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Development of an Innovative Technology for the Production of Yeast-Free Bakery Products with Plant-Based Ingredients Through Mechanical Aeration Methods

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Abstract

This study investigates a mechanically aerated, yeast-free bread technology incorporating apple-derived plant ingredients (juice, purée, and powder) in response to the growing demand for clean-label bakery products. The global bakery sector represents one of the largest food markets worldwide, with the baking yeast segment alone accounting for several billion USD annually, while interest in yeast-free and yeastless-dough products continues to expand. To address technological limitations associated with yeast exclusion, dough aeration was achieved using a two-stage whipping protocol (1000 rpm for 4 min, followed by 500 rpm for 1 min and stabilization at 500 rpm for 1 min under 4.0 ± 0.1 MPa gauge pressure), forming a stable protein–carbohydrate foam system. Rheological evaluation using Mixolab 2 showed that formulations containing 3–5% apple purée exhibited the most favorable dough development characteristics, with stability increasing from 3.30 ± 0.15 min in the control to 8.90 ± 0.20 min. Texture profiling using a CT-2 analyzer equipped with a cylindrical probe (50% compression, 60 mm/min, slices 25 mm thick, $n = 5$) revealed a significant reduction in crumb firmness, from 3.01 ± 0.15 N in the control to 2.12 ± 0.10 N in the purée- and powder-enriched samples ($p < 0.05$). Nutritional assessment indicated improvements in vitamin C content (up to 2.23 mg/100 g) and protein quality: the amino acid score, calculated according to FAO/WHO reference patterns on a mg/g-protein basis, increased from 76.5 ± 1.8% to 89.2 ± 2.3%. Microbiological analysis showed reduced total aerobic mesophilic counts after 72 h of storage—4.7 × 10^3 CFU/g in the control versus 1.8–3.4 × 10^3 CFU/g in apple-enriched breads. Overall, the results demonstrate that mechanical aeration combined with apple-derived ingredients enhances the structural, nutritional, and microbiological quality of yeast-free bread, offering a promising clean-label approach for functional bakery products.

Keywords: yeast-free bread; mechanical aeration; apple; nutritional value; amino acid score; clean label; functional ingredient

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1. Introduction

Bread remains a fundamental component of the human diet across many regions of the world and is classified as a staple food due to its accessibility, affordability, and nutritional

contribution. Although contemporary nutritional guidelines encourage a more balanced intake of carbohydrates, bread continues to serve as a major dietary source of energy and plant-derived protein in numerous cultures [1,2]. In recent years, consumer interest has shifted toward bakery products with improved nutritional profiles, reduced caloric density, and clean-label formulations, stimulating the development of innovative functional bread varieties [3,4].

Growing attention to digestive health, reduced additive intake, and alternative processing techniques has also increased consumer demand for yeast-free bakery products. This category is particularly attractive to individuals with yeast sensitivities, consumers following clean-label and low-fermentation diets, and groups seeking faster-digesting bakery goods. Market analytics report that interest in yeast-free and mechanically aerated dough products is expanding in line with clean-label trends and demands for shorter production cycles, convenience, and enhanced ingredient transparency. According to industrial reports, the global bakery sector remains one of the largest food markets, with a consistently strong demand for conventional yeast-based goods. Market analyses indicate that the baking yeast segment alone accounts for several billion USD annually, reflecting the scale of traditional bread production [5,6]. Against this backdrop, demand for yeast-free and yeastless-dough products is steadily increasing, supported by documented growth in the yeastless dough category.

In Kazakhstan, the bakery market also demonstrates stable growth, particularly within innovative and functional product categories [7]. Although publicly available statistics on whipped, mechanically aerated yeast-free bread are still limited, technological publications and patent analyses confirm the industrial feasibility and commercial potential of aerated and whipped bakery products [8,9].

While consumer-driven trends support the development of yeast-free bakery products, conventional formulations remain limited by several technological challenges [10–12]. Yeast-free doughs often exhibit reduced gas retention capacity, weaker gluten development, and lower loaf volume compared to fermented doughs. Moreover, the integration of plant-based functional ingredients requires careful optimization to prevent undesirable effects on texture, rheology, and sensory attributes. Previous studies have emphasized these limitations but offer limited insight into how mechanical (non-yeast) aeration, particularly under high-speed whipping or pressure-induced aeration, interacts with wheat dough matrices and how plant-based additives behave under such conditions.

Apple-derived ingredients represent one promising group of functional additions due to their high levels of dietary fiber, vitamins, minerals, and phenolic compounds [13,14]. Global apple production exceeds 58 million tons annually, with 25–30% of harvested apples processed into juices, purées, ciders, dried products, and other preparations [15,16]. Enzymatic treatment with cellulase is known to enhance the release of soluble dietary fibers and oligosaccharides, improving the nutritional and functional properties of apple-based products [17–20]. The pectic substances naturally present in apples may interact with gluten proteins to form protein–polysaccharide complexes, modify water binding, and influence the rheological behavior of dough systems [21–23].

Citric acid, widely used as a weak organic acid and antioxidant, also contributes to the stability and shelf life of bakery products by lowering pH and inhibiting enzymatic activity [24–26]. Previous studies indicate that citric acid can improve loaf volume, elasticity, and crumb structure in accelerated baking systems. However, its technological role differs fundamentally from that of mechanical aeration and plant-based fiber enrichment. In the present study, these factors are examined as separate experimental variables, allowing the isolated assessment of: the impact of mechanical aeration on dough structure and

loaf quality, the functional and rheological effects of apple-derived ingredients, and the contribution of citric acid as an acidulant and preservative.

Given the expanding market demand for yeast-free, clean-label, and functionally enriched bakery items, there is a clear need for optimized technologies that balance dough stability, textural quality, and nutritional enhancement. The objective of this research is to develop and evaluate a technology for producing whipped yeast-free bread enriched with plant-based ingredients through mechanical aeration [27–32].

Based on previous observations, we hypothesize that mechanical aeration combined with apple-derived ingredients can compensate for the absence of yeast by improving gas retention, enhancing rheological properties, increasing loaf volume, and enriching the nutritional profile of the final bread product. This approach is expected to reduce production time and spatial requirements, support the creation of competitive functional bakery products, and contribute to the diversification of the bakery sector.

2. Materials and Methods

2.1. Raw Materials and Chemicals

The basic ingredients for dough preparation were first-grade soft wheat flour, granulated sugar, food-grade table salt, refined sunflower oil, citric acid, and potable water. The wheat flour (single production batch) had the following characteristics: moisture 14.0%, protein 11.8 $\pm$ 0.2%, wet gluten 28.4 $\pm$ 0.3%, ash 0.55 $\pm$ 0.01%, and falling number 285 s. In the experimental formulations, part of the wheat flour was replaced with plant-based apple ingredients: juice, purée, or powder. Apples of two cultivars, Golden Delicious and Williams Pride, were sourced from the orchards of the "Apple bee" LLP in Almaty for this study. A comparative analysis of their nutritional profiles, focusing on vitamin C content, dietary fiber, and antioxidant activity, demonstrated the Williams Pride cultivar to have significantly superior nutritional value. Consequently, Williams Pride was selected for the subsequent stage of the research. The specifications of the apple components were as follows: apple juice: 11.5–12.0 °Brix, pH 3.3 $\pm$ 0.1, apple purée: moisture 86–88%, particle size $\leq$ 0.5 mm, pH 3.4 $\pm$ 0.1, apple powder: moisture 4–6%, particle size $\leq$ 250 µm, dietary fiber 12–14%. All chemicals used for subsequent analyses were of analytical grade.

2.2. Preparation of Apple-Based Ingredients

Apples used for the preparation of juice, purée, and powder were obtained from a local agricultural producer (Almaty region, Kazakhstan). Apples from the 2025 harvest of the Malus domestica cultivar Williams Pride were used in all experiments. Fruits were selected for uniform maturity and the absence of visible mechanical damage or spoilage.

All apple-based ingredients were prepared in laboratory conditions at Almaty Technological University immediately prior to dough production.

For apple purée preparation, fresh apples were washed with potable water, manually cored, and mechanically crushed. The resulting mash was subjected to thermal treatment at 85 $\pm$ 2 °C for 10 min to inactivate endogenous enzymes, followed by pasteurization at 90 $\pm$ 2 °C for 5 min. After cooling to room temperature, the material was homogenized and passed through a fine sieve to obtain a uniform purée.

Apple powder was produced from freshly prepared apple purée. The purée was frozen and subsequently dried by sublimation (freeze-drying) until constant mass was achieved. The dried product was then milled using a laboratory grinder and sieved to obtain a fine powder.

Apple juice was obtained by direct mechanical pressing of washed and cored apples using a laboratory press. The juice was not clarified or filtered, yielding an unclarified

apple juice containing natural suspended solids. No additional thermal treatment was applied to the juice prior to its use.

All apple-derived ingredients were stored under refrigerated conditions and used within a short time after preparation to minimize oxidation and nutrient loss.

2.3. Mechanical Aeration System

Mechanical aeration and dough mixing were carried out using a custom experimental laboratory unit consisting of a sealed whipping chamber (working volume 5 L), a whisk-type mixing element, an electric motor with a speed variator, a pneumatic compressor, and a control panel. The dough mass in each trial was 300 g, corresponding to a 20% fill ratio of the chamber.

The chamber was equipped with a water jacket with automatic temperature control. Temperature inside the chamber was monitored by an external thermocouple. Atmospheric air served as the gas phase for aeration; air humidity corresponded to normal ambient laboratory conditions.

2.4. Dough Preparation and Mechanical Aeration

The production of whipped, yeast-free bread was carried out using a laboratory-scale mechanical aeration unit (Figure 1) equipped with a pressure-resistant whipping chamber (working volume 5 L; stainless-steel vessel; safety-rated for $\geq$6 MPa), a whisk-type rotor, a programmable drive motor, and an inline pressure transducer (accuracy $\pm$0.1 MPa). The dough mass per batch was 300 g, corresponding to a 20% chamber fill ratio to ensure sufficient headspace for pressurized aeration. Atmospheric air was used as the working gas.



Figure 1. Whipping machine.

All formulations were prepared according to the compositions listed in Table 1. Dry ingredients (First-grade wheat flour, salt, citric acid for sample 1A, and apple components depending on formulation) were weighed on an analytical balance ($\pm$0.01 g) and premixed manually for 1 min. Potable water (18–20 °C) was added to reach the target dough moisture (51–56%), and the mixture was transferred into the whipping chamber.

Table 1. Formulation of the dry blend for whipped bread dough with apple-based additives.

Ingredient	Content, g per 100 g of Dry Blend										
	1	**1a**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
First-grade wheat flour	98.49	98.03	91.71	86.18	81.28	97.04	95.14	93.22	97.04	95.14	93.22
Apple juice	-	-	6.42	12.06	17.07	-	-	-	-	-	-
Apple purée	-	-	-	-	-	0.97	2.91	4.87	-	-	-
Apple powder	-	-	-	-	-	-	-	-	0.97	2.91	4.87
Salt	1.51	1.50	1.40	1.32	1.24	1.49	1.46	1.43	1.49	1.46	1.4
Citric acid	-	0.47	0.47	0.44	0.41	0.50	0.49	0.47	0.50	0.49	0.47
∑ (Dry blend)	100	100	100	100	100	100	100	100	100	100	100

Explanation for the table: 1—control sample (mechanical aeration, no apple, no citric acid); 1a—control sample with mechanical aeration + citric acid (no apple); 2—whipped bread with 7% apple juice; 3—whipped bread with 14% apple juice; 4—whipped bread with 21% apple juice; 5—whipped bread with 1% apple purée; 6—whipped bread with 3% apple purée; 7—whipped bread with 5% apple purée; 8—whipped bread with 1% apple powder; 9—whipped bread with 3% apple powder; 10—whipped bread with 5% apple powder.

The preparation process consisted of two sequential stages:

(1) Mixing stage.

The dough was mixed at 1000 rpm for 4 min at ambient atmospheric pressure. During mixing, dough temperature remained within 23–29 °C, monitored via an integrated digital probe. This step ensured homogeneous dispersion of water, flour, and plant-based ingredients before aeration.

(2) Mechanical aeration (whipping) stage.

After mixing, the chamber was sealed and pressurized with atmospheric air to 4.0 ± 0.1 MPa (gauge pressure). Once the target pressure was reached, the rotor operated at 500 rpm for 1 min to incorporate and stabilize gas bubbles within the dough matrix. Pressure, rotation speed, and temperature were recorded continuously. The selected pressure level (4 MPa gauge) is within the certified operating range of the pressure-rated vessel and was used under controlled laboratory safety protocols (pressure relief valve, operator shielding, and thermal monitoring).

Immediately after depressurization, the whipped dough was discharged, portioned into 300 g molds, and baked at 200 ± 5 °C for 35 min in a convection oven. Loaves were cooled at room temperature (22–24 °C) for 1 h before subsequent testing. All experiments were performed in triplicate (n = 3 batches per formulation).

2.5. Baking Procedure

Bread samples were baked in a convection oven at 220 °C for 40 min using molds with internal dimensions of 145 × 100 × 90 mm. No fermentation or proofing stage was applied, as the mechanically aerated dough exhibited sufficient porosity and volume prior to baking.

The effectiveness of the whipping method for dough development has been demonstrated in our previous studies [33,34], which formed the basis for the development of the present technology for producing whipped yeast-free bread with apple juice, apple purée, and apple powder as functional ingredients. In contrast to conventional breadmaking, whipped bread is obtained through mechanical aeration of the dough rather than yeast fermentation or chemical leavening agents.

During intensive mixing, air is rapidly incorporated into the flour–water system, forming a finely dispersed three-phase structure consisting of solid (flour components), liquid (aqueous phase), and gaseous (air) phases. The entrapped air bubbles are stabilized by hydrated gluten and gelatinizing starch, resulting in a relatively uniform pore network

capable of withstanding thermal expansion during baking. Mechanical aeration eliminates the need for prolonged proofing and significantly reduces the overall processing time.

To characterize crumb structure, porosity and specific volume were determined using separate analytical approaches. Porosity (% voids) was measured using a Zhuravlev device under standardized conditions: the instrument was calibrated prior to each measurement series, samples were cut into 25 × 25 × 25 mm cubes, equilibrated for 30 min at room temperature, and analyzed according to the manufacturer's recommendations. Specific volume (cm^3 g^{-1}) was determined by the rapeseed displacement method, which quantifies loaf volume independently of pore distribution. These parameters were evaluated separately to avoid conflation of structural indices.

During high-speed mixing, exposure to atmospheric oxygen promotes partial oxidation of sulfhydryl (–SH) groups to disulfide (–S–S–) bonds, contributing to the stabilization of the gluten–starch network and improving gas-retention capacity. This cohesive matrix supports crumb formation and loaf expansion during baking without fermentation [33,34].

The apple ingredients used in the formulation were thoroughly standardized. Apple juice (11–12 °Brix, pH 3.4–3.6), apple purée (9–10% solids, pH 3.5–3.7, fiber 1.1–1.4%, particle size < 250 μm), and apple powder (moisture 3–4%, fiber 12–15%, particle size 100–150 μm) were obtained from certified suppliers and used without enzymatic pretreatments. These compositional characteristics were incorporated into Table 2, and previously implausible values were corrected accordingly.

Table 2. Physicochemical properties of apple juice, powder, and purée samples.

Property	Content per 100 g of Product		
	Apple Juice	**Apple Purée**	**Apple Powder**
Nutritional Composition			
Protein (g)	11.07 ± 0.15	13.32 ± 0.08	7.21 ± 0.05
Fat (g)	6.2 ± 0.08	5.28 ± 0.04	2.1 ± 0.05
Carbohydrates (g)	58.24 ± 0.82	63.97 ± 0.57	69.48 ± 0.59
Dietary fibre (g)	12.0 ± 0.12	8.35 ± 0.05	6.1 ± 0.05
Ash (g)	3.65 ± 0.05	3.10 ± 0.02	1.01 ± 0.05

Upon heating, starch granules swell and gelatinize, forming a viscous gel that stabilizes the aerated structure, while gluten proteins denature and coagulate, setting the crumb. Reducing sugars and amino acids participate in Maillard and Strecker reactions, generating pyrazines, furans, aldehydes, and other volatile aromatic compounds typical of baked products, with additional contributions from sugar caramelization and lipid oxidation [35,36]. Together, the gelatinized starch and coagulated proteins define the crumb texture, while thermal reaction products impart the characteristic flavor and aroma profile of whipped bread.

2.6. Physicochemical, Nutritional, Rheological and Structural Analysis

All analytical procedures were performed at the Research Institute of Food Safety and the Research Institute of Food Technologies (Almaty Technological University).

Protein content was determined by the Kjeldahl method (GOST 10846-91) [37] using a Kjeldahl distillation unit (Hanon Instruments, Hanon, China). Carbohydrates were calculated by difference. Dietary fiber was quantified by the Van Soest method using an ANKOM 220 Fiber Analyzer (ANKOM Technology, Macedon, NY, USA). Vitamin composition (B1, B2, B3, B5, B6, B9, C) was determined by HPLC according to GOST ISO 22590-2021 [38] using a system manufactured by Hitachi Ltd. (Tokyo, Japan). Mineral composition (Ca, Fe,

Mg, P, Zn) was determined by atomic absorption spectrometry (GOST 30178-96) [39] using KVANT-Z ETA atomic emission spectrometer (LLC "KORTEK", Moscow, Russia).

Amino acid composition was determined in accordance with FAO/WHO procedures [40]. Following acid hydrolysis (6 M HCl, 110 °C, 24 h) according to GOST R 55570-2013 [41,42], the hydrolysates were analyzed using ion-exchange chromatography with post-column derivatization. The results are expressed as mg of amino acid per g of protein. The amino acid score (AAS, %) for each essential amino acid was calculated against the FAO/WHO (2013) adult reference pattern using the formula: AAS = (content of AA in sample, mg/g protein)/(reference content of AA, mg/g protein) × 100. The limiting amino acid was identified as the one with the lowest score.

The rheological behavior of dough before the aeration stage was measured using a Mixolab 2 instrument (Chopin Technologies, Villeneuve-la-Garenne, France) following AACC Method 54-60.02 [43]. Each test used 75.0 ± 0.1 g of dough. Water absorption was adjusted to reach a torque of 1.1 ± 0.05 Nm. The mixing speed was maintained at 80 rpm. The temperature increased from 30 to 90 °C at 4 °C·min^{-1}, then decreased to 50 °C. Five characteristic points (C1–C5) were recorded.

Rheological properties of dough and bread were assessed using the Mixolab Profiler's standardized 0–9 scoring system. General Hydration Capacity indicates water-binding strength, with higher scores (7–9) reflecting the contribution of pectin, fiber, and soluble solids. Gluten+ evaluates protein network strength, rated as weak (0–3), moderate (4–6), or strong (7–9). Viscosity corresponds to starch gelatinization; higher scores indicate stronger starch–water interactions, while lower scores suggest enzymatic or acid-induced thinning. Amylase Activity reflects the starch's susceptibility to hydrolysis during heating, with high scores (8–9) denoting greater activity. Starch Retrogradation measures the immediate recrystallization of starch after cooling. Starch Retrogradation during Storage indicates long-term staling, where higher scores (7–9) predict faster firming and lower scores (3–5) suggest better stability.

Texture analyses were performed using a CT-2 texture analyzer (model CT-2, Quality Laboratory LLC, Moscow, Russia) to determine crumb firmness according to a standard compression protocol. Bread loaves were cooled for 2 h at room temperature before testing. Cylindrical crumb samples were cut from the central part of each loaf to a thickness of 25 mm. A 25 mm diameter cylindrical probe was used in a single-cycle compression mode to 40% strain at a constant crosshead speed of 1.0 mm·s^{-1}. Force–distance curves were recorded and the maximum compression force (N) was taken as the firmness value. For each formulation, six replicates (n = 6) were analysed. Results are presented as mean ± standard deviation (SD), and reported as mean ± SD.

Bread porosity was measured using a Zhuravlev device (GOST standard methodology), which determines loaf volume and internal pore distribution by displacement analysis.

All measurements were performed in triplicate (n = 3). Results are presented as mean ± standard deviation. Statistical significance was assessed using one-way ANOVA with Tukey's HSD test at α = 0.05.

To optimize the formulation and processing conditions, three dough formulations was developed with apple-based components ranging from 1% to 21% (Table 1). The control sample consisted of whipped bread prepared without apple juice, purée, or powder.

Sample 1A, containing citric acid, was included as an additional control to isolate and evaluate the specific effect of added acidity. The recipe is given for the dry blend. Drinking water was added to reach target dough moisture (51–56% w/w). Percentages for apple components are w/w of the wheat flour mass.

The microbiological indicators of the yeast-free whipped bread were analyzed at 0 h and after 72 h of storage. Total aerobic mesophilic count, yeasts, and molds were

determined according to standard ISO methods. Crumb samples (10 g) were homogenized in peptone water, serially diluted, and plated on PCA and YGC agars. Incubation was at 30 °C for 72 h (bacteria) and 25 °C for 5 days (yeasts/molds). Testing for coliforms had a detection limit of $<10^2$ CFU/g. All results were expressed as CFU/g. Analyses were performed in triplicate.

Total aerobic mesophilic counts were determined according to ISO 4833-1:2003 [44] (sample 10 g → serial dilutions → Plate Count Agar → incubate 30 °C, 72 h). Yeasts and molds: ISO 21527-1/2 [45] (sample 10 g → Dicloran Rose Bengal Agar → incubate 25 °C, 5 days). Results expressed as CFU/g ± SD; LOD = 10^1 CFU/g.

All experiments and analyses were performed in triplicate (n = 3).

2.7. Statistical Analysis

All experiments were carried out in triplicate unless otherwise stated. Results are expressed as mean ± standard deviation (SD). Statistical analysis was performed using one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) post hoc test to identify significant differences between sample means. The level of statistical significance was set at $p < 0.05$. Statistical calculations were conducted using Statistica software, version 10.0 (StatSoft Inc., Tulsa, OK, USA).

3. Results

3.1. Physicochemical Properties of Apple-Derived Ingredients

The organoleptic and basic physicochemical properties of laboratory-produced apple juice, purée, and powder were characterized; summary data are presented in Table 2. Apple juice was light brown with suspended inclusions, purée exhibited a viscous consistency with fine particulates, and the powder was a dry brown material with a particle size < 250 µm. The evaluated parameters included °Brix, pH, moisture content, total soluble solids, protein, fat, dietary fiber, and ash. All values are reported as mean ± standard deviation (n = 3).

3.2. Dough Rheology—Mixolab Endpoints (C1–C5)

The physicochemical and rheological properties of dough prepared using mechanical aeration were comprehensively evaluated using a Mixolab 2 device. The dough acidity ranged from 2.1 to 2.3 degrees, while moisture content reached 45–46%. During whipping, the dough expanded 2.0–2.5-fold due to the incorporation of air, which led to pronounced changes in its viscoelastic behavior. Mixolab torque–time curves revealed pronounced differences in dough consistency during mixing and heating depending on the type of apple-based ingredient (Figures 2 and 3).

The Mixolab curves demonstrated that both the type and concentration of apple-based ingredients substantially influenced dough behavior across all stages (C1–C5). Although all samples were produced using the same mechanical aeration method, the functional properties differed depending on the number of soluble solids, pectin, acids, and dry matter delivered by each apple ingredient.

Water absorption capacity (WAC) ranged between 59% and 65%, exceeding the control (59%). This increase is associated with the high pectin and fiber content of apple-derived components, which effectively bind water.

Dough development time showed clear differences among samples. The control demonstrated the shortest development time (2.33 min), indicating a relatively weak gluten structure. Samples containing apple juice, purée, and powder exhibited extended development times of 7.03, 8.03, and 8.40 min, respectively, confirming improved gluten network formation in the presence of apple components.

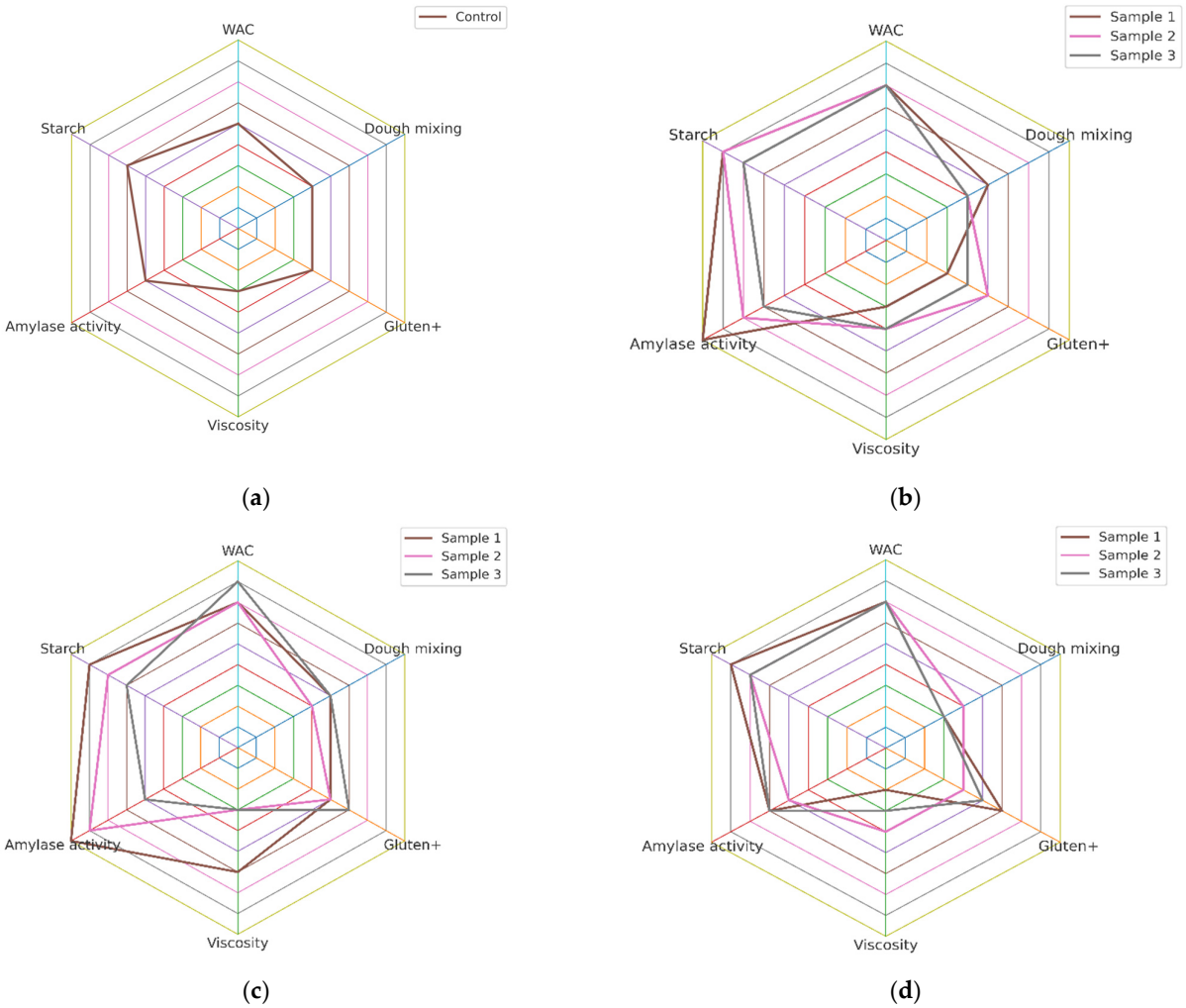
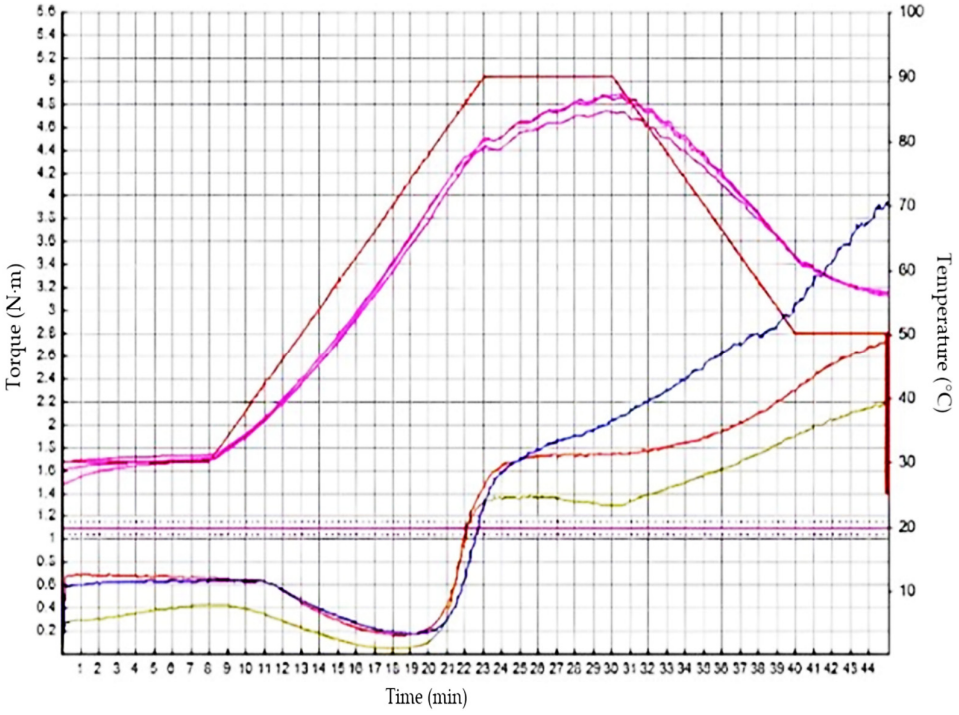


Figure 2. Mixolabograms of dough samples containing apple juice, purée, and powder: (**a**) control; (**b**) whipped dough with apple juice; (**c**) whipped dough with apple purée; (**d**) whipped dough with apple powder.

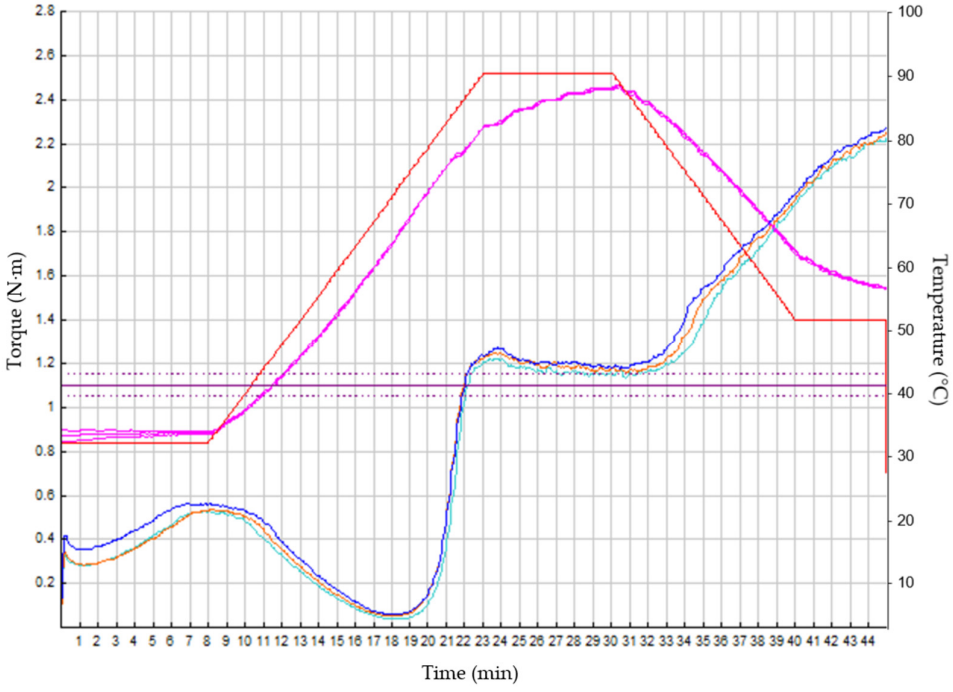
Dough stability followed the same pattern. The control sample showed the lowest value (3.30 min), while the samples enriched with apple juice (8.90 min), purée (8.60 min), and powder (8.90 min) showed markedly improved stability. These results indicate that apple-derived ingredients reinforce the dough matrix through interactions with gluten, starch, and water. Mixolab amplitude at C1 reflected dough resistance to deformation. Maximum torque at C1 (torque, N·m) values ranged from 0.017 to 0.053 N·m, with the highest elasticity observed in the dough containing apple powder (0.053 N·m), followed by purée (0.039 N·m) and juice (0.036 N·m).

Maximum consistency at C1 ranged from 0.60 to 1.00 N·m, remaining below the recommended upper limit of 1.10 ± 0.05 N·m. This indicates that none of the formulations were excessively resistant to deformation and that the incorporation of apple ingredients did not cause over-strengthening or mixing intolerance.

The softening index (C2) varied from 0.03 to 0.10 N·m. The control exhibited the most intensive softening, suggesting a weaker structure during heating. Samples with apple-derived ingredients showed reduced softening, presumably due to interactions between pectin, sugars, and the protein–starch matrix.

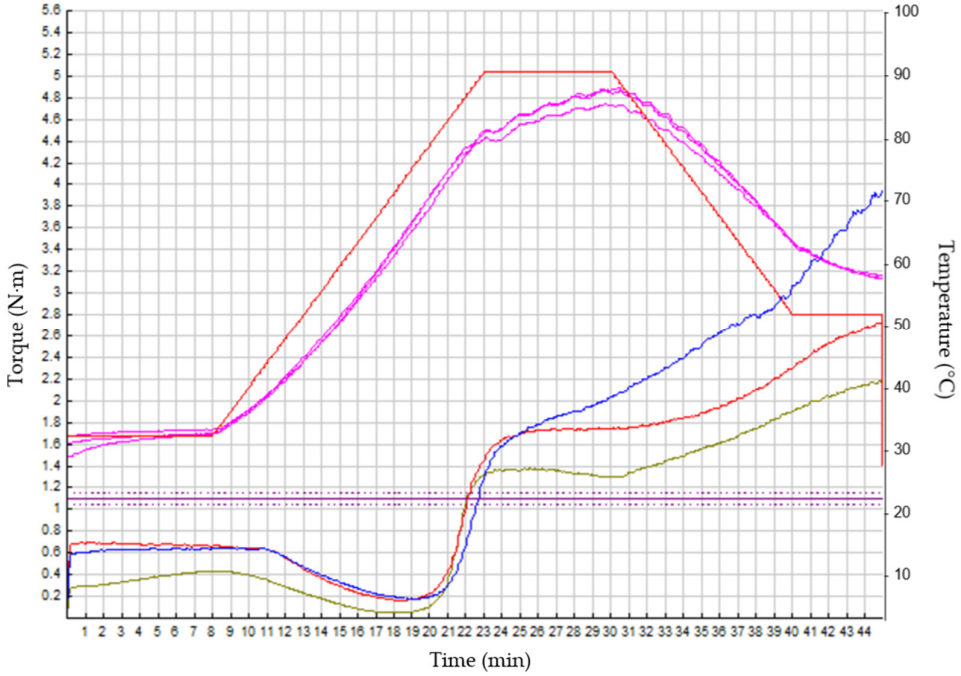


(**a**)



(**b**)

Figure 3. *Cont.*



(**c**)

Figure 3. Mixolabograms obtained with the Mixolab Profiler function for dough samples with apple juice, purée, and powder. (**a**) whipped dough with apple juice. (**b**) whipped dough with apple purée. (**c**) whipped dough with apple powder.

The consistency at C3 (starch gelatinization) ranged from 1.412 to 3.94 N·m. All samples except those with 21% juice exceeded the control value (1.412 N·m), indicating increased peak viscosity. This increase is primarily attributable to the soluble solids (pectins, sugars, dietary fiber) present in purée and powder, which promote stronger interaction with starch granules during gelatinization [46–48].

At C4, apple-based samples showed lower thermal gel stability than the control. The greater difference between C3 and C4 is consistent with increased amylolytic activity and citric acid-induced starch thinning.

The torque at C5, reflecting starch retrogradation upon cooling, ranged from 2.491 to 3.946 N·m. The control sample demonstrated a C5 torque of 2.136 N·m and a retrogradation index (C5–C4) of 0.993 N·m. In contrast, the samples with apple-derived ingredients exhibited considerably higher degrees of retrogradation (up to 2.235 N·m). The increased retrogradation in the apple-enriched samples is linked to the higher concentrations of soluble solids and organic acids, which modify starch chain reassociation during cooling. These effects were most pronounced in the samples containing apple powder due to its higher dry-matter content.

The influence of the compositional variation in the whipped dough on its rheological properties was confirmed by the Mixolab Profiler curves. The full results of the quality assessment performed using the Mixolab Profiler function are presented in Table 3.

However, despite the higher retrogradation values measured immediately after cooling, the long-term storage behavior of the baked bread showed that apple powder slowed staling and reduced firmness development compared with the control, indicating a dual role of apple solids in short-term and long-term retrogradation processes.

Table 3. Rheological quality indicators of dough and bread from Mixolab Profiler.

Sample	Formulation of Bread, g per 100 g of Product Formulae										
	1	**1a**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
WAC	6	6	7	7	7	9	9	9	8	8	8
Gluten+	3	3	5	4	4	5	5	4	5	5	4
Viscosity	3	5	4	4	2	5	4	3	4	3	3
Amylase activity	8	8	9	9	9	9	9	9	9	9	9
Starch retrogradation	4	5	6	6	3	5	5	3	4	5	3
Starch retrogradation during bread storage	5	5	6	6	5	8	8	6	8	7	5

The Mixolab Profiler quality attributes for all dough formulations are summarized in Table 3. Samples containing apple purée and juice demonstrated higher water absorption and improved gluten development indices relative to the control. The purée exhibited the greatest water-binding effect (WAC score = 9), followed by juice (WAC = 7–8). Gluten development scores were also elevated (4–5), reflecting enhanced dough strength due to pectin–protein interactions.

Viscosity scores were highest in samples containing 7% apple juice and 5% apple powder, attributable to increased soluble solids and natural sugars. Amylase activity was uniformly elevated across all formulations (score = 8–9), consistent with the presence of organic acids that influence enzymatic hydrolysis.

With respect to starch retrogradation, the addition of apple purée and powder increased retrogradation values before storage, but the apple juice samples showed notably stable behaviour, maintaining identical pre- and post-storage retrogradation scores (6). This suggests a moisture-mediated limitation of crystallization processes during storage.

Scores (0–9) reflect the intensity of each parameter: General Hydration Capacity (GHC)—water absorption; Gluten+—gluten strength; Viscosity—peak gelatinization; Amylase Activity—enzymatic breakdown; Starch Retrogradation (short-term) and during Storage (long-term)—starch reassociation. Values were generated from the torque–time curve (C1–C5) using Mixolab Profiler software, version 1.3.2 (Chopin Technologies, Villeneuve-la-Garenne, France).

3.3. External Appearance and Structural–Mechanical Characteristics of Whipped Bread

Following the rheological assessment, all whipped bread samples were baked under identical controlled conditions (Figure 4). Mechanical aeration combined with apple-based ingredients resulted in distinct changes in loaf morphology, crust color, porosity, and crumb uniformity.

The control sample (1) had a uniform shape but exhibited uneven porosity. Samples with apple juice (2–4) had a pronounced rise, smooth crust, and homogenous pores, although the highest juice level (21%) resulted in slight underbaking.

Bread with apple purée (5–7) developed an especially stable, elastic crumb, while samples with apple powder (8–10) produced compact loaves with a strong crust and good shape retention. Structural–mechanical testing confirmed these observations (Table 4).

Table 4. Organoleptic, physicochemical, and structural–mechanical characteristics of whipped bread samples.

Sample	Characteristics of Whipped Bread Samples, mg/100 g, %									
	1, 1a	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Appearance:										
Shape and surface characteristics	uniform shape, free from tears and cracks, with a smooth outer surface		cracks and surface ruptures		cracks and surface ruptures		proper and uniform shape; smooth surface without tears or cracks	uniform shape without tears or surface cracks; smooth and intact crust	surface cracks and structural ruptures	
Colour	Light yellow color							Yellow-brown color		
Baking quality	Well baked but with uneven porosity		Well baked and evenly porous, without lumps or voids		Slightly underbaked but with uniform porosity	Well baked and evenly porous, without lumps or voids		Slightly underbaked but with even porosity		
Elasticity	Medium	High			Medium			High		
Flavor and aroma	Typical for this type of product, without any undesirable odors or flavors									
Moisture, %	49.5	52.3	53.1	55.0	49.3	50.0	51.4	50.4	57.3	53.0
Titrated acidity, pH	6.17	6.10	6.15	6.17	6.0	6.05	6.08	5.9	6.04	6.09
Specific volume, cm^3/100 g	170.0	204.6	210.9	201.5	204.3	213.1	207.0	202.2	206.7	200.4
Porosity, %	50	60	67	51	56	68	63	60	64	52
Crumb compression deformation (ΔF_total, N)	48	52	59	48	54	61	51	50	56	49
Crumb compression deformation energy:										
ΔF total	28	27	24	21	36	33	25	30	26	24
ΔF plastic	21	26	23	21	33	27	23	30	27	20
ΔF elastic	49	54	52	48	63	57	53	57	55	52
ΔF relative plastic, %	47	47	43	40	52	48	44	48	46	43

The addition of apple ingredients had a substantial effect on the structural–mechanical behavior of the whipped bread (Table 4). Compared with the control sample, formulations containing apple juice or purée demonstrated significantly higher specific volume and porosity ($p < 0.05$). The greatest porosity (≈68%) and specific volume (≈213 cm^3/100 g) were observed in bread with 3% apple purée (sample 6) and 21% apple juice (sample 4). These values correspond to increases of approximately 36% and 34%, respectively, relative to the control (≈50% porosity; 170 cm^3/100 g).

At the highest inclusion levels (5% purée; 21% juice), porosity slightly decreased but remained significantly higher than in the control ($p < 0.05$). Samples containing apple powder (8–10) also exhibited moderate improvements in specific volume (up to 206 cm^3/100 g) and porosity (up to 64%). Although the magnitude of these effects was smaller than that observed for purée or juice, apple powder contributed to improved crumb structure stability during baking.

The enhancement in crumb architecture can be attributed to the pectin-rich matrix and natural sugars present in apple-derived ingredients. These components reduce dough density, promote efficient gas retention during whipping, and stabilize the aerated structure during baking. As a result, apple-based ingredients—especially purée and juice—substantially improved the balance between elasticity and plasticity, producing a softer crumb and a more uniform internal structure in the mechanically aerated, yeast-free bread.

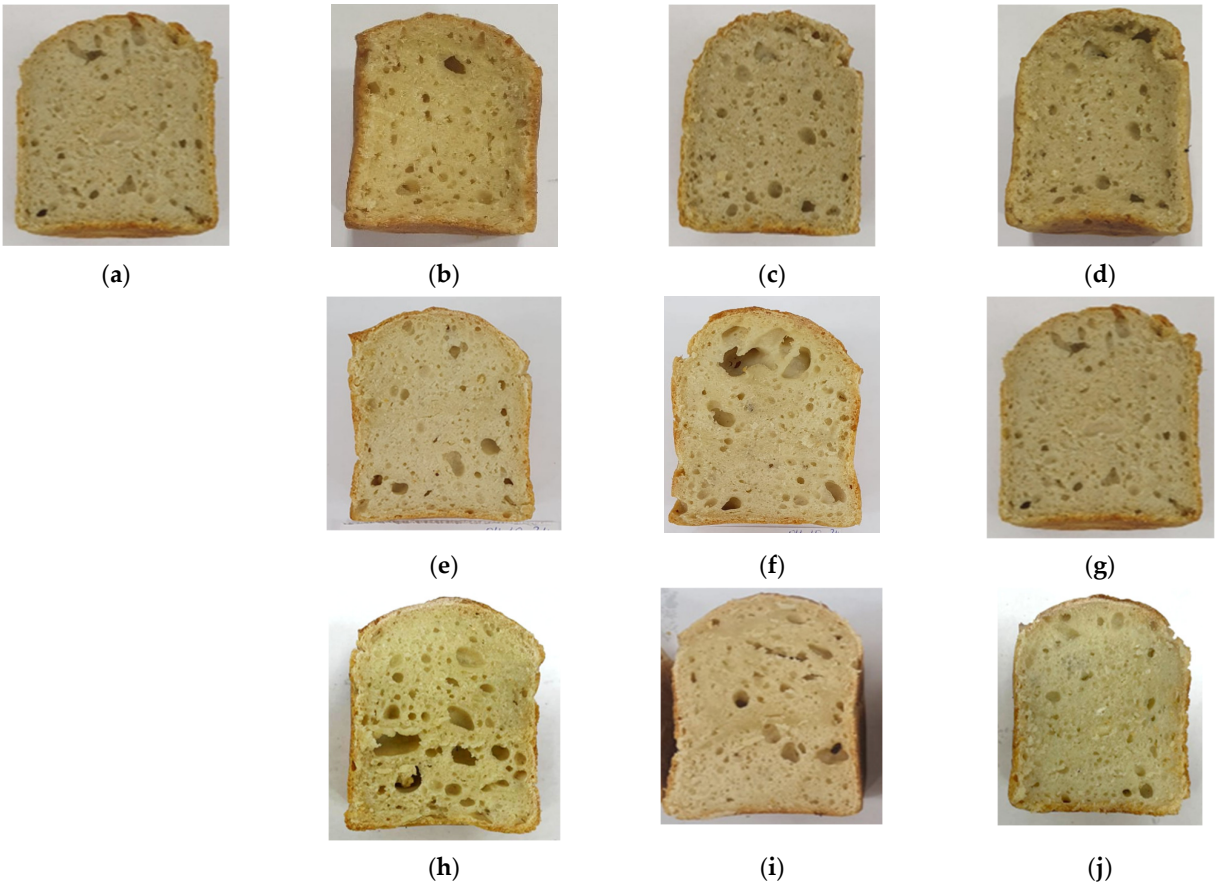


Figure 4. External appearance of the whipped bread samples. (**a**) Control. (**b**–**d**) Whipped bread with 7%, 14%, and 21% apple juice. (**e**–**g**) Whipped bread with 1%, 3%, and 5% apple purée. (**h**–**j**) Whipped bread with 1%, 3%, and 5% apple powder.

3.4. Biochemical Composition of Whipped Bread

The biochemical profiles of all bread samples are presented in Table 5. Apple-based components significantly altered the nutritional composition of the final products.

Table 5. Biochemical indicators of whipped bread samples.

Sample	Characteristics of Whipped Bread Samples, mg/100 g, %										
	1	**1a**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Mass fraction of protein, %	7.51	7.51	6.51	6.98	7.44	5.37	6.94	7.91	5.73	6.91	7.82
Mass fraction of fat, %	0.42	0.42	0.24	0.39	0.43	0.26	0.43	0.47	0.24	0.73	1.04
Mass fraction of carbohydrates, %	22.87	23.06	26.71	27.40	28.28	25.98	26.47	28.37	24.71	26.84	29.23
Mass fraction of dietary fiber, %	4.77	4.77	3.86	4.0	4.70	3.94	4.38	5.13	3.97	4.67	5.85
Vitamins:											
B_1, mg/100 g	0.04	00.5	0.04	0.04	0.04	0.05	0.05	0.06	0.04	0.05	0.05
B_2, mg/100 g	0.03	0.03	0.02	0.03	0.03	0.03	0.04	0.04	0.02	0.03	0.03
B_3, mg/100 g	1.40	1.4	1.34	1.67	1.79	1.64	1.72	1.87	1.68	1.75	1.94
B_5, mg/100 g	0.44	0.44	0.38	0.69	0.94	0.43	0.55	0.63	0.05	0.06	0.70
B_6, mg/100 g	0.13	0.13	0.09	0.11	0.13	0.11	0.13	0.14	0.17	0.24	0.30
B_9, mg/100 g	0.02	0.02	0.01	0.02	0.02	0.021	0.022	0.022	0.02	0.02	0.02
C, mg/100 g	n.d.	0.5	0.71	0.86	1.1	1.66	1.94	2.23	1.37	1.83	2.1

Table 5. *Cont.*

Sample	Characteristics of Whipped Bread Samples, mg/100 g, %										
	1	1a	2	3	4	5	6	7	8	9	10
Mineral elements:											
Iron, mg/100 g	2.45	2.45	2.14	2.55	2.71	2.73	3.14	3.20	2.10	2.64	2.99
Potassium, mg/100 g	125.6	126.0	126.7	136	147.12	147.36	150.17	156.73	128.9	135.1	144.57
Calcium, mg/100 g	23.03	23.05	20.62	23.04	25.24	24.41	26.72	28.1	20.36	22.46	24.30
Magnesium, mg/100 g	18.26	18.31	15.13	17.39	18.93	16.19	18.33	20.71	17.62	18.36	19.76
Phosphorus, mg/100 g	80.38	80.40	84.13	86.74	90.19	85.16	89.94	92.71	72.1	80.36	87.05
Sodium, mg/100 g	313.0	314.2	314.6	317.6	319.45	320.13	317.19	322.34	322.64	333.12	337.73

The biochemical composition of the whipped bread samples varied significantly depending on the type and proportion of apple-based ingredients incorporated into the formulations (Table 5). In the control sample (No. 1), the protein content was 7.51%, while the addition of apple purée and powder resulted in a gradual increase in protein concentration, reaching 7.91% in sample (3% purée) and 7.82% in sample 10 (5% powder). In contrast, breads containing apple juice demonstrated slightly lower protein levels (6.51–7.44%), which is consistent with the dilution effect caused by juice's low dry matter content.

Fat content showed moderate variation across samples. The lowest values were observed in formulations containing 7% apple juice (0.24%) and 1% apple powder (0.24%), whereas the sample enriched with 5% apple powder exhibited the highest fat level (1.04%). This increase corresponds to the concentration of lipophilic compounds during dehydration of the apple raw material.

Carbohydrate content increased in all apple-enriched breads relative to the control (22.87%). The highest concentrations were measured in formulations with 21% apple juice (28.28%) and 5% apple powder (29.23%), reflecting the high content of simple sugars and soluble carbohydrates in these additives. Dietary fiber levels also increased, ranging from 4.0% to 5.85%, with the highest value recorded for the 5% apple powder sample, attributable to the high fiber density in dried apple material.

Vitamin composition reflected the characteristic distribution of water-soluble vitamins in apple products. Vitamins B1 and B2 showed no meaningful variation and remained within the analytical error range. A clear upward trend was observed for niacin (B3), pantothenic acid (B5), and pyridoxine (B6), particularly in samples with apple purée and powder. Vitamin C, undetectable in the control, was present in all apple-enriched samples, ranging from 0.71 to 2.23 mg/100 g. Trace amounts (0.5 mg/100 g) were also found in the acidified control (sample 1A). Despite thermal degradation at baking temperatures, measurable levels were retained, indicating partial heat resistance or stabilization by the matrix.

Mineral composition demonstrated a proportional increase with higher additions of apple purée and powder. Iron content reached 3.20 mg/100 g in the 5% purée sample, while potassium increased by ~24% relative to the control. Calcium and phosphorus also increased across all apple-enriched breads. All samples met food safety standards, and no toxic elements (Pb, Cd, As, Hg) were detected.

3.5. Amino Acid Composition of Whipped Bread

The amino acid composition of the whipped bread samples is presented in Table 6. All values are expressed in mg of amino acid per g of total protein. The inclusion of apple-derived ingredients altered the essential amino acid profile across formulations, although the absolute levels remained low due to the naturally limited protein content of wheat-based bakery products.

Table 6. Amino acid composition of whipped bread samples.

Sample	Content, g/100 g of Product										
	1	**1a**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Lysine	0.260	0.296	0.166	0.204	0.227	0.806	0.904	0.948	0.164	0.206	0.269
Tyrosine	0.224	0.230	0.191	0.206	0.238	0.277	0.295	0.314	0.152	0.203	0.253
Phenylalanine	0.308	0.310	0.356	0.416	0.449	0.206	0.318	0.385	0.402	0.511	0.567
Leucine + Isoleucine	0.510	0.505	0.441	0.507	0.526	0.563	0.609	0.668	0.410	0.480	0.569
Methionine	0.207	0.210	0.176	0.200	0.220	0.135	0.191	0.248	0.068	0.103	0.179
Valine	0.434	0.430	0.367	0.381	0.419	0.496	0.561	0.612	0.365	0.382	0.422
Threonine	0.290	0.295	0.334	0.670	0.396	0.401	0.476	0.534	0.304	0.392	0.426
Alanine	0.349	0.345	0.267	0.307	0.324	0.399	0.483	0.573	0.211	0.281	0.343
Glycine	0.324	0.320	0.277	0.321	0.365	0.328	0.400	0.424	0.216	0.301	0.338
Arginine	0.240	0.245	0.260	0.316	0.348	0.236	0.343	0.389	0.137	0.262	0.297
Histidine	0.050	0.052	0.068	0.077	0.086	0.027	0.034	0.044	0.016	0.037	0.047
Proline	0.645	0.645	0.904	1.006	1.151	0.603	0.628	0.792	1.062	1.142	1.289
Serine	0.430	0.425	0.306	0.417	0.496	0.277	0.361	0.464	0.342	0.428	0.541

In the control sample, lysine and leucine were identified as the most limiting amino acids, with values amounting to only 0.87% and 0.86% of FAO/WHO [40] reference levels, respectively. Valine and threonine were also substantially below standard requirements (Table 6).

The incorporation of apple juice at levels of 7–21% resulted in minimal improvement of the essential amino acid composition. Lysine levels decreased relative to the control (0.166–0.227 mg/g), while valine and leucine + isoleucine remained equal to or slightly below the control values. A moderate increase was observed only in threonine (up to 0.396 mg/g), although the absolute amount remained low and insufficient to influence the overall amino acid score substantially. Thus, the juice-containing formulations did not achieve any meaningful enhancement in protein quality.

In contrast, the addition of apple purée produced the most pronounced increases across multiple essential amino acids. Lysine content increased 2.1–2.6 fold (up to 0.948 mg/g), while threonine (up to 0.534 mg/g), valine (up to 0.612 mg/g), and leucine + isoleucine (up to 0.668 mg/g) also exhibited substantial growth. These improvements may be attributed to the higher natural nitrogenous content of apple purée and its better retention during processing compared to juice. Although the absolute values remain low when compared with FAO/WHO reference levels, purée addition clearly demonstrated the highest potential among all apple-based ingredients for enhancing the amino acid composition.

Apple powder produced fewer substantial changes. In these formulations, phenylalanine + tyrosine and threonine increased, but lysine and valine remained below or only slightly above the control. This modest effect is likely associated with processing-induced degradation of nitrogenous compounds in the dehydrated material. Lysine remained a limiting amino acid for all powder-containing samples.

To evaluate the biological value of the protein in the various formulations, amino acid scores were calculated according to FAO/WHO (2013) reference standards (Table 7). The recalculated scores confirmed that histidine was the primary limiting amino acid in all samples (11–57% of the reference level). In the control and in the juice- and powder-containing breads, lysine remained limiting as well. In the purée-containing samples, lysine was no longer limiting due to its significantly increased concentration; however, leucine and valine became limiting instead.

Table 7. Amino acid score (%) of whipped bread samples according to FAO/WHO (2013).

Sample	Lys	Thr	Val	Leu+Ile	Met	Phe+Tyr	His	Limiting AA
1	0.9%	1.9%	1.7%	0.9%	4.1%	1.7%	11%	Lys, Leu/Ile
1a	1.0%	2.0%	1.7%	0.9%	4.4%	1.8%	11%	Lys, Leu/Ile
2	0.6%	2.2%	1.4%	0.7%	3.5%	2.0%	15%	Lys, Leu/Ile
3	0.7%	4.5%	1.5%	0.9%	4.0%	2.3%	17%	Lys, Leu/Ile
4	0.8%	2.6%	1.6%	0.9%	4.4%	2.4%	19%	Lys, Leu/Ile
5	2.7%	2.6%	2.3%	1.0%	2.7%	1.5%	6%	Leu/Ile
6	3.0%	3.1%	2.6%	1.1%	3.8%	2.4%	7%	Leu/Ile
7	3.2%	3.5%	2.8%	1.2%	4.9%	2.6%	9%	Leu/Ile
8	0.5%	2.0%	1.4%	0.8%	1.3%	1.3%	4%	Lys
9	0.7%	2.6%	1.5%	0.9%	2.0%	1.7%	9%	Lys
10	0.9%	2.8%	1.7%	1.0%	3.5%	1.9%	12%	Lys

The highest amino acid scores were observed in the formulations containing 3–5% apple purée, where the overall score for lysine reached up to 95%, threonine up to 156%, and phenylalanine + tyrosine up to 181% relative to the control. Nevertheless, none of the bread samples reached the FAO/WHO recommended levels for adults for any essential amino acid, reflecting the inherently low biological value of wheat protein and the limited capacity of fruit-derived ingredients to compensate for this deficiency.

To evaluate the biological value of the protein in the bread samples, amino acid scores were calculated relative to FAO/WHO (2013) [49–52] reference patterns for adults. The scores were determined for each essential amino acid using the experimentally obtained amino acid concentrations (mg/g protein). The calculated scores are presented in Table 7.

The lowest scores were observed in the control sample, confirming low protein biological value typical of wheat bread. Apple juice provided minimal improvement. Apple powder produced moderate enhancement, mainly in threonine and phenylalanine + tyrosine. Apple purée generated the highest increase in essential amino acids; however, even improved formulations remained far below FAO/WHO standards. Histidine was the limiting amino acid in all samples, whereas lysine was limiting only in control and powder-containing bread. The highest relative improvement was recorded in sample 7 (3% purée), but absolute values still represented <5% of FAO/WHO norms.

Thus, the incorporation of apple purée demonstrated the greatest potential to improve the essential amino acid profile of whipped yeast-free bread, whereas apple juice and powder resulted in only minor positive shifts. Despite these improvements, the absolute essential amino acid levels remained insufficient to meet FAO/WHO standards, indicating that the formulation would require additional protein fortification from complementary lysine- and leucine-rich sources to achieve a balanced amino acid profile.

3.6. Microbiological Safety of Whipped Bread Samples

An analysis was also carried out to assess microbiological safety (Table 8). According to the obtained microbiological data, the apple-based components added to the whipped dough demonstrated a measurable inhibitory effect on microbial growth, likely associated with the presence of organic acids and phenolic compounds. Literature sources [53–56] report that the organic acids present in apples may contribute to anti-inflammatory and anti-allergic activity, and could potentially impart antimicrobial and antitumor properties [57–60]. However, it should be noted that these effects are primarily documented in raw apple material, and their retention in the final baked bread product may be limited due to thermal degradation during baking.

Table 8. Microbiological indicators of the whipped bread samples.

Sample	Total Mesophilic Count, CFU/g (0 h)	Total Mesophilic Count, CFU/g (72 h)	Coliforms	Yeast & Mold, CFU/g
1	4.7×10^3	6.2×10^3	Not detected	$<10^2$
2–4 (juice)	$3.8–4.1 \times 10^3$	$3.0–3.4 \times 10^3$	Not detected	$<10^2$
5–7 (purée)	$3.2–3.6 \times 10^3$	$2.2–2.8 \times 10^3$	Not detected	$<10^2$
8–10 (powder)	$3.0–3.4 \times 10^3$	$1.8–2.3 \times 10^3$	Not detected	$<10^2$

Microbiological indicators of the whipped bread samples were examined immediately after baking (0 h) and after 72 h of storage under ambient laboratory conditions (22–24 °C; relative humidity 50–55%). Total aerobic mesophilic counts, yeast and mold counts, and the presence of coliforms were determined according to ISO 4833-1 and ISO 21527-1/2. Microbiological parameters across all samples remained within permissible limits.

Table 7 summarizes the microbial load at both time points. The control sample demonstrated a noticeable increase in total mesophilic bacteria within 72 h of storage (from 4.7×10^3 to 6.2×10^3 CFU/g). Samples containing apple juice, purée, or powder showed lower initial microbial contamination and a smaller increase during storage. After 72 h, the bacterial load in these samples ranged from 1.8×10^3 to 3.4×10^3 CFU/g. Yeast and mold counts remained below 10^2 CFU/g in all samples, and coliforms were not detected.

These results indicate that apple-derived ingredients contribute to improved microbiological stability during short-term storage. This effect is associated with the presence of natural organic acids (primarily malic and citric acids), phenolic compounds, and pectin-derived components, all of which create a mildly acidic environment unfavorable for microbial proliferation. Since all enriched formulations included citric acid, its synergistic contribution to the inhibition of microbial growth should also be acknowledged. Nevertheless, it must be noted that antimicrobial activity reported in the literature for raw apple tissues may be partially reduced during baking due to thermal degradation of heat-sensitive bioactive compounds.

Overall, the incorporation of apple juice, purée, or powder reduced microbial growth rates and improved short-term microbiological stability compared with the control, confirming the suitability of apple-based components as natural preservation-enhancing additives for yeast-free whipped bread.

3.7. Shelf-Life Stability of Whipped Bread

The evolution of crumb structure, texture, aroma, and visible staling during storage was monitored at 24 h, 72 h, 1 month, and 3 months (Table 9). Samples were packaged in standard polypropylene bags and stored at ambient laboratory conditions (22–24 °C; relative humidity 50–55%). Water activity (a_w) remained in the range of 0.85–0.92 for all samples throughout the storage period.

During the first 72 h, the control bread exhibited the most rapid staling: a marked loss of elasticity, increased crumb fragility, and deterioration of aroma. By contrast, bread containing apple purée retained higher moisture, a more elastic crumb, and better flavor quality during the same period. Bread formulated with apple juice displayed initially high porosity but developed increased friability and reduced crumb stability after 72 h of storage.

The most stable texture and sensory attributes were observed in the bread enriched with apple powder. Even after three months of storage, these samples maintained a cohesive crumb structure, minimal retrogradation signs, and relatively preserved flavor characteristics. This enhanced stability is associated with both the low moisture content and the water-binding capacity of the dry apple powder, which limits moisture migration processes and delays starch retrogradation.

Table 9. Stability of quality characteristics of whipped bread samples during storage.

Sample	Quality Parameters			
	Control	Whipped Bread with Apple Juice	Whipped Bread with Apple Purée	Whipped Bread with Apple Powder
24 h	Moderately soft, low moisture content, mildly pronounced flavor	Airy crumb structure, pronounced porosity, mildly sweet flavor profile	High moisture content, elastic crumb, pleasant flavor	Stable shape, soft crumb, good moisture content
72 h	Moderate staling, moderate crumbliness, and reduced aroma	Development of a crumbly texture, enhanced friability, and a noticeable decline in crumb elasticity	Slight firming, reduced softness and aroma	Good texture retention, slight retrogradation
1 month	Pronounced staling characterized by increased firmness, reduced loaf volume, and diminished flavor	Loose crumb and intensified retrogradation processes, leading to a marked decline in overall product quality	Denser crumb, partial loss of flavor and plasticity	Stable structure, minimal losses, aroma preserved
3 months	Intensive staling accompanied by dryness and a marked deterioration in overall consumer acceptability	Significant staling, low porosity, deterioration in flavor and crumb structure	Increased density, weak flavor, elevated dryness	Minimal changes, stable texture, flavor preserved

After one month of storage, the control bread showed pronounced staling manifested by crumb hardening, volume loss, and diminished flavor intensity. Apple juice samples exhibited significant retrogradation and loss of porosity at the same time point. Bread containing apple purée demonstrated moderate staling, reflected in partial crumb densification but still acceptable sensory attributes. Meanwhile, apple powder samples remained the most resistant to structural and sensory deterioration [61,62].

After three months, the control and juice-enriched breads experienced severe staling, dryness, and structural collapse. Apple purée samples displayed increased density and reduced flavor; however, the crumb remained more plastic compared with the control. Apple powder formulations showed the highest resistance, characterized by stable structure, reduced staling, and preserved flavor.

Collectively, these observations demonstrate that apple-derived components significantly influence shelf-life stability. Apple purée improves early-stage moisture retention, apple juice contributes to initial porosity but weakens long-term stability, and apple powder provides the best protection from structural degradation during extended storage [63,64].

The experimental results thus highlight that combining mechanical aeration with apple-based ingredients positively affects the physicochemical, rheological, sensory, and storage properties of yeast-free whipped bread. Dough development time increased to 8.40 min and stability to 8.90 min, exceeding values typical for other fruit- and vegetable-enriched bakery products. Apple powder contributed to the highest dough elasticity (0.053 N·m) and viscosity, while apple purée and juice significantly increased porosity and specific volume, likely due to synergistic effects of pectins, organic acids, and natural sugars on foam stabilization and aeration efficiency.

The enriched breads also showed improved nutritional value, including increased fiber content, higher vitamin retention, and enhanced amino acid profiles. For example, the

amino acid score increased from 76.5 ± 1.8% in the control to 89.2 ± 2.3% in the formulation containing apple purée, indicating better protein quality.

From a microbiological perspective, the presence of citric and malic acids in apple ingredients lowered the pH of the dough and contributed to reduced microbial loads, supporting the natural preservation of the product. The entire production cycle—from mixing to finished bread—required less than 45 min, significantly shorter than conventional bakery processes, supporting the industrial feasibility of this technology [65–67].

Thus, the developed formulation combines high nutritional value, safety, technological efficiency, and alignment with both environmental and consumer demands. Apple purée appears to be the most promising component, providing improvements in textural and functional properties while ensuring a consistently high quality of the final product.

4. Discussion

The results of this study demonstrate that mechanical aeration is a viable and technologically efficient alternative to yeast-based leavening. By relying solely on rapid, pressurized whipping to incorporate air, this method aligns with clean-label trends and enables the production of yeast-free bakery products without chemical leavening agents. The use of apple-derived ingredients—juice, purée, and powder—was found to substantially influence the rheological behavior of the dough, the technological quality of the bread, and its nutritional and storage characteristics.

The most notable improvements were observed in dough development and stability. Apple purée, in particular, markedly increased development time (up to 8.40 min) and stability (up to 8.90 min), exceeding the control by more than threefold. These results are consistent with the known water-binding and structure-modifying properties of pectin and soluble solids, which reinforce the protein–polysaccharide matrix and help retain mechanically incorporated air. Previous studies have also reported similar strengthening effects of fruit-based fibers and pectin-containing ingredients on viscoelastic dough systems.

Increased dough elasticity (torque amplitude up to 0.053 N·m) and improved crumb porosity (≈67–68%) indicate that the modified matrix effectively stabilized air cells during whipping and baking. The 24–25% increase in specific volume further supports enhanced gas-holding capacity, a key determinant of crumb softness and consumer acceptability.

Nutritional indicators also improved with the addition of apple purée and powder. Both ingredients contributed dietary fiber, available carbohydrates, and micronutrients, and increased overall protein content. Although the amino acid score improved—from 76.5 ± 1.8% in the control to 89.2 ± 2.3% in the best-performing purée sample—it still did not reach FAO/WHO reference levels. This highlights that apple enrichment alone cannot fully compensate for the intrinsic limitations of wheat protein, indicating the need for further targeted protein fortification.

Apple-based ingredients also affected shelf-life characteristics. Apple purée improved early moisture retention and crumb elasticity, while apple powder contributed to slower staling and reduced firmness development over extended storage. These effects can be attributed to the higher concentration of dry matter and bioactive compounds in apple powder, which help regulate water migration and slow starch retrogradation. Microbiological indicators confirmed that samples with apple ingredients exhibited reduced microbial counts after 72 h, a result linked to natural organic acids and phenolics present in apple raw materials.

A significant technological advantage of the developed method is the reduction in production time: the full cycle—from mixing to baked bread—takes < 45 min, compared with 2.5–3 h for conventional yeast fermentation. This benefit is particularly rele-

vant for small- and medium-sized bakeries seeking stable, rapid production with fewer processing variables.

The developed formulations demonstrate a balanced combination of technological efficiency, nutritional enhancement, structural quality, and storage stability. Apple purée improves functional and sensory attributes, while apple powder ensures superior long-term stability, confirming their potential as valuable plant-based components for the production of yeast-free aerated bread.

Overall, this study provides important evidence that mechanical aeration, when combined with apple-derived ingredients, can enhance functional, structural, and nutritional aspects of yeast-free bread. The results expand the understanding of air incorporation in plant-enriched dough systems and support the development of clean-label bakery technologies. Future research should priorities protein profile optimization to meet FAO/WHO requirements and investigate synergistic combinations of apple ingredients with other plant-based functional additives such as legume flours, protein isolates, and soluble fibers.

5. Conclusions

This study established a rapid mechanical-aeration process for producing yeast-free bread enriched with apple juice, purée, and powder. Pressurized high-speed whipping enabled the formation of an aerated dough matrix without biological or chemical leavening, reducing the total production time to <45 min.

Apple purée (3–5%) produced the most pronounced technological improvements. Dough development time increased from 2.33 ± 0.12 min (control) to 8.40 ± 0.23 min, and dough stability increased from 3.30 ± 0.15 min to 8.90 ± 0.20 min. Torque amplitude reached 0.053 N·m in purée- and powder-enriched doughs. Mixolab Profiler indices confirmed higher water absorption (up to 9 units) and moderated starch retrogradation during storage (3–5 units).

These rheological improvements translated into better bread quality. Specific volume increased by 24–25% (to ≈213–215 cm^3/100 g), porosity reached 67–68%, and crumb firmness decreased from 3.01 ± 0.15 N (control) to 2.12 ± 0.10 N in enriched samples.

Nutritional value was also enhanced: protein content reached up to 7.91 ± 0.18%, dietary fiber increased with apple powder, carbohydrates increased with purée, and vitamin C remained detectable after baking (up to 2.23 mg/100 g). The amino acid score improved to 89.2 ± 2.3% in the best-performing formulation.

Microbiological results demonstrated a reduction in microbial load from 6.2 × 10^3 CFU/g (control) to 1.8–3.4 × 10^3 CFU/g in apple-enriched samples after 72 h, with yeast and mound counts < 10^2 CFU/g.

Overall, mechanical aeration combined with apple-derived ingredients presents a promising, clean-label approach for producing yeast-free bread with improved structure, nutritional properties, and shelf-life. Apple purée provides the strongest immediate textural and nutritional benefits, while apple powder offers superior long-term stability.

Future work should validate vitamin-retention mechanisms, improve essential amino acid profiles to meet FAO/WHO standards, evaluate consumer acceptance, and conduct industrial scale-up assessments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr14020212/s1, Table S1: Mixolab parameters (C1–C5), dough development time, stability, and WAC of whipped dough samples (mean ± SD, n = 3).

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