{a}	8.49 ± 0.12 ^{a}	7.66 ± 0.36 ^{c}	8.72 ± 0.16 ^{a}	7.43 ± 0.21 ^{cd}	7.91 ± 0.10 ^{b}
Adhesiveness	6.40 ± 0.16 ^{de}	7.48 ± 0.14 ^{b}	7.28 ± 0.11 ^{bc}	7.22 ± 0.28 ^{c}	9.28 ± 0.16 ^{a}	6.25 ± 0.18 ^{e}	6.61 ± 0.10 ^{d}
Chewiness	8.49 ± 0.18 ^{b}	7.25 ± 0.11 ^{d}	8.28 ± 0.11 ^{c}	8.53 ± 0.25 ^{b}	10.50 ± 0.16 ^{a}	8.54 ± 0.20 ^{b}	8.41 ± 0.10 ^{bc}
Cohesiveness	7.50 ± 0.14 ^{c}	6.35 ± 0.14 ^{e}	7.70 ± 0.12 ^{b}	7.35 ± 0.23 ^{cd}	8.94 ± 0.16 ^{a}	7.24 ± 0.15 ^{d}	7.51 ± 0.10 ^{bc}
Crumbliness	6.52 ± 0.21 ^{d}	5.69 ± 0.13 ^{e}	6.55 ± 0.08 ^{d}	6.78 ± 0.28 ^{bc}	9.39 ± 0.16 ^{a}	6.60 ± 0.16 ^{cd}	6.91 ± 0.10 ^{b}

[1] Values are mean ± SD (15-cm intensity scale). Within each sensory attribute (row), values sharing at least one superscript letter are not significantly different according to Tukey's test ($p < 0.05$). The prefix E- denotes the egg-replacement series. E-CC, conventional control; E-AC, aquafaba; E-BC, banana; E-FC, flaxseed; E-PC, psyllium; E-SWC, soapwort; E-CHC, chia.

Flaxseed-based muffins (E-FC) exhibited the lowest crust and crumb color intensities and pore homogeneity, whereas psyllium-based muffins (E-PC) showed relatively low crust color intensity and pore homogeneity (Table 2). The lower appearance preference associated with E-PC was discussed in relation to its instrumental crumb color characteristics, particularly yellowness (b*) [1]. The QDA results provide further information on individual appearance attributes, including perceived color intensity and pore structure. Differences among formulations may be associated with the functional properties of the plant-based egg replacers and their effects on batter structure during preparation and baking [7]. Related effects of biopolymer incorporation on muffin structure and sensory characteristics have been reported by Herranz et al. [16].

3.1.2. Aroma

The aroma profiles varied significantly ($p < 0.05$) among formulations, particularly in terms of baked-product, legume, banana, and cereal notes. E-BC exhibited the highest baked-product and banana aroma intensities, distinguishing it from the other formulations. Our previous study [1] reported favorable hedonic flavor ratings for banana-based muffins and overall acceptability approaching that of the conventional control. These earlier findings provide descriptive context for the present aroma profile. However, the present QDA results do not establish whether higher banana or baked-product aroma intensities contribute to greater consumer liking.

Aquafaba-based muffins (E-AC) exhibited the highest legume aroma intensity (8.50 ± 0.16), consistent with the chickpea origin of aquafaba (Table 2). Aquafaba contains soluble constituents released during chickpea cooking, and its composition and processing conditions can influence its functional properties [24–26]. The QDA findings indicate that a characteristic legume-related aroma remained perceptible in the baked muffins. However, because volatile compounds were not analyzed, the specific chemical constituents responsible for this sensory perception cannot be identified from the present results.

Psyllium-based muffins (E-PC) exhibited the highest cereal aroma intensity, followed by flaxseed-based muffins (E-FC) (Table 2). Together with the pronounced legume aroma of E-AC and banana aroma of E-BC, these findings demonstrate that different plant-based egg replacers were associated with distinct sensory profiles. Such ingredient-associated attributes were not individually quantified in the previous hedonic evaluation [1]. QDA therefore provides complementary information by identifying and measuring specific aroma characteristics that distinguish the formulations.

3.1.3. Taste

Significant differences were observed among formulations in sweetness, raw-legume note, bitterness, and aftertaste intensity (Table 2). Banana-based muffins (E-BC) exhibited the highest sweetness intensity, whereas flaxseed-based muffins (E-FC) showed the lowest. The pronounced sweetness of E-BC, together with its characteristic banana and baked-product aromas, complements the favorable hedonic flavor ratings reported previously [1]. The natural sugars present in banana purée may have contributed to perceived sweetness; however, the individual contributions of sweetness and aroma to hedonic acceptance cannot be determined from the present QDA data.

Aquafaba-based muffins (E-AC) exhibited the highest raw-legume note intensity, whereas E-BC showed the lowest (Table 2). E-AC also had the highest legume aroma intensity, indicating that legume-associated characteristics were prominent in both its aroma and flavor profiles. Although aquafaba has functional properties relevant to egg replacement [24–26], its incorporation did not produce a sensory-neutral muffin formulation. Identification of the volatile and nonvolatile compounds associated with these sensory characteristics would require additional chemical analyses.

E-PC exhibited the highest bitterness and aftertaste intensities, distinguishing it from the other formulations. In our previous study [1], hedonic flavor and taste ratings of flaxseed, psyllium, soapwort, and chia-based muffins did not differ significantly. These previous findings put the current QDA results in context. However, the comparison is descriptive since there was no joint analysis to test differences in QDA attributes specifically for formulations that were not significantly different in the previous hedonic evaluation. The elevated bitterness and aftertaste of E-PC may be relevant to formulation optimization, although their chemical origins and individual contributions to consumer acceptance remain undetermined. E-SWC exhibited sweetness and bitterness intensities comparable to those of E-CC, whereas raw-legume note and aftertaste were significantly higher ($p < 0.05$). Çelik et al. [27] investigated the use of soapwort extract as a partial egg

white replacer in sponge cakes, demonstrating its potential application in bakery formulations. The present QDA results provide a more detailed characterization of individual taste attributes, indicating that soapwort incorporation was associated with increased aftertaste intensity without a corresponding increase in perceived bitterness relative to E-CC. A possible nonvolatile chemical context for the discussion of these taste attributes is provided by saponins. The foaming properties of soapwort saponins and their potential taste characteristics, including bitterness, were discussed by Çelik et al. [27]. The chickpea aquafaba powders have also been studied in terms of their saponins and foaming properties [28]. But their simple presence does not prove their sensory contribution in baked muffins. The present study did not find a significant difference in bitterness between E-SWC and E-CC, and the bitterness was lower in E-AC than in E-CC (Table 2). The concentrations of saponins were not measured, so it is not possible to definitively attribute the observed bitterness and aftertaste to these compounds.

The present QDA results show formulation-specific taste characteristics that are consistent with the hedonic evaluations reported previously [1]. In particular, the pronounced raw-legume note of E-AC, the elevated bitterness and aftertaste of E-PC, and the increased aftertaste of E-SWC identify distinct taste-related features that may be relevant to subsequent formulation development.

3.1.4. Texture

Egg replacer had a significant ($p < 0.05$) effect on the perceived hardness, moistness, adhesiveness, chewiness, cohesiveness and crumbliness. E-PC showed the highest values of hardness, adhesiveness, chewiness, cohesiveness and crumbliness. Interestingly, E-PC was also in the highest moistness group along with E-AC and E-BC. The simultaneous occurrence of these sensory attributes of high perceived hardness and moistness indicates that they are not necessarily inversely related.

The sensory profile may be associated with the water-binding properties of psyllium. Psyllium husk is rich in polysaccharides (arabinoxylans) that have strong interactions with water and can influence the water distribution and rheological properties of food matrices. Franco et al. [29] studied the influence of psyllium on the water dynamics and mechanical properties of dough and bread systems, which is a relevant basis for considering hydration-related characteristics and resistance to deformation separately. However, it is not possible to determine the mechanisms responsible for the simultaneous high intensities of hardness and moistness observed in E-PC from the present QDA results alone.

In the present QDA, the highest mean perceived hardness score was observed for the psyllium-based muffins (E-PC), followed by the chia-based muffins (E-CHC). E-CHC was the hardest instrumentally in our previous study [1]. This comparison is for descriptive purposes only, as measurements were performed in separate studies and no rank-correlation or agreement analysis was performed. This comparison allows us to establish no relation between the instrumental and perceived hardness.

E-CHC had a relatively high perceived hardness in the present QDA. Lower hedonic softness ratings reported in our previous study [1] provide additional descriptive context, but hedonic softness ratings reflect liking while QDA hardness scores reflect perceived intensity, and their relationship was not tested. The relevance of gel-forming ingredients in bakery formulation is supported by the effects of chia and flaxseed gels as egg replacers on the textural and sensory properties of cakes reported by Burkay and Alkan [30].

E-AC had the lowest perceived intensity of hardness, chewiness, cohesiveness and crumbliness, but relatively high moistness (Table 2). This combination set E-AC apart from the more cohesive, firmer sensory profiles of E-PC and E-CHC. The foaming and emulsifying properties of aquafaba are dependent on the composition and concentration of its soluble constituents [24–26]. These properties might have contributed to batter

aeration and structural development, but their direct impact on the sensory texture profile of E-AC was not assessed in the present study.

Most of the texture attributes had intermediate intensities in muffins with soapwort (E-SWC), and the perceived hardness and chewiness scores were similar to those of E-CC. Moistness scores did not differ significantly between E-SWC and E-CC (Table 2). Soapwort extracts contain surface-active saponins, which are involved in the formation and stabilization of foam. Some previous studies have been conducted on the use of soapwort extract in sponge cakes [27] and the correlations between extract processing, saponin content and foaming properties [31]. However, the contribution of these characteristics to the specific sensory texture profile of E-SWC is not yet known.

The QDA profiles of E-PC, E-CHC, E-AC and E-SWC were different in some perceived texture attributes, underlining the multidimensional nature of sensory texture. These attribute-level results supplement the instrumental and hedonic evaluations reported previously [1]. Comparisons across studies are descriptive.

3.2. Quantitative Descriptive Sensory Profiles of Milk-Replacement Muffins

The quantitative descriptive analysis (QDA) revealed significant differences ($p < 0.05$) in the sensory characteristics of muffins prepared with different plant-based milk alternatives (Table 3 and Figure 2). These differences were particularly evident in aroma, taste, and texture attributes, whereas some appearance characteristics remained relatively consistent across formulations. The findings complement the previously reported hedonic and instrumental evaluations [2] by providing a more detailed characterization of the sensory attributes associated with individual milk alternatives.

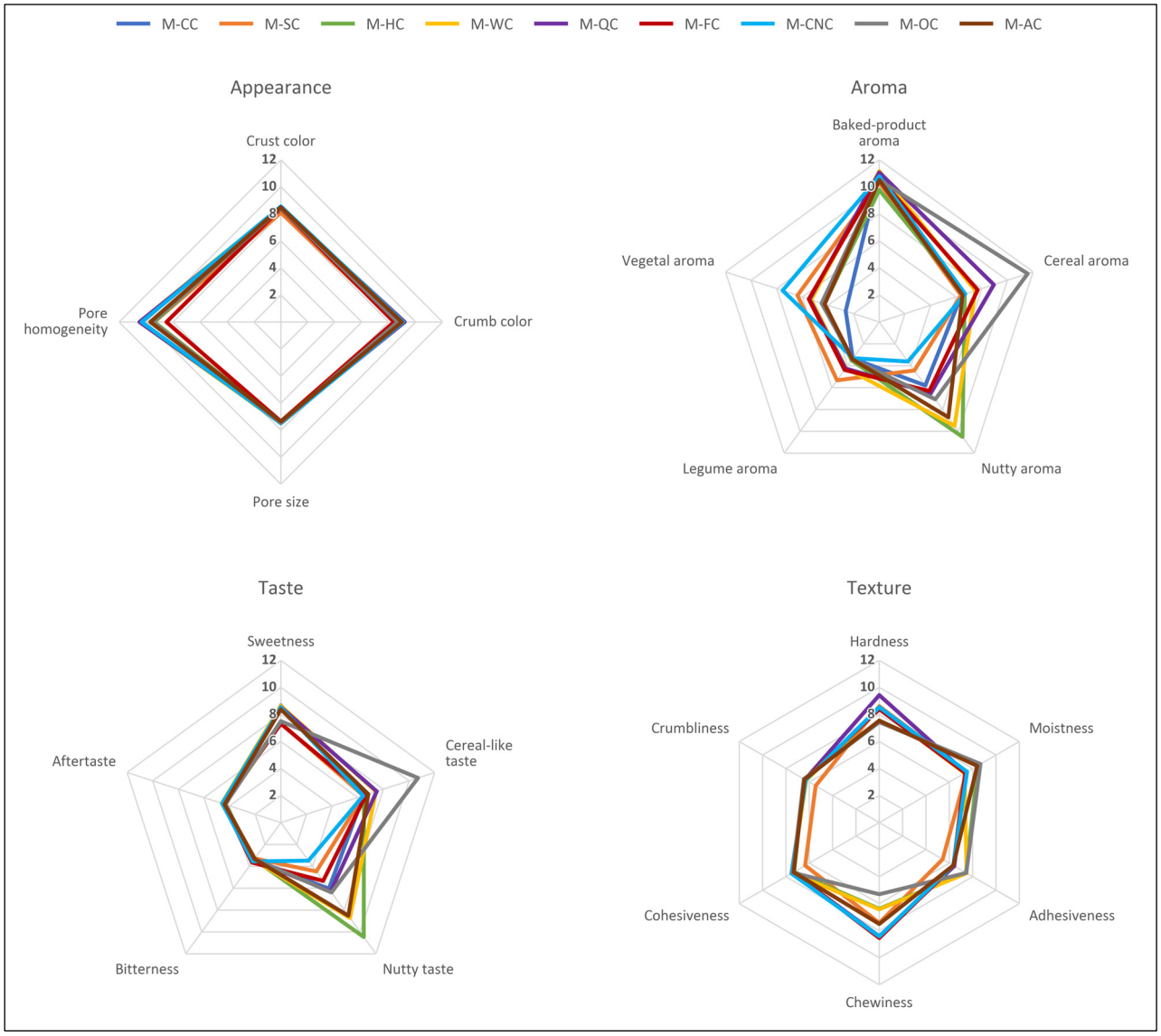


Figure 2. Radar plots of quantitative descriptive analysis (QDA) profiles for the milk-replacement muffin series. Values represent mean sensory intensity scores from 12 trained assessors on 15-cm scales (0–15) for appearance, aroma, taste, and texture attributes. The prefix M- denotes the milk-replacement series. M-CC, conventional control containing whole eggs and cow's milk; M-SC, soy milk; M-HC, hazelnut milk; M-WC, walnut milk; M-QC, quinoa milk; M-FC, flaxseed milk; M-CNC, coconut milk; M-OC, oat milk; M-AC, almond milk. Statistical comparisons among formulations are reported in Table 3.

3.2.1. Appearance

The milk replacer formulations differed significantly for crust color, crumb color and pore homogeneity but not for perceived pore size (Table 3). The lowest crust color intensity was recorded for soy milk muffins (M-SC). The other formulations were statistically similar for crust color scores. The numerical intensity of the crumb color was highest for the quinoa milk muffins (M-QC), although there were no significant differences between the conventional control (M-CC), coconut milk (M-CNC), almond milk (M-AC) and walnut milk (M-WC) muffins. Flaxseed milk (M-FC), hazelnut milk (M-HC) and M-SC formulations have shown lower crumb color intensities. The M-FC had the poorest pore homogeneity, suggesting that differences in the uniformity of the crumb were more accentuated than differences in perceived pore size.

The differences in the color intensity observed could be related to the variations in the protein, carbohydrate and pigment composition of the plant-based milk alternatives, which can affect the color development during baking [3,8,10]. But from the present sensory data, the individual contributions of the constituents cannot be determined. The QDA results add to the instrumental color measurements presented in our previous study [2] by explaining the perception of differences in muffin coloration by trained assessors. Instrumental color coordinates are related to sensory color intensity, but they are different measurements and should be interpreted as complementary indicators.

3.2.2. Aroma

Aroma profiles were strongly influenced by the type of milk alternative, particularly the intensities of baked-product, cereal, nutty, legume and vegetal aromas. The highest intensities of baked-product aroma were recorded in M-WC and M-CC, with a statistically similar response in M-QC. Conversely, M-HC had the lowest baked-product aroma intensity, although it had the most prominent nutty aroma.

The nutty aroma was highest in M-HC, followed by M-WC and almond milk muffins (M-AC), suggesting differences in the perceived nut-associated characteristics of these formulations (Table 3). Sensory differences in plant-based milk alternatives have been reported by Magwere et al. [32], including nutty notes associated with almond milk. The present findings extend this ingredient-level context to baked muffin formulations by demonstrating that nut-derived milk alternatives were associated with distinguishable nutty aroma intensities. However, the fate or transformation of individual aroma-active volatile compounds during baking was not studied.

Legume aroma intensity was highest in soy milk muffins (M-SC), in agreement with the characteristic beany notes usually associated with soy-based beverages [10,32]. Swanson et al. [33] investigated the use of soy milk as a dairy milk substitute in muffins, and they found similar hedonic evaluations for some sensory attributes in comparison with conventional recipes. The current QDA results provide complementary information by characterizing legume aroma as a signature attribute of M-SC. The intensity of this aroma, however, should not be taken as a direct measure of consumer liking.

Oat milk muffins (M-OC) had the highest cereal aroma intensity, followed by quinoa milk muffins (M-QC) (Table 3). This intense cereal-related character is in line with previous results showing that the sensory properties of oat-based milk alternatives are influenced by their physical and chemical properties, such as volatile composition. McCarron et al. [34] detected hexanal, a volatile aldehyde associated with green notes, in oat-based milk alternatives and reported a positive correlation with wet-oats flavor. This provides a possible chemical basis for ingredient-related sensory notes in plant-based formulations. However, the wet-oats descriptor used in that study is not the same as the cereal aroma descriptor used here. Since volatile compounds were not analyzed in the present study, it is not possible to determine the contribution of hexanal to the aroma profiles of the muffins or its fate during baking.

The vegetal aroma intensity was the highest for coconut milk muffins (M-CNC) and the lowest for M-CC (Table 3). This attribute, as defined by the sensory lexicon, refers to green or grassy notes of aroma and not the characteristic coconut note of aroma. However, the higher vegetal aroma score is a specific sensory characteristic of M-CNC, although the compounds responsible for this perception were not identified.

3.2.3. Taste

The milk-substitute formulations differed significantly in sweetness, cereal-like taste, nutty taste, bitterness, and aftertaste intensity (Table 3). The numerically highest sweetness scores were observed for the conventional control (M-CC) and walnut milk

muffins (M-WC), although these formulations did not differ significantly from M-HC, M-QC, and M-CNC. The lowest intensities were observed in the soy milk (M-SC), flaxseed milk (M-FC), and oat milk (M-OC) muffins. These differences may relate to variation in the composition of the milk alternatives and interactions among sensory attributes. The carbohydrate and sugar profiles of the plant-based milk alternatives vary [10], but the current QDA data do not permit determination of the contributions of these constituents to sweetness perception in the finished muffins.

Oat milk muffins (M-OC) presented the highest cereal-like taste intensity, in accordance with the strong cereal aroma (Table 3). The quinoa milk (M-QC) and M-WC muffins also had relatively high cereal-like taste scores, although both were significantly lower than M-OC. The concurrent dominance of cereal aroma and flavor in M-OC suggests that the cereal-related attributes were perceived across sensory dimensions in the final product. Ingredient-dependent sensory properties of oat-based milk alternatives have been reported in previous studies [34], but the exact compounds that contributed to the cereal-like taste perception occurring after baking were not studied.

Hazelnut milk muffins (M-HC) had the highest intensity of nutty taste, followed by M-WC and almond milk muffins (M-AC), and both formulations showed statistically comparable scores (Table 3). M-HC had the highest intensity of both nutty aroma and nutty taste. However, M-WC and M-AC differed significantly in nutty aroma, whereas their nutty taste scores did not differ significantly (Table 3). However, the differences between M-HC, M-WC and M-AC indicate that the nut-based milk alternatives were associated with different sensory intensities, rather than a consistent nutty taste.

Flaxseed milk muffins (M-FC) exhibited the numerically highest bitterness intensity, although the difference from coconut milk muffins (M-CNC) was not statistically significant (Table 3). There were differences in the intensity of bitterness among the milk-replacement formulations. Descriptively, the differences in bitterness were less pronounced than the distinctive cereal-like taste profile in M-OC and the nutty taste profile in M-HC. However, the individual attribute scores do not allow us to determine the relative contribution of bitterness to overall sensory differentiation.

M-WC exhibited the numerically highest aftertaste intensity, but did not differ significantly from M-CNC or M-FC (Table 3). M-WC obtained a high score in aftertaste, which was associated with high intensities of nutty aroma and flavor, revealing a unique and persistent sensory profile. In our previous hedonic study [2], M-WC was rated relatively low for taste and overall acceptance. However, hereafter taste was rated as the persistence of taste or flavor after swallowing, with no indication of its pleasantness or unpleasantness. Therefore, the contribution of this attribute to the already observed hedonic ratings cannot be inferred from the present data.

Table 3. Quantitative descriptive analysis (QDA) scores of muffins prepared with different milk replacers [1].

Sensory Attribute	M-CC	M-SC	M-HC	M-WC	M-QC	M-FC	M-CNC	M-⚜C	M-AC
					Appearance				
Crust color	8.46 ± 0.20 ^{a}	8.09 ± 0.27 ^{b}	8.55 ± 0.20 ^{a}	8.51 ± 0.16 ^{a}	8.44 ± 0.19 ^{a}	8.41 ± 0.18 ^{a}	8.56 ± 0.20 ^{a}	8.44 ± 0.20 ^{a}	8.49 ± 0.17 ^{a}
Crumb color	9.04 ± 0.29 ^{a}	8.52 ± 0.21 ^{c}	8.50 ± 0.28 ^{c}	8.90 ± 0.23 ^{ab}	9.19 ± 0.18 ^{a}	8.39 ± 0.17 ^{c}	9.08 ± 0.24 ^{a}	8.67 ± 0.25 ^{bc}	8.98 ± 0.25 ^{a}
Pore size	7.39 ± 0.16 ^{a}	7.39 ± 0.20 ^{a}	7.42 ± 0.18 ^{a}	7.50 ± 0.20 ^{a}	7.42 ± 0.18 ^{a}	7.35 ± 0.14 ^{a}	7.50 ± 0.18 ^{a}	7.45 ± 0.15 ^{a}	7.36 ± 0.16 ^{a}
Pore homogeneity	10.43 ± 0.17 ^{a}	9.39 ± 0.17 ^{c}	9.40 ± 0.18 ^{c}	10.50 ± 0.20 ^{a}	10.49 ± 0.21 ^{a}	8.49 ± 0.14 ^{d}	10.33 ± 0.17 ^{a}	9.51 ± 0.22 ^{bc}	9.69 ± 0.15 ^{b}

Aroma									
Baked-product aroma	11.13 ± 0.20 ^{a}	10.32 ± 0.27 ^{d}	9.77 ± 0.30 ^{e}	11.16 ± 0.25 ^{a}	11.07 ± 0.24 ^{ab}	10.67 ± 0.16 ^{c}	10.78 ± 0.27 ^{bc}	10.50 ± 0.20 ^{cd}	10.50 ± 0.24 ^{cd}
Cereal aroma	6.42 ± 0.16 ^{e}	6.38 ± 0.17 ^{e}	6.67 ± 0.28 ^{d}	7.50 ± 0.22 ^{c}	8.94 ± 0.23 ^{b}	7.68 ± 0.12 ^{c}	6.71 ± 0.12 ^{d}	11.58 ± 0.19 ^{a}	6.50 ± 0.16 ^{de}
Nutty aroma	5.80 ± 0.16 ^{f}	4.43 ± 0.20 ^{g}	10.50 ± 0.28 ^{a}	9.50 ± 0.21 ^{b}	6.51 ± 0.16 ^{e}	6.31 ± 0.15 ^{e}	3.61 ± 0.11 ^{h}	7.07 ± 0.18 ^{d}	8.72 ± 0.16 ^{c}
Legume aroma	3.34 ± 0.17 ^{c}	5.33 ± 0.15 ^{a}	3.50 ± 0.16 ^{c}	4.22 ± 0.10 ^{b}	4.25 ± 0.11 ^{b}	4.38 ± 0.17 ^{b}	3.31 ± 0.14 ^{c}	3.40 ± 0.16 ^{c}	3.40 ± 0.12 ^{c}
Vegetal aroma	2.62 ± 0.14 ^{f}	6.38 ± 0.15 ^{b}	4.28 ± 0.13 ^{e}	5.31 ± 0.14 ^{c}	5.44 ± 0.18 ^{c}	5.50 ± 0.15 ^{c}	7.54 ± 0.18 ^{a}	4.50 ± 0.11 ^{d}	4.26 ± 0.10 ^{e}
Taste									
Sweetness	8.67 ± 0.17 ^{a}	7.35 ± 0.14 ^{c}	8.52 ± 0.22 ^{ab}	8.64 ± 0.14 ^{a}	8.54 ± 0.20 ^{ab}	7.31 ± 0.15 ^{c}	8.52 ± 0.19 ^{ab}	7.50 ± 0.14 ^{c}	8.38 ± 0.17 ^{b}
Cereal-like taste	6.46 ± 0.15 ^{de}	6.44 ± 0.16 ^{e}	6.48 ± 0.21 ^{de}	7.42 ± 0.16 ^{b}	7.48 ± 0.16 ^{b}	6.65 ± 0.18 ^{cd}	6.43 ± 0.13 ^{e}	10.70 ± 0.12 ^{a}	6.82 ± 0.17 ^{c}
Nutty taste	6.05 ± 0.16 ^{d}	4.47 ± 0.16 ^{f}	10.46 ± 0.20 ^{a}	8.72 ± 0.16 ^{b}	6.29 ± 0.14 ^{c}	5.33 ± 0.12 ^{e}	3.48 ± 0.14 ^{g}	6.39 ± 0.12 ^{c}	8.52 ± 0.13 ^{b}
Bitterness	3.38 ± 0.18 ^{bc}	3.28 ± 0.12 ^{c}	3.36 ± 0.17 ^{c}	3.42 ± 0.14 ^{bc}	3.44 ± 0.17 ^{bc}	3.65 ± 0.13 ^{a}	3.55 ± 0.12 ^{ab}	3.34 ± 0.14 ^{c}	3.32 ± 0.13 ^{c}
Aftertaste	4.32 ± 0.15 ^{c}	4.40 ± 0.15 ^{bc}	4.31 ± 0.14 ^{c}	4.61 ± 0.15 ^{a}	4.35 ± 0.18 ^{c}	4.48 ± 0.14 ^{abc}	4.58 ± 0.17 ^{ab}	4.35 ± 0.14 ^{c}	4.39 ± 0.16 ^{bc}
Texture									
Hardness	8.39 ± 0.18 ^{b}	8.61 ± 0.14 ^{b}	7.55 ± 0.19 ^{c}	8.44 ± 0.17 ^{b}	9.43 ± 0.20 ^{a}	8.39 ± 0.14 ^{b}	8.54 ± 0.15 ^{b}	7.43 ± 0.17 ^{c}	7.54 ± 0.16 ^{c}
Moistness	7.41 ± 0.17 ^{cd}	7.49 ± 0.16 ^{cd}	8.46 ± 0.24 ^{b}	7.31 ± 0.14 ^{d}	7.40 ± 0.18 ^{cd}	7.36 ± 0.13 ^{cd}	7.52 ± 0.12 ^{c}	8.67 ± 0.13 ^{a}	8.39 ± 0.14 ^{b}
Adhesiveness	6.35 ± 0.11 ^{b}	5.43 ± 0.14 ^{c}	7.42 ± 0.19 ^{a}	7.48 ± 0.14 ^{a}	6.43 ± 0.20 ^{b}	6.35 ± 0.18 ^{b}	6.34 ± 0.18 ^{b}	7.45 ± 0.14 ^{a}	6.34 ± 0.15 ^{b}
Chewiness	8.54 ± 0.14 ^{a}	7.42 ± 0.17 ^{b}	6.38 ± 0.14 ^{c}	6.42 ± 0.14 ^{c}	8.41 ± 0.18 ^{a}	8.54 ± 0.14 ^{a}	8.42 ± 0.14 ^{a}	5.30 ± 0.11 ^{d}	7.50 ± 0.14 ^{b}
Cohesiveness	7.39 ± 0.16 ^{ab}	6.35 ± 0.14 ^{c}	7.30 ± 0.14 ^{b}	7.46 ± 0.15 ^{ab}	7.42 ± 0.14 ^{ab}	7.38 ± 0.14 ^{ab}	7.53 ± 0.14 ^{a}	7.41 ± 0.11 ^{ab}	7.34 ± 0.14 ^{b}
Crumbliness	6.34 ± 0.15 ^{ab}	5.45 ± 0.14 ^{c}	6.45 ± 0.17 ^{a}	6.26 ± 0.14 ^{b}	6.37 ± 0.15 ^{ab}	6.38 ± 0.12 ^{ab}	6.30 ± 0.13 ^{ab}	6.46 ± 0.12 ^{a}	6.40 ± 0.12 ^{ab}

[1] Values are mean ± SD (15-cm intensity scale). Within each sensory attribute (row), values sharing at least one superscript letter are not significantly different according to Tukey's test ($p < 0.05$). The prefix M- denotes the milk-replacement series. M-CC, conventional control; M-SC, soy milk; M-HC, hazelnut milk; M-WC, walnut milk; M-QC, quinoa milk; M-FC, flaxseed milk; M-CNC, coconut milk; M-OC, oat milk; M-AC, almond milk.

3.2.4. Texture

Significant differences were observed among milk-replacement formulations in perceived hardness, moistness, adhesiveness, chewiness, cohesiveness, and crumbliness (Table 3). The highest hardness intensity was recorded in quinoa milk muffins (M-QC). Muffins made of oat milk (M-OC), hazelnut milk (M-HC) and almond milk (M-AC) were clustered in the lowest statistical group. The significant perceived hardness of M-QC could be compared to the relatively high viscoelastic properties previously reported for quinoa milk batters [2]. Studies with quinoa flour in gluten-free cakes have also shown effects on batter rheology and cake texture [35]. However, quinoa flour and quinoa milk have different compositions and mechanisms related to the increase in sensory hardness of M-QC cannot be determined from the present results.

M-OC had the highest perceived moistness and lowest chewiness intensity, and one of the lowest hardness scores (Table 3). M-HC and M-AC also had relatively high moistness intensities, while M-WC was in the lowest moistness group. The M-OC oral texture profile was distinct from the other formulations due to this combination of high moistness and low hardness and chewiness. The water-binding and viscosity-modifying properties of soluble polysaccharides derived from oats, e.g., β-glucans, can affect the texture of food products [34]. The contribution of these constituents to the perceived moistness and chewiness of the present muffins was not directly assessed.

The highest intensities of adhesiveness were found in M-WC, M-OC and M-HC, while the lowest score was found in M-SC (Table 3). M-OC had high perceived moistness and adhesiveness, but low hardness and chewiness, suggesting that sensory attributes represent different aspects of oral texture. M-HC also had a similar combination of relatively low hardness and high moistness and adhesiveness. These results emphasize the necessity of assessing multiple texture attributes and not just hardness when characterizing the sensory texture of muffins.

M-CC, M-FC, M-QC and M-CNC were in the highest statistical group for perceived chewiness, while M-OC showed the lowest intensity (Table 3). The relatively high chewiness of M-FC may be associated with the functional properties of flaxseed polysaccharides. Flaxseed mucilage exhibits water-binding, thickening and structure-forming properties that can influence the rheology of food systems [36]. These properties can be a context for the viscoelastic characteristics previously reported for flaxseed milk batters [2]. However, the exact contribution of flaxseed mucilage to the perceived chewiness of M-FC was not elucidated in the present study.

The highest numerical cohesiveness score was obtained by M-CNC, but this value was not statistically different from those obtained by M-CC, M-WC, M-QC, M-FC, and M-OC (Table 3). M-SC showed the lowest level of cohesiveness intensity. The relatively high cohesiveness and chewiness of M-CNC suggest that this formulation was perceived to require more chewing effort, while maintaining the structural integrity during oral processing. The lipid-rich dispersed phase of coconut milk could potentially influence interactions between batter constituents [10]. However, their specific role in these sensory attributes is unknown.

Numerically, the highest crumbliness scores were for M-OC and M-HC, but several other formulations were in the same statistical group, with M-SC having the lowest intensity (Table 3). The M-OC was relatively high in moistness, adhesiveness and crumbliness and low in hardness and chewiness, indicating that perceived moisture and fragmentation during oral processing do not necessarily follow the same pattern. Together, these results demonstrate the added value of QDA in addition to the already published instrumental and rheological assessments [2], especially in the differentiation of oral texture characteristics that are not fully captured by a single mechanical measurement.

3.3. Pearson Correlation Analysis of Sensory Attributes

Pearson correlation analysis was conducted to investigate the relationships among the sensory attributes of egg and milk-replacement muffins (Tables 4 and 5). Instrumental color parameters were excluded from the analysis. Significant correlations were observed among appearance, aroma, taste, and texture attributes, with different patterns emerging for the two groups of formulations.

3.3.1. Egg-Replacement Muffins

In the egg replacement series, pore homogeneity was strongly correlated with baked-product aroma ($r = 0.97$, $p < 0.01$) and sweetness ($r = 0.95$, $p < 0.01$). The aroma of the baked

product was also positively correlated with the sweetness (r = 0.95, $p < 0.01$) (Table 4). These associations were in agreement with the sensory profiles of E-BC, E-CC and E-SWC that had relatively homogeneous pore structures and pronounced baked-product aroma and sweetness. However, the correlations are indicative of the concomitant variation of these sensory attributes across formulations rather than a direct relationship between crumb structure and flavor development.

The cereal aroma was positively correlated with bitterness (r = 0.78, $p < 0.05$), hardness (r = 0.76, $p < 0.05$), chewiness (r = 0.91, $p < 0.01$), cohesiveness (r = 0.84, $p < 0.05$) and crumbliness (r = 0.92, $p < 0.01$) (Table 4). The correlation between cereal aroma and adhesiveness was positive but not statistically significant (r = 0.66, $p > 0.05$). These associations were consistent with the specific sensory profile of psyllium muffins (E-PC) characterized by increased cereal aroma, bitterness and some texture intensities. The correlations suggest that these attributes were likely to have co-occurred across the formulations evaluated, but the magnitude of these correlations may have been impacted by the strong profile of E-PC and should not be taken as evidence of direct interactions between aroma-related constituents and texture.

Chewiness and cohesiveness (r = 0.96, $p < 0.01$), chewiness and crumbliness (r = 0.98, $p < 0.01$) and cohesiveness and crumbliness (r = 0.94, $p < 0.01$) had significant positive correlations (Table 4). The correlation between chewiness and cohesiveness suggests that formulations that required more effort to chew also tended to receive higher scores for structural integrity during oral evaluation. Although cohesiveness and crumbliness are conceptually different texture attributes, their positive correlation is a reflection of the specific distribution of sensory intensities in the assessed formulations, especially E-PC. This finding should not be taken as evidence that more cohesiveness causes more crumbliness.

Table 4. Pearson correlation coefficients among quantitative descriptive sensory attributes of muffins formulated with different egg substitutes.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. Crust color	1.00	0.80 *	0.57	0.87 *	0.81 *	−0.55	0.59	−0.29	0.90 **	−0.87 *	−0.03	−0.48	0.17	−0.09	−0.30	0.07	0.22	0.01
2. Crumb color		1.00	0.49	0.77 *	0.87 *	−0.43	0.58	0.04	0.87 *	−0.57	0.25	0.02	0.16	0.19	0.18	0.44	0.54	0.37
3. Pore size			1.00	0.87 *	0.83 *	−0.16	0.77 *	−0.74	0.75	−0.48	−0.61	−0.53	−0.60	−0.17	−0.52	−0.50	−0.37	−0.59
4. Pore homogeneity				1.00	0.97 **	−0.34	0.70	−0.55	0.95 **	−0.69	−0.25	−0.47	−0.21	−0.17	−0.42	−0.18	−0.05	−0.28
5. Baked-product aroma					1.00	−0.28	0.68	−0.42	0.95 **	−0.57	−0.12	−0.26	−0.20	−0.05	−0.22	−0.02	0.08	−0.12
6. Legume aroma						1.00	−0.57	−0.29	−0.28	0.84 *	−0.05	0.17	−0.51	0.30	0.19	−0.39	−0.57	−0.29
7. Banana aroma							1.00	−0.35	0.66	−0.70	−0.55	−0.48	−0.36	0.12	−0.17	−0.15	0.09	−0.21
8. Cereal aroma								1.00	−0.44	0.18	0.78 *	0.78 *	0.76 *	0.13	0.66	0.91 **	0.84 *	0.92 **
9. Sweetness									1.00	−0.65	−0.13	−0.40	−0.16	0.11	−0.16	−0.04	0.09	−0.09
10. Raw-legume note										1.00	0.20	0.58	−0.24	0.24	0.42	−0.05	−0.26	0.03
11. Bitterness											1.00	0.75	0.80 *	−0.02	0.50	0.86 *	0.71	0.84 *
12. Aftertaste												1.00	0.41	0.08	0.62	0.73	0.54	0.70
13. Hardness													1.00	−0.27	0.17	0.79 *	0.73	0.74
14. Moistness														1.00	0.79 *	0.15	0.23	0.32
15. Adhesiveness															1.00	0.64	0.62	0.76 *
16. Chewiness																1.00	0.96 **	0.98 **
17. Cohesiveness																	1.00	0.94 **
18. Crumbliness																		1.00

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

Table 5. Pearson correlation coefficients among quantitative descriptive sensory attributes of muffins formulated with different milk substitutes.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1. Crust color	1.00	0.40	0.41	0.33	0.15	0.07	0.44	−0.82 **	−0.21	0.68 *	0.06	0.43	0.34	0.17	−0.26	0.23	0.68 *	−0.06	0.93 **	0.90 **
2. Crumb color		1.00	0.35	0.89 **	0.68 *	−0.04	−0.17	−0.39	−0.03	0.74 *	−0.04	−0.11	−0.04	0.11	0.42	−0.24	−0.05	0.36	0.45	0.27
3. Pore size			1.00	0.59	0.24	0.26	0.01	−0.23	0.41	0.41	0.30	−0.01	0.06	0.54	0.11	−0.05	0.52	−0.36	0.35	0.13
4. Pore homogeneity				1.00	0.62	−0.07	−0.06	−0.28	−0.04	0.80 **	−0.02	0.01	−0.21	0.17	0.41	−0.29	0.12	0.12	0.32	0.10
5. Baked-product aroma					1.00	0.10	−0.30	0.00	−0.02	0.33	0.03	−0.34	0.32	0.40	0.62	−0.68 *	−0.08	0.43	0.39	0.12
6. Cereal aroma						1.00	0.06	−0.12	−0.05	−0.34	0.95 **	−0.04	0.00	−0.17	−0.13	0.36	0.48	−0.51	0.29	0.34
7. Nutty aroma							1.00	−0.24	−0.50	0.32	0.13	0.98 **	−0.28	−0.17	−0.51	0.48	0.72 *	−0.57	0.29	0.46
8. Legume aroma								1.00	0.41	−0.53	−0.21	−0.27	−0.02	0.16	0.51	−0.51	−0.50	0.12	−0.76 *	−0.80 **
9. Vegetal aroma									1.00	−0.24	−0.15	−0.55	0.40	0.65	0.41	−0.34	−0.31	0.17	−0.22	−0.41

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10. Sweetness	1.00	−0.31	0.41	−0.08	0.07	0.14	−0.10	0.30	0.16	0.53	0.42
11. Cereal-like taste		1.00	0.05	−0.22	−0.17	−0.34	0.51	0.53	−0.69 *	0.22	0.29
12. Nutty taste			1.00	−0.38	−0.26	−0.50	0.50	0.67	−0.53	0.24	0.42
13. Bitterness				1.00	0.53	0.36	−0.49	−0.03	0.53	0.48	0.34
14. Aftertaste					1.00	0.25	−0.50	0.05	0.10	0.19	−0.10
15. Hardness						1.00	−0.86 **	−0.47	0.66	−0.10	−0.32
16. Moistness							1.00	0.46	−0.69 *	0.10	0.36
17. Adhesiveness								1.00	−0.70 *	0.61	0.67
18. Chewiness									1.00	0.04	−0.08
19. Cohesiveness										1.00	0.94 **
20. Crumbliness											1.00

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

3.3.2. Milk Replacement Muffins

Cereal aroma was highly correlated with cereal-like taste (r = 0.95, $p < 0.01$), and nutty aroma was similarly correlated with nutty taste (r = 0.98, $p < 0.01$). These relationships were consistent with the characteristic sensory profiles described in Section 3.2. M-OC, in particular, showed the highest cereal aroma and cereal-like taste intensities, while M-HC was characterized by pronounced nutty aroma and flavor. M-WC and M-AC also contributed to variability in nutty features. The high correlation between aroma and flavor descriptors suggests that the typical notes associated with these plant-based milk alternatives were perceived consistently in olfactory and oral sensory evaluation. This finding is consistent with past reports on cereal and nutty sensory attributes in plant-based milk alternatives [10,11,32,34].

Hardness was strongly and negatively correlated with moistness (r = −0.86, $p < 0.01$), indicating that muffins that were perceived as harder generally received lower moistness scores. The relationship was in agreement with the different texture profiles of M-QC and M-OC. The hardness intensity was highest in M-QC, moistness was highest in M-OC, and chewiness was lowest in M-OC. Moistness was also negatively correlated with chewiness (r = −0.69, $p < 0.05$). These associations imply that differences in perceived moisture were associated with differences in the effort required for chewing. Relevant context to these sensory observations is provided by differences in batter rheology and physical characteristics among milk-replacement formulations [2], although direct correspondence between instrumental measurements and sensory texture cannot be assumed.

Cohesiveness was highly positively correlated with crumbliness (r = 0.94, $p < 0.01$). This association, as with the egg-replacement preparations, should not be taken as proof that increased cohesiveness causes increased crumbliness. Rather, it describes how these characteristics differed across the particular formulations that were tested. In addition, legume aroma was negatively correlated with cohesiveness (r = −0.76, $p < 0.05$) and crumbliness (r = −0.80, $p < 0.01$). These relations were consistent with the typical profile of M-SC, which showed the highest legume aroma and the lowest cohesiveness and crumbliness. Thus, the correlations represent the soy milk formulation sensory attributes at the same time, with no causality between legume aroma and texture.

To summarize, the patterns of correlation confirmed the individual results from the QDA, demonstrating sensory attributes that changed together across the different formulations. In the egg-replacement group, several important associations related to cereal aroma and texture characteristics were observed. For the milk-replacement group, associations between corresponding aroma and flavor descriptors, and between hardness and moistness were particularly strong. These relationships were then studied within the framework of multivariate sample distributions obtained by PCA and HCA.

3.4. Principal Component Analysis (PCA)

Separate principal component analyses (PCA) were carried out on the egg and milk-replacement series to explore the multivariate patterns in the quantitative descriptive sensory profiles. The corresponding eigenvalues, explained variance percentages, cumulative explained variance, and sensory attribute loadings are presented in the Supplementary Materials (Tables S1 and S2), while the score and loading plots are shown in Figures 3 and 4. Scores represent the positions of individual formulations in the principal component space, whereas loadings describe the relationships between sensory attributes and the principal components.

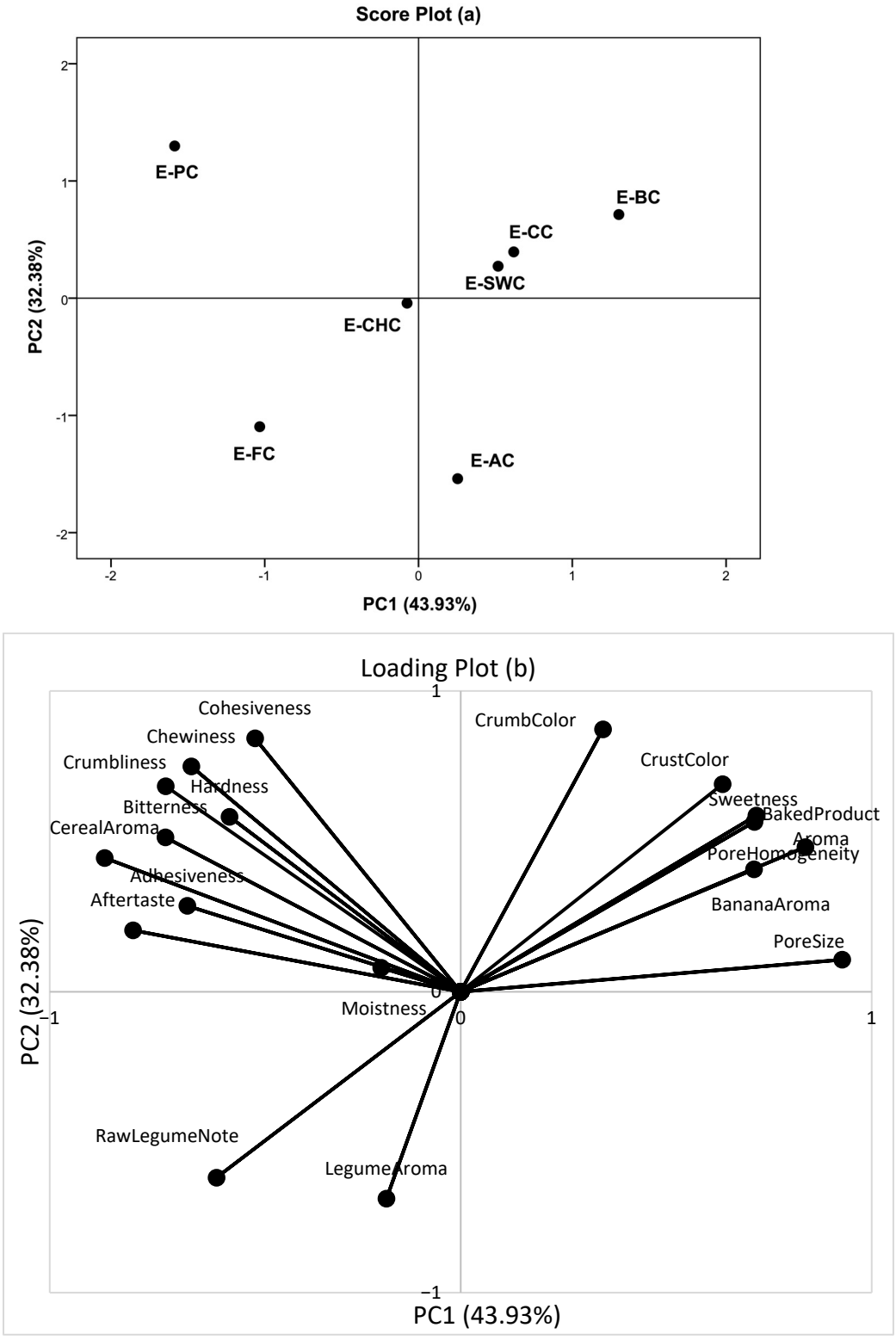
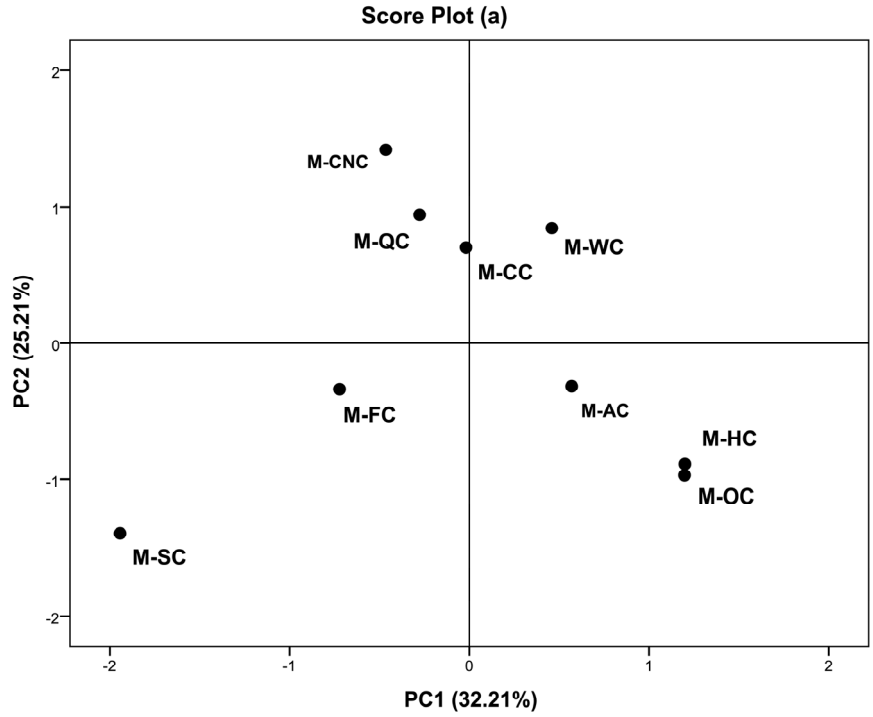


Figure 3. Principal component analysis (PCA) of the egg-replacement muffin series based on formulation mean scores from 12 trained assessors for 18 sensory attributes: (**a**) score plot showing the positions of muffin formulations and (**b**) loading plot showing the relationships between sensory attributes and principal components. PC1 and PC2 explain 43.93% and 32.38% of the total variance, respectively (76.31% cumulatively). PCA was performed without rotation. The prefix E- denotes the egg-replacement series. E-CC, conventional control containing whole eggs and cow's milk; E-AC, aquafaba; E-BC, banana purée; E-FC, flaxseed gel; E-PC, psyllium gel; E-SWC, soapwort extract; E-CHC, chia gel. Sensory attribute loadings are provided in Table S1.



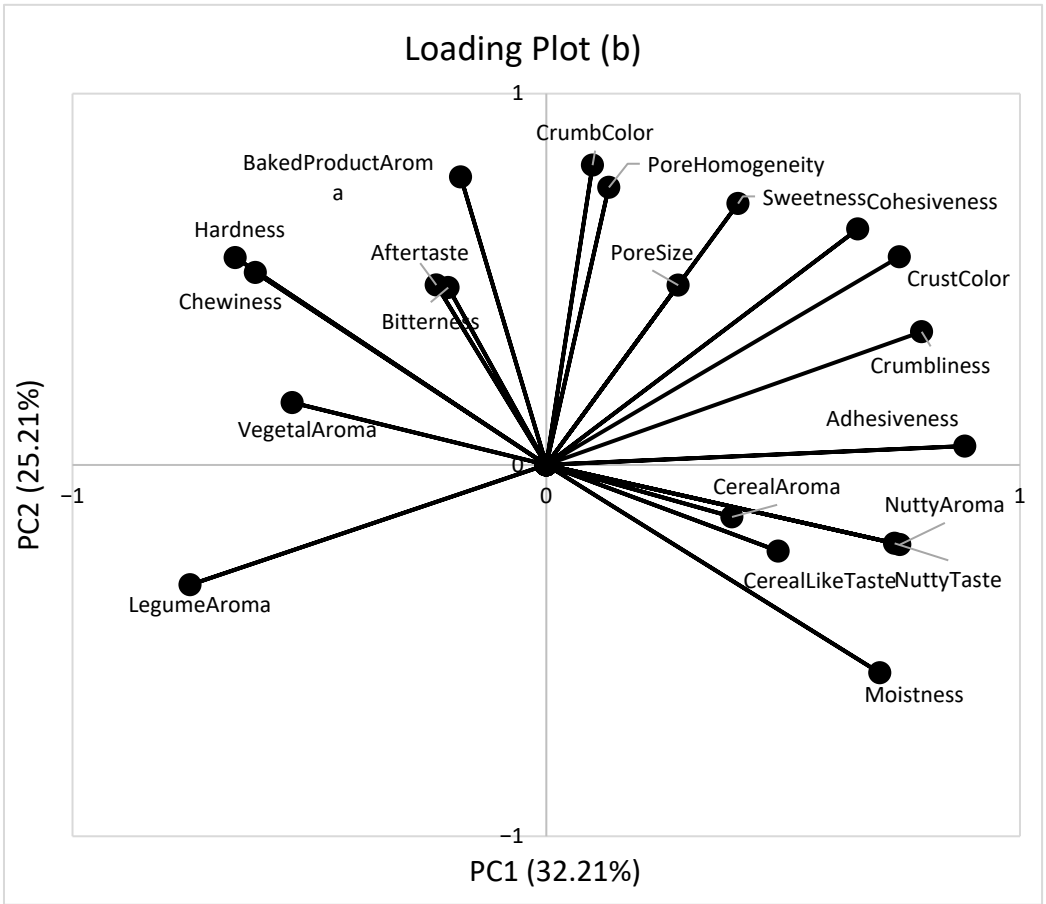


Figure 4. Principal component analysis (PCA) of the milk-replacement muffin series based on formulation mean scores from 12 trained assessors for 20 sensory attributes: (**a**) score plot showing the positions of muffin formulations and (**b**) loading plot showing the relationships between sensory attributes and principal components. PC1 and PC2 explain 32.21% and 25.21% of the total variance,

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respectively (57.42% cumulatively). PCA was performed without rotation. The prefix M- denotes the milk-replacement series. M-CC, conventional control containing whole eggs and cow's milk; M-SC, soy milk; M-HC, hazelnut milk; M-WC, walnut milk; M-QC, quinoa milk; M-FC, flaxseed milk; M-CNC, coconut milk; M-OC, oat milk; M-AC, almond milk. Sensory attribute loadings are provided in Table S2.

3.4.1. Egg-Replacement Muffins

The first two principal components accounted for 76.31% of the total variance in the egg-replacement series, with PC1 and PC2 explaining 43.93% and 32.38%, respectively. In the score plot (Figure 3a), E-CC and E-SWC were clustered together, while E-BC was located in the region of positive PC1 and PC2 scores. The corresponding loading plot (Figure 3b) correlated this region with pore size, pore homogeneity, baked product aroma, banana aroma and sweetness. The patterns were consistent with the individual QDA results, in particular the strong banana aroma and sweetness of E-BC and some sensory similarities between E-CC and E-SWC. However, the similarity of E-CC and E-SWC in the two-dimensional PCA plot does not mean equality in all sensory attributes.

E-PC differentiation was associated with negative loadings on PC1 for cereal aroma, aftertaste, bitterness and adhesiveness, as well as a number of texture attributes (Table S1). Moreover, chewiness and cohesiveness had high positive loadings on PC2. These multivariate patterns were consistent with the high cereal aroma, bitterness, hardness, chewiness, cohesiveness and crumbliness reported for E-PC in Section 3.1. Thus, the unique position in the PCA score plot was due to a combination of sensory characteristics rather than a single dominant descriptor.

3.4.2. Milk-Replacement Muffins

In the milk replacer series, PC1 and PC2 explained 32.21% and 25.21% of the total variance, respectively, and together accounted for 57.42% (Table S2). The first two components accounted for a smaller proportion of the total sensory variation than in the egg-replacement series. As such, the sample distributions in Figure 4a should be interpreted as a two-dimensional summary of the multivariate sensory profiles rather than a complete picture of differences between formulations.

M-HC, M-AC and M-OC are located in the lower right region with positive PC1 scores in the PCA score plot (Figure 4a). The loading plot (Figure 4b) showed that positive PC1 was associated with nutty aroma, nutty taste, moistness, adhesiveness and crumbliness. M-HC and M-AC were located together due to their relatively strong nutty sensory properties. M-OC was characterized by high perceived moistness and adhesiveness and low hardness. Despite these formulations being similar in the PCA plot, their individual QDA profiles differed, especially for cereal-associated aroma and flavor attributes. Thus, the proximity of the two indicates resemblance on some sensory dimensions, not the precise sensory characteristics.

In the PCA score plot (Figure 4a), M-SC and M-FC were placed on the negative side of PC1. The negative loading of legume aroma on PC1 (−0.752) was in agreement with the strong intensity of the legume aroma of M-SC. M-FC and M-SC were on the same side of the first principal component, but their sensory profiles were different, especially in terms of bitterness intensity. However, bitterness had a low negative loading on PC1 (−0.207), meaning that this attribute alone cannot explain the position of M-FC. Hence, the distribution of these formulations was according to their combined sensory characteristics and not a common dominant attribute of aroma or taste.

M-CC, M-QC, M-WC and M-CNC were found in the upper region of the PCA score plot (Figure 4a) corresponding to positive PC2 scores. (Figure 4b) The loading plot showed that positive PC2 was related to crumb color, baked product aroma, pore homogeneity,

sweetness and some texture attributes. These associations were generally consistent with the QDA results, although the formulations differed on several individual descriptors. M-QC was rated the hardest, and M-WC was notable for a strong nutty aroma and flavor. Thus, the clustering of these samples in the same region of the PCA plot indicated similarities between selected sensory attribute combinations, rather than similarities in the overall sensory profiles.

The PCA results gave an overall multivariate perspective on the sensory differences among the milk-replacement formulations and complemented the individual QDA results. However, the first two principal components accounted for 57.42% of the total variance, indicating that a large amount of sensory variation was captured by the subsequent components. PC3 accounted for a further 13.22% of the total variance, resulting in a cumulative explained variance of 70.64% for the first three principal components (Table S2). PC3 had the largest positive loadings for cereal aroma (0.749) and cereal-like taste (0.702) in particular, suggesting that variation in these cereal-associated attributes was also explained outside of the PC1–PC2 plane. Thus, the two-dimensional PCA plots should be considered together with the supplementary component loadings and the individual QDA results to give a more complete picture of formulation-dependent differences in sensory perception.

Given the limited number of formulations relative to the number of sensory attributes, the PCA results were interpreted as exploratory patterns of sensory differentiation. The small number of formulations limits conclusions about the stability and generalizability of the observed patterns. Accordingly, the PCA plots were interpreted alongside the individual QDA results and the sensory attribute loadings.

3.5. Hierarchical Cluster Analysis (HCA)

Hierarchical cluster analysis (HCA) was performed separately for the egg and milk replacement formulations to explore similarities in their quantitative descriptive sensory profiles. Clustering was performed using Ward's linkage method and squared Euclidean distance as described in Section 2.4. The resulting dendrograms for the egg and milk-replacement formulations are presented in Figures 5 and 6, respectively.

In the egg replacer series, E-CC and E-SWC were grouped closest to each other, suggesting that they were similar in their combined sensory profiles (Figure 5). This grouping was consistent with their proximity in the PCA score plot (Figure 3a) and with the QDA results showing similarities in a number of appearance, aroma, taste and texture attributes. Later, E-CHC and E-BC were also added to this cluster at larger linkage distances. E-BC was defined by high banana aroma and sweetness, and its clustering with this group reflected similarities across other sensory descriptors including pore homogeneity and baked-product aroma. Thus, the cluster structure represented multivariate sensory relationships, rather than equivalence in individual attribute intensities.

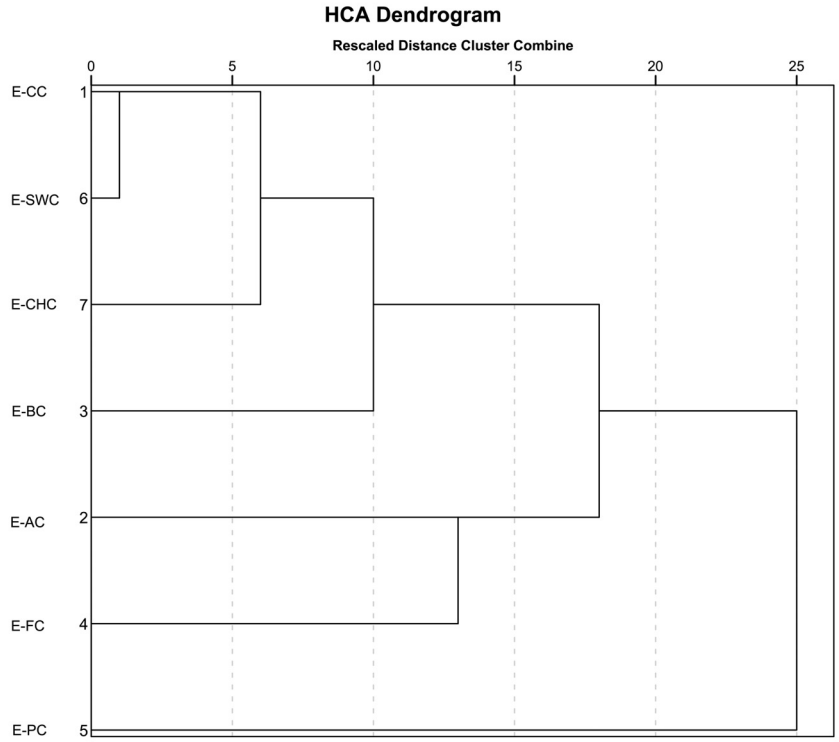


Figure 5. Hierarchical cluster analysis (HCA) dendrogram of the egg-replacement muffin series based on formulation mean scores from 12 trained assessors for 18 sensory attributes. Attribute means were Z-score standardized, and clustering was performed using Ward's linkage method and squared Euclidean distance. Clusters represent similarities in overall sensory profiles and do not imply equivalence in every individual sensory attribute. The prefix E- denotes the egg-replacement series. E-CC, conventional control containing whole eggs and cow's milk; E-AC, aquafaba; E-BC, banana purée; E-FC, flaxseed gel; E-PC, psyllium gel; E-SWC, soapwort extract; E-CHC, chia gel.

E-AC and E-FC formed a separate cluster despite the differences in characteristic aroma and taste attributes. Their association suggested similarity in their combined sensory profiles, although the QDA results showed that they were not the same in individual descriptors. E-PC was the most distinct formulation in the dendrogram, consistent with its position in the PCA score plot (Figure 3a). This separation was also in agreement with the pronounced cereal aroma, bitterness, hardness, chewiness, cohesiveness and crumbliness identified for E-PC in the descriptive sensory analysis. These results supported the unique multivariate sensory profile of the psyllium-based formulation.

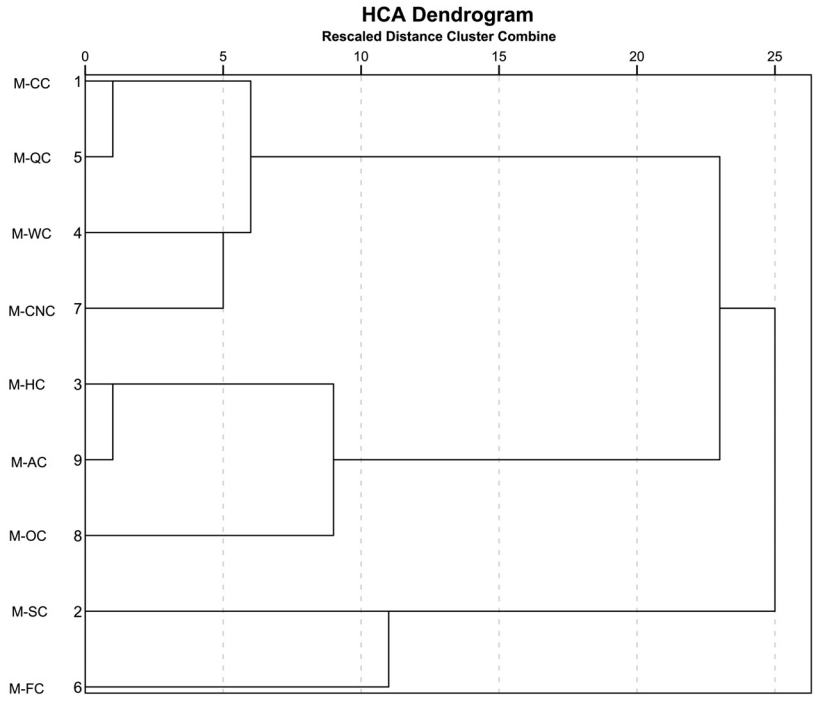


Figure 6. Hierarchical cluster analysis (HCA) dendrogram of the milk-replacement muffin series based on formulation mean scores from 12 trained assessors for 20 sensory attributes. Attribute means were Z-score standardized, and clustering was performed using Ward's linkage method and squared Euclidean distance. Clusters represent similarities in overall sensory profiles and do not imply equivalence in every individual sensory attribute. The prefix M- denotes the milk-replacement series. M-CC, conventional control containing whole eggs and cow's milk; M-SC, soy milk; M-HC, hazelnut milk; M-WC, walnut milk; M-QC, quinoa milk; M-FC, flaxseed milk; M-CNC, coconut milk; M-OC, oat milk; M-AC, almond milk.

In the milk-replacement series, M-CC and M-QC were grouped closest, followed by M-WC and M-CNC at higher linkage distances (Figure 6). This clustering was generally consistent with the location of these formulations in the upper part of the PCA score plot (Figure 4a). M-CC and M-QC were comparable for selected appearance and aroma attributes such as crust color, pore homogeneity, and baked product aroma. However, M-QC was perceived to be harder than M-CC, indicating that their clustering did not imply similarity in all texture attributes. The later grouping of M-WC and M-CNC with this group was in accordance with similarities in their combined sensory profiles, although differences in characteristic aroma and flavor intensities were observed.

M-HC and M-AC also formed a closely associated pair, to which M-OC later joined (Figure 6). The association of M-HC with M-AC was in line with the relatively strong nutty aroma and flavor. M-OC was characterized by its typical cereal aroma and cereal-like taste, with high perceived moistness and relatively low hardness. Thus, the presence of M-OC in this cluster indicated similarities across the combined sensory attributes, rather than a shared dominant flavor profile. The clustering generally followed the PCA score plot (Figure 4a), with M-HC, M-AC and M-OC being in the same general area.

M-SC and M-FC formed a separate cluster in the milk-replacement dendrogram (Figure 6). The M-SC was characterized by a strong aroma of legumes and the M-FC by a high intensity of bitterness, but both formulations showed relatively low sweetness and homogeneity of pores. These shared characteristics may have led to their grouping, although their individual aroma and taste profiles vary. Their clustering was also

generally consistent with their positions on the negative side of PC1 in the PCA score plot (Figure 4a). However, this correspondence should be interpreted as similarity in multivariate sensory patterns and not as evidence for identical sensory characteristics.

In general, the HCA results were in broad agreement with the sensory patterns visualized by PCA. In the egg-replacement series, both PCA and HCA highlighted the close association between E-CC and E-SWC and the distinct sensory position of E-PC. In addition, the clustering of M-HC, M-AC and M-OC was mirrored in the PCA score plot in the milk-replacement series. However, substantial differences in individual QDA attributes were still observed within several clusters. Thus, HCA was used to complement PCA in describing the relations between the formulations based on the combined sensory characteristics, without implying equivalence in a particular appearance, aroma, taste or texture attribute.

4. Conclusions

Quantitative descriptive analysis (QDA) highlighted formulation-dependent differences in sensory profiles of muffins with plant-based egg and milk alternatives, providing attribute-specific information complementing previously reported hedonic and instrumental evaluations. The banana muffins had strong banana and baked-product aromas, sweetness, and distinctive appearance characteristics and stood out among the egg-replacement formulations. Perceived hardness and chewiness of aquafaba muffins were relatively low and moistness high, but the muffins were characterized by legume-related aroma and flavor notes. The psyllium muffins had the highest intensities of perceived hardness, chewiness, bitterness and aftertaste. The soapwort muffins had similar sensory characteristics to the control in some appearance, aroma and taste attributes. The current QDA results provide attribute-level sensory information that adds to the hedonic evaluations reported earlier [1]. Comparisons with those earlier findings were descriptive, as no joint analysis of hedonic ratings and QDA data was carried out.

Sensory attributes of the milk-replacement formulations were also different. Oat milk muffins had a strong cereal aroma and cereal-like taste, high perceived moistness and low chewiness. Muffins made with hazelnut milk had the highest intensities of nutty aroma and flavor, and those made with soy milk were characterized by strong legume aroma. Quinoa milk muffins were the hardest in perceived hardness. Such differences were observed even with relatively low variability in some appearance attributes, in particular pore size. The results suggest that the choice of plant-based milk alternatives was associated with differences in the aroma, flavor and texture profiles of the assessed muffins.

Pearson correlation analysis revealed correlations between sensory descriptors, while PCA and HCA provided complementary perspectives on similarities and differences among formulations. Both multivariate analyses indicated the close association of control and soapwort muffins and the distinct sensory position of psyllium muffins in the egg-replacement series. The muffins of the milk-replacement series, based on hazelnut, almond, and oat milk, had similar overall sensory profiles, although they differed in some characteristic aroma and flavor attributes. These findings highlight the importance of interpreting multivariate patterns alongside individual QDA measurements, as cluster membership does not imply similarity across all sensory attributes.

The QDA profiles can guide ingredient selection for the development of commercial vegan muffins according to the intended sensory target. Within the egg-replacement series, the favorable hedonic ratings previously reported for banana-based muffins [1], considered alongside their distinctive banana aroma and pronounced sweetness observed here, suggest their potential for banana-flavored vegan product development. This comparison is descriptive and does not establish these attributes as drivers of consumer liking.

Aquafaba may be considered for a relatively low-hardness, moist profile, although its legume-related aroma and taste notes may require attention. The pronounced hardness, chewiness, bitterness, and aftertaste of the psyllium formulation identify attributes to monitor when optimizing its inclusion level and hydration conditions. Within the milk-replacement series, oat milk may suit a cereal-associated profile with high perceived moistness and low chewiness, whereas hazelnut milk may suit products targeting pronounced nutty notes. These findings identify priorities for formulation trials. Changes to ingredient levels, ingredient combinations, and processing conditions require further testing, followed by consumer acceptance studies before commercial adoption.

The QDA results reported here complement the hedonic and instrumental findings in our previous studies [1,2]. Comparisons between these studies are descriptive, and no joint analysis of hedonic ratings and QDA data or rank-correlation or agreement analysis between instrumental and perceived hardness was performed. The findings describe sensory attribute intensities perceived by a trained descriptive panel and do not directly establish consumer preference or overall market acceptability. Higher intensity of a sensory attribute should not be interpreted as greater consumer liking. Future research could explore the associations between QDA profiles and consumer liking with larger and more diverse consumer panels. The combination of descriptive sensory analysis, volatile compound profiling and instrumental texture measurements may also contribute to clarifying factors related to characteristic aroma, flavor and texture perceptions. Further investigation into combinations of plant-based egg and milk alternatives could lead to targeted modification of sensory characteristics. Taken together, these results provide a descriptive sensory basis for the selection and optimization of plant-based ingredients for use in muffin formulations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/foods15234311/s1, Table S1. Eigenvalues, explained variance, cumulative explained variance, and sensory attribute loadings for the principal components obtained from PCA of egg-replacement muffin formulations. Table S2. Eigenvalues, explained variance, cumulative explained variance, and sensory attribute loadings for the principal components obtained from PCA of milk-replacement muffin formulations.

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Institutional Review Board Statement: Ethical approval for the sensory analysis was obtained from Maltepe University on 28 November 2024 (Approval No: 2024/22−09).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Each participant received an information sheet detailing the study's purpose, procedures, potential risks, and their rights, and written informed consent was obtained from all participants.

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

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

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