Scientific Papers. Series D. Animal Science. Vol. LXIX, No. 1, 2026
ISSN 2285-5750; ISSN CD-ROM 2285-5769; ISSN Online 2393-2260; ISSN-L 2285-5750

THE IMPACT OF EGGPLANT, ZUCCHINI, AND APPLE PEEL POWDER ADDITION ON THE PROXIMATE COMPOSITION, POROSITY AND SENSORY PROFILE OF SAVORY MUFFINS

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Abstract

Fruit and vegetable peels contain a variety of health-beneficial nutrients and serve as excellent nutritional sources. Their utilization contributes to the reduction of food waste, having a positive impact on both the environment and the economy. This article presents a study on the advanced valorization of apple, zucchini, and eggplant peels for the development of savory muffins. Four types of savory muffins were formulated using apple (MA), zucchini (MZ), eggplant (ME) peel flours, and control (MC). These were subjected to sensory evaluation and physicochemical analysis. The MA, MZ, and ME muffins demonstrated a high degree of acceptability. Proximate composition analysis revealed that the ME variant had the highest protein content. MA muffins recorded the highest levels of carbohydrates and dry matter, as well as the highest acidity. MZ and ME muffins had a higher salt content, while the ME variant exhibited the best porosity.

Key words*: acidity, antiradical activity, moisture, muffins, peel powder, porosity.*

INTRODUCTION

Globally, the massive generation and deficient management of waste resulting from the post-harvest processing of horticultural products exert considerable pressure on waste management systems, simultaneously generating negative environmental externalities and public health risks (Sharma et al., 2022). In this context, the valorization of residual fractions and by-products from the fruit and vegetable industry constitutes a fundamental pillar of sustainable agri-food systems, offering strategic opportunities for value-added generation. Implementing circular economy principles requires the adoption of integrated and collaborative strategies among value chain actors to reintegrate these resources into the productive circuit (Geissdoerfer et al., 2017; Kumar et al., 2024). The fruit and vegetable processing industry, a critical component of the agri-food sector, generates significant volumes of residual biomass throughout the technological flow, from cultivation and harvesting phases to conditioning and packaging. These flows include lignocellulosic plant remains (leaves, stems, roots), as well as specific processing by-products: peels, seeds, pits, exhausted pulp, and other organic materials. Although traditionally classified as waste, current scientific evidence (FAO, 2019) highlights their high bioconversion potential, transforming them into essential resources for the transition toward a sustainable food system. Optimizing the management of these flows not only mitigates the ecological footprint by reducing landfill disposal but also facilitates the procurement of high commercial value products, such as functional food ingredients, energy biomass, bio-fertilizers, and chemical

precursors (Kumar et al., 2021). Under the pressure of climate change and global demographic growth, the valorization of horticultural by-products becomes an imperative necessity, offering multidimensional benefits. Thus, food waste is minimized by reintegrating by-products into the consumption chain, optimizing the material balance and reducing net biomass losses, while generating added value and economic innovation by transforming residues into biocompounds with applications in the food, pharmaceutical, and cosmetic industries (Chemat et al., 2017), thereby stimulating economic growth. For example, the peels of certain fruits represent dense sources of dietary fiber and polyphenolic antioxidants with demonstrated benefits for human health. The integral valorization of biomass reduces dependence on virgin raw materials and optimizes resource consumption associated with primary production. Furthermore, substituting the linear model with a circular one diminishes greenhouse gas (GHG) emissions, prevents soil and water resource contamination, and reduces specific energy consumption related to waste management (D'Adamo et al., 2022).

Plant by-products are defined as morphological parts and fractions derived from primary agri-food production processes. As global fruit and vegetable production intensifies, the recovery of nutrients and bioactive compounds from these matrices has become a subject of maximum interest in biochemical and nutritional research (Tsegay et al., 2024). Valorization methodologies are diverse, including composting (Soltan et al., 2019), biogas production, extraction of bioactive compounds (Călinoiu & Vodnar, 2018), and the development of functional food ingredients (Mirabella et al., 2014).

Despite evident benefits, the valorization process faces critical barriers, such as material composition heterogeneity, technological costs, and infrastructure limitations. Nevertheless, the current context offers unprecedented opportunities through advances in biotechnology and the increasing demand for sustainable products. These initiatives align with the objectives of the European Green Deal and the Circular Economy Action Plan, which impose strict targets on member states for reducing landfilled biodegradable waste and promoting long-term sustainability. Given that the Green Deal places immense emphasis on transforming waste into resources, a strategic component of this endeavor is the valorization of peels, which represent excellent reservoirs of polyphenols, antioxidants, dietary fibers (pectins, cellulose), and essential micronutrients. The recovery of these compounds not only minimizes organic waste volume but also opens new horizons for innovative industrial applications. Thus, transforming peels from „residue" into „secondary raw material" becomes an essential case study for the resilience of the entire agri-food value chain. The valorization of fruit and vegetable peels represents a critical opportunity to recover essential nutrients that are traditionally eliminated from the food chain. These matrices are concentrated sources of fiber, vitamins, minerals, and phytochemicals, whose reintroduction into the consumption circuit has a positive multidimensional impact on the environment and the economy.

Apple peel (*Malus domestica*) constitutes an exceptional natural source of bioactive compounds, with concentrations of phenolic compounds, fiber, and minerals significantly higher than the fruit pulp (Henríquez et al., 2010a). A particularly relevant aspect is the presence of quercetin, a flavonoid with recognized anti-inflammatory and anti-allergic properties. Fundamental research by Wolfe and Liu (2003) demonstrated that waste from the apple puree industry can be transformed into a valuable food ingredient in powder form. The study highlighted the importance of preservation techniques; blanching treatments for 10 seconds proved most effective in preserving the phenolic profile. Through lyophilization and air drying, a powder with very strong antioxidant activity was obtained: 1 g of powder has an antioxidant potential equivalent to 220 mg of vitamin C. Physiologically, the soluble and insoluble fibers in apple peel regulate intestinal transit, prevent constipation, and favor a balanced probiotic environment. Additionally, the intake of B-complex vitamins (B_6) and vitamin C supports energy metabolism and protects cells against oxidative stress (Boyer & Liu, 2004).

Zucchini peel (*Cucurbita pepo*) is appreciated for its low caloric value; however, its peel, representing approximately 10% of the fruit's mass, concentrates the majority of nutrients. Compositional studies reveal major differences between tissues. Thus, the peel presents double the concentrations of soluble solids (Brix degrees) compared to the core. The level of total flavonoids is 59.06 mg CE/100 g in the peel, and antioxidant capacity is 159.13 µmol TEAC/100 g (Gomes et al., 2023). Nutritional profile (per 100 g fresh matter): 2.5% fiber, 1.41% protein, and a diversified vitamin intake (Vitamin C – 15.1 mg, Vitamin A, B_1, and B_2) (Li et al., 2021).

Eggplant peel (*Solanum melongena*) is recognized for its high anthocyanin content, particularly nasunin. This powerful antioxidant protects lipids in brain cell membranes and has demonstrated anti-cancer properties (Noda et al., 2000). The antioxidant activity is 250.94 µmol TEAC/100 g, with a polyphenol content between 51-63 mg tannic acid/g DM (Gomes et al., 2023). The presence of chlorogenic acid and vitamin K contributes to reducing inflammation and supports bone and vascular health.

To transform these by-products into high-quality secondary raw materials, such as functional flours, the contemporary industry implements state-of-the-art extraction techniques that maximize nutrient recovery. Among these, ultrasound- or microwave-assisted extraction plays a crucial role, allowing efficient isolation of polyphenols without causing thermal degradation, while encapsulation technologies are used to protect sensitive compounds and ensure their controlled release in finished products. Moreover, directed fermentation processes, carried out through the action of specific microorganisms, contribute significantly to enhancing the bioavailability of bioactive compounds, thus optimizing the nutritional profile of the resulting products.

Beyond technical benefits, the valorization of fruit and vegetable peels represents a strategic move for economic efficiency, surpassing simple ecological responsibility. By transforming waste into value-added products, production units manage to considerably reduce logistic costs associated with organic residue management and disposal. Simultaneously, this approach generates new revenue streams by accessing market niches dedicated to functional foods and „clean label" products. Ultimately, adopting these innovations strengthens the competitiveness of agri-food companies and reduces dependence on virgin raw materials, facilitating the transition toward a circular, sustainable, and resilient production cycle in the long term.

In this context, the present study aims to incorporate powders obtained from apple, zucchini, and eggplant peels into the recipe for savory muffins, evaluating their impact on proximate properties, porosity, acidity, scavenging capacity and the sensory profile.

MATERIALS AND METHODS

Raw materials and ingredients

The raw materials used in the manufacturing process were selected to ensure a high degree of reproducibility and food safety. The basic ingredients required for the preparation of the control sample (Control) and the fortified variants were purchased from the local commercial network: white wheat flour (type 000), fresh eggs, sunflower vegetable oil, milk (1.5% fat), telemea cheese (traditional Romanian brined cheese), green onions, fresh dill, and a leavening agent (baking powder). Particular attention was paid to the plant materials intended for fortification, represented by the peels of apple (*Malus domestica*), zucchini (*Cucurbita pepo*), and eggplant (*Solanum melongena*). The raw material was selected exclusively from the category of products originating from organic farming (BIO certified), a critical condition in this study to guarantee the absence of pesticide residues and other chemical contaminants that tend to accumulate predominantly in the outer layers of fruits and vegetables.

Production of functional flours from horticultural by-products

The transformation of horticultural by-products into secondary raw materials (functional flours) was carried out through a rigorous preliminary processing protocol, designed to maximize the preservation of bioactive compounds. The process was structured into several technological stages:

Sanitization and preparation. Apple, zucchini, and eggplant samples were subjected to rigorous washing with deionized water to ensure the complete removal of mechanical impurities and potential surface microorganisms.

Mechanical separation. The peeling of the samples was performed manually using stainless steel utensils to minimize the risk of enzymatic oxidation of phenolic compounds upon contact with air and metallic surfaces (Figure 1).



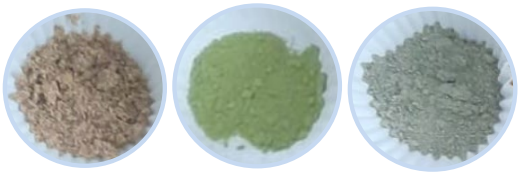
Figure 1. Cleaning of apple, zucchini, and eggplant peel (original source)

Controlled dehydration. The plant material was subjected to controlled dehydration in a professional device (Figure 2) at a constant temperature of 45°C. This thermal treatment lasted between 12 and 24 hours, depending on the specific moisture content of each matrix. Maintaining such moderate conditions was critical to prevent the degradation of thermolabile fractions and to preserve antioxidant stability. The process was rigorously monitored until reaching a residual moisture threshold of 15%, ensuring both microbiological and mechanical stability for subsequent processing.



Figure 2. Dehydration of apple, zucchini, and eggplant peel (original source)

Grinding and sorting. Subsequently, the dehydrated plant material underwent a fine grinding process using a laboratory mill, resulting in three types of homogeneous functional flours (Figure 3). To prevent the degradation of bioactive compounds, these were stored in hermetically sealed amber glass containers, thus ensuring protection against oxidative factors, light, and ambient humidity until their incorporation into the muffin matrix.



Apple peel flour (APF) | Zucchini peel flour (ZPF) | Eggplant peel flour (EPF)

Figure 3. Apple, zucchini, and eggplant peel flour (original source)

Manufacturing technology of the functional muffins

The manufacturing process followed a standardized technological flow, designed to ensure sample reproducibility and the stability of the food matrix. The experimental design included a control sample (Control) and three fortified (experimental) variants, developed by partially substituting wheat flour with functional flours derived from apple, zucchini, and eggplant peels at a ratio of 3% (w/w). The preparation protocol was structured into successive homogenization stages:

Preparation of the protein-lipid base. The process began by mixing the eggs and salt, followed by the incorporation of the liquid phase (milk and vegetable oil), ensuring the formation of a stable emulsion.

Formation of the structural matrix. The solid fraction, consisting of wheat flour, the leavening agent, and the specific functional flour for each sample, was gradually integrated under continuous mechanical stirring. This stage was monitored until a dough with specific rheological properties (dense-elastic texture) was obtained, ensuring a uniform distribution of fibers within the gluten network.

Incorporation of texture ingredients. In the final mixing phase, *telemea* cheese and aromatic ingredients (green onions and fresh

dill) were added, maintaining their structural integrity.

Thermal treatment (baking). The dough, portioned into standardized molds, was subjected to a baking process under controlled conditions at a temperature of 180°C for 25-30 minutes. This standardization was essential to ensure sample uniformity and to allow for an objective evaluation of physicochemical indicators, such as porosity, and sensory attributes.

Analysis methods for raw materials and finished products

Sensory evaluation

The sensory profile of the fortified muffins was determined using the intensity profile method, conducted by a panel of regular consumers (untrained tasters) to simulate actual market perception. The evaluation focused on several critical sensory attributes: general appearance, color, crumb consistency (texture), odor, taste, and flavor persistence (after-taste). A 5-point hedonic scale was employed for quantification, where: 1 represented minimum intensity/low acceptability and 5 indicated superior quality/ maximum acceptability. The data were aggregated to establish the comparative sensory profile of the samples. Overall acceptability represents the mean of all sensory attributes and constitutes the decisive indicator for the market potential of the fortified muffins.

Determination of crumb porosity

Crumb porosity was determined using the volumetric method, a parameter that indicates the ratio between the volume of interstitial spaces (pores) and the total volume of the crumb sample. The experimental procedure involved extracting three crumb cylinders from the central area of each sample using a punch of known geometry and dimensions. The porosity calculation was based on determining the specific mass of the compact crumb using the following mathematical relationships:

$$Porosity, \% = \frac{V_p - V_{cc}}{V_p} \cdot 100$$

$$V_{cc} = \frac{m}{\rho}$$

Where:

V_p - volume of the cylinder containing pores (cm^3); V_{cc} - volume of the compact crumb (pore-free, cm^3); m is the mass of the sample (g); ρ - density of the compact crumb, experimentally established at 1.26 g/cm^3.

This methodology allowed for the evaluation of how the addition of fruit and vegetable peel flours influenced the alveolar structure of the muffins, providing a quantitative basis for the structural changes observed in the fortified samples.

Determination of total acidity

The total acidity of the bakery products was considered a quality parameter, representing the sum of free acids and acid-reacting compounds formed during the fermentation and baking processes. The method was based on the neutralization of acids within the aqueous extract of the analyzed sample by titration with a 0.1 N sodium hydroxide solution. Phenolphthalein was used as a pH indicator. The endpoint of the titration was identified by the appearance of a faint pink coloration that persisted for at least 30-60 seconds. Acidity was expressed in acidity degrees, where one degree represented the acidity in 100 g of sample that was neutralized by 1ml 1 N NaOH solution. The following formula was used for the calculation:

$$Acidity\ (degrees) = \frac{V \cdot 0{,}1}{m} \cdot 100$$

Where:

V - volume of 0.1N NaOH solution used for titration (ml); m - mass of the sample taken for analysis (g); 0.1 - the normality factor of the sodium hydroxide solution; 100 - conversion factor to report the result per 100 g of product.

Proximate chemical analysis and nutritional evaluation

The proximate composition of the muffins was determined to establish their nutritional profile and to evaluate the impact of functional flour incorporation. This analysis included the determination of moisture, minerals (as salt content), proteins, lipids, and carbohydrates.

The crude chemical composition (proteins, lipids, and carbohydrates) and the total energy value were estimated using a theoretical calculation method. This involved integrating the nutritional data for each ingredient from standardized databases (nutritionvalue.org). Results were expressed per 100 g of finished

product, and the energy value was calculated using the Atwater conversion factors.

As a fundamental component of the proximate analysis, the water content was determined using the standard gravimetric method. Muffin samples were finely homogenized using a mortar and pestle. Approximately 5 g of each sample was weighed and dried in a thermostatic oven at 105 ± 2°C until a constant mass was achieved. The moisture content was calculated based on the weight loss during heating:

$$Moisture(\%) = \frac{m_1 - m_2}{m_1 - m_0} \cdot 100$$

Where:

m_0 represents the tare of the empty vessel; m_1 is the initial mass of the vessel containing the homogenized muffin sample; m_2 is the final mass recorded after oven-drying at 105 ± 2°C until a constant weight was achieved.

All determinations were performed in triplicate to ensure data precision.

The salt content (NaCl) was quantified through direct argentometric titration according to the Mohr method. Chloride ions were extracted into an aqueous phase and titrated with 0.1 N silver nitrate ($AgNO_3$) in the presence of potassium chromate (K_2CrO_4) as a pH - sensitive indicator. The process was conducted within a strictly controlled pH range (6.5 - 8.5). The final NaCl percentage was calculated by correcting the titrant volume with a blank sample and relating it to the initial sample mass. The sodium chloride content (NaCl, %) was calculated using the following formula:

$$NaCl, \% = \frac{(V_{AgNO3} - V_{blank}) \cdot N_{AgNO3} \cdot M_{NaCl} \cdot \frac{V_{extract}}{V_{aliquot}}}{m_{sample}} \cdot 100$$

Where:

V_{AgNO3} volume of silver nitrate solution used for sample titration (ml); V_{blank} volume of silver nitrate solution used for the blank titration (ml);

N_{AgNO3} normality of the silver nitrate solution (typically 0.1 N); M_{NaCl} milliequivalent weight of sodium chloride (0.05844 g/meq); $V_{extract}$ total volume of the initial aqueous extract (ml); $V_{aliquot}$ volume of the extract taken for titration (ml); m_{sample} mass of the muffin sample taken for analysis (g).

All determinations were performed in triplicate.

Methodology for determining antioxidant inhibition (DPPH Assay)

The antioxidant capacity of the functional flours (apple, zucchini, and eggplant) was evaluated using the DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging assay. The principle of this method relies on the ability of bioactive compounds to reduce the stable DPPH radical, resulting in a colorimetric change from deep purple to yellow. Hydroalcoholic extracts were prepared from the functional flour samples. Due to the high concentration of bioactive constituents, the final extracts were subjected to a 1:100 (v/v) dilution in 70% ethanol to ensure that absorbance readings remained within the linear range of the spectrophotometer. The reaction system was set to a final volume of 3.2 ml. To ensure optimal interaction between the reactant species, the components were added into the reaction cuvettes according to the following specific sequence: 0.3 ml of diluted extract, 0.3 ml of DPPH radical solution (1 mM concentration) and 2.6 ml of 70% ethanol (solvent). Following the sequential addition, the mixture was thoroughly homogenized. The samples were then kept in the dark at room temperature for 30 minutes to allow the radical scavenging reaction to reach equilibrium. The absorbance of the samples (A_{sample}) was recorded at 517 nm using a UV-VIS spectrophotometer. A DPPH stock solution was used as a control (blank), prepared using the same addition sequence but replacing the extract with the solvent. The antioxidant activity was expressed as a percentage of inhibition (I%), calculated as follows:

$$I, \% = \frac{A_{blank} - A_{sample}}{V_{blank}} \cdot 100$$

All measurements were performed in triplicate, and the results were expressed as the mean value of the determinations.

RESULTS AND DISCUSSIONS

The sensory analysis of the fortified muffins

The sensory characteristics of the muffins were evaluated to determine the impact of the

functional ingredients on the final product's quality.

External appearance. The muffins exhibited a well-defined, rounded shape with a slightly domed top and a stable base. The crust was thin, crisp, and slightly firm to the touch, featuring a fine texture. The color profile ranged from light golden-green to golden-brown on the surface and edges, indicating uniform baking. Occasional darker spots were observed due to the caramelization or melting of the cheese on the surface. Fresh green dill specks and lightly browned cheese fragments were clearly visible on the exterior.

Cross-sectional appearance. The cross-section (Figure 4) reveals a slightly moist and aerated crumb with a uniform yellowish-cream hue, punctuated by subtle green inclusions.



Figure 4. Apple, zucchini, and eggplant peel muffins (original source)

The internal structure exhibits a well-developed medium-to-high porosity, indicating a soft and elastic matrix without dense or gummy zones. Cheese fragments are clearly visible and evenly distributed, contributing to the overall structural complexity, while the darker nuances in certain areas mark the optimal integration of the ingredients into the dough.

Color. Sample MA achieved the highest score for color (4.77), while the Control sample (C) obtained a lower score (4.57). These results are in agreement with those reported by Henríquez et al. (2010b), demonstrating that natural pigments from apples increase visual appeal.

Aroma. The aroma was of moderate to high intensity, characteristic of freshly baked pastry. The profile was dominated by the distinctive, sweet-herbal scent of fresh dill, which was well-balanced by the lactic, slightly acidic, and salty notes of the cheese. Subtle undertones of baked dough (cereal and egg) were also perceived, with no off-odors (such as rancid or burnt notes) detected.

Flavor. The taste was rich and savory, providing a harmonious balance between the key ingredients. It featured specific notes of salty, creamy, and slightly tangy cheese, complemented by the herbal and fresh anise-like flavor of the dill. The dough provided a neutral to slightly sweet base that integrated the aromatic notes perfectly. Salt levels were optimal, enhancing the overall flavor profile without being overpowering. The integration of apple peel powder resulted in a higher score for the fortified products compared to the control. Similar results were also reported by Alongi et al. (2019).

Texture and after-taste. The texture was described as crisp on the outside while remaining light and tender on the inside. The after-taste had a pleasant, medium persistence, leaving a fresh sensation of dill and a discrete salty-lactic note from the cheese.

The sensory evaluation, synthesized through the spider plot (Figure 5), provided a detailed perspectiveon the impact of partially replacing wheat flour with functional powders derived from vegetable by-products (apple, zucchini, and eggplant peels) on consumer perception. The control sample served as a benchmark for structural stability, achieving maximum scores for external appearance (4.8) and section appearance (4.8). These results confirm that the classic muffin meets the traditional visual standards of consumers. However, the control sample recorded the lowest score for the taste parameter (4.08), being perceived as having a less complex aromatic profile compared to the fortified variants.

The MA variant emerged as the favorite of the tasting panel, achieving an optimal harmony between innovation and acceptability. It obtained the highest score (4.77), suggesting that the natural pigments in the apple peel conferred an attractive, warm golden hue to the product. With a score of 4.57, the MA sample outperformed the control (4.44), demonstrating that the addition of apple by-products enhances the overall sensory profile through aromatic complexity. The high score for after-taste (4.5) indicated a pleasant balance between native sugars and the organic acidity of the apple. Muffins fortified with zucchini and eggplant

presented acceptability scores very close to the control, demonstrating the feasibility of integrating these by-products without negatively altering sensory perception.

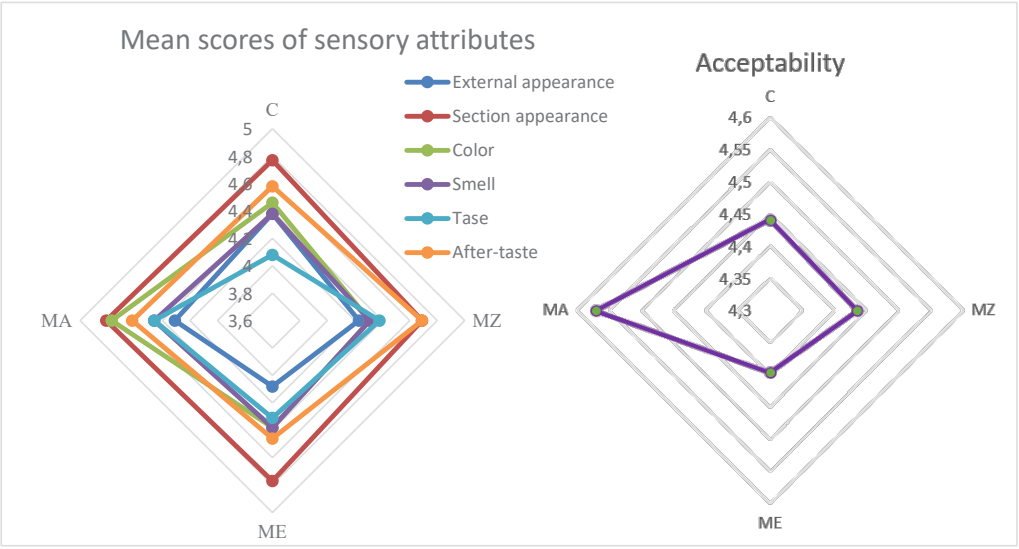


Figure 5. Sensory profile of the muffins

The MZ sample stood out for its balanced profile, with high scores for after-taste (4.5) and section appearance (4.5). The greenish nuances were perceived by consumers as indicators of "freshness" and a "natural product".

Although it recorded slightly lower scores for external appearance (4.3) and smell (4.3) due to darker pigments, the ME sample excelled in internal structure (4.6).

A key conclusion of the study is that all samples with added functional powders (MZ: 4.38; ME: 4.31; MA: 4.46) were rated superior to the control sample in terms of taste. This observation suggests that the fibers and compounds within the peels not only increase biological value but also appear to enhance the savory flavors (cheese and green onions) within the product matrix. Furthermore, the high scores for after-taste (above 4.46 for all samples) confirmed the absence of residual bitter or astringent tastes, which are often associated with the use of vegetable by-products in bakery applications.

Sample MA achieved the highest overall acceptability score (4.57), significantly outperforming the control sample (4.44). This suggests that the addition of apple peel is not only a method for increasing nutritional value but also enhances the global sensory profile, as the product was perceived to have a more complex aroma and superior aesthetics (due to the golden hues).

Samples MZ and ME recorded acceptability scores nearly identical to the control sample (approximately 4.45). This observation is crucial for the food industry: it demonstrates that by-products such as zucchini or eggplant peels can be integrated into muffins without negatively altering consumer perception, while maintaining the quality standards of the traditional product.

Our sensory results align with the findings of Henríquez et al. (2010a), Valková et al. (2022), who reported that apple peel inclusion significantly enhances the golden hue and overall appeal of bakery items. Furthermore, the high acceptability scores for zucchini and eggplant variants (MZ and ME) are consistent with the research of Lucera et al. (2012) and Mirani & Goli (2021), proving that these by-products can be successfully upcycled into savory matrices without compromising consumer perception. The absence of bitter notes in the after-taste (scores > 4.46) further validates the use of a gentle drying process at 45°C, as suggested by literature for preserving thermolabile aromatic compounds.

Muffin porosity results

The crumb porosity results reflect the direct impact of partially replacing wheat flour with fruit and vegetable peel powders on the alveolar architecture of the muffins. In the baking industry, porosity is a critical quality indicator, directly influencing texture and the consumer's perception of ”freshness”. The porosity values obtained for the analyzed muffins ranged between 52.82% and 53.14% (Figure 6).

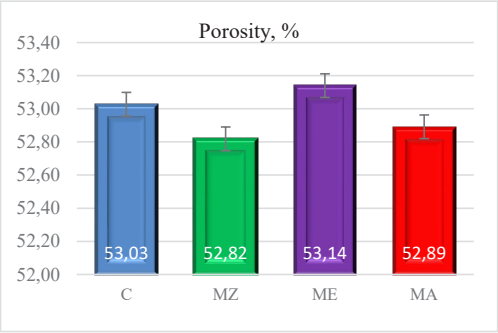


Figure 6. Muffin porosity

Although these values are lower than the porosity of a classic white bread (which frequently exceeds 62%), they fall perfectly within the standards for muffins or savory muffins, where the optimal range reported in the literature is 45-55%.

The control sample (C) exhibited a porosity of 53.03%, indicating an optimal gas-holding capacity and a well-developed gluten network. The ME sample recorded the highest value (53.14%). This phenomenon suggests that the fibers in the eggplant peel may act as stabilizers for the gas bubbles, preventing the network from collapsing during baking - an observation supported by the research of Lucera et al. (2012) and Mirani & Goli (2021). Samples MZ (52.82%) and MA (52.89%) showed minor decreases compared to the control. This trend is explained by the mechanical interference of the fibers within the protein matrix, partially reducing the dough's elasticity, as reported by Stojceska et al. (2009) in studies regarding fortification with vegetable by-products.

The minimal variations in porosity between samples (less than 0.3%) demonstrate an excellent integration of the functional powders into the muffin matrix. The uniform, yet relatively dense, alveolar structure is the result of two key factors: lipid intake and the presence of solid ingredients. The presence of oil and telemea cheese creates a ”shortening effect” on the gluten network, resulting in smaller alveoli and a more tender texture, according to studies by Alongi et al. (2019). Furthermore, the spring onion fragments and dill specks act as physical barriers to large alveolar expansion, favoring a fine and homogeneous porosity.

The crumb density, correlated with a porosity of approximately 53%, ensured high structural integrity, avoiding the formation of dense or gummy areas. This physical stability explains the superior sensory scores obtained for section appearance (4.6-4.8), confirming that the muffins maintained their aerated and ”soft and fluffy” character despite the addition of fibers.

Results regarding the titratable acidity of muffins

Titratable acidity is an essential physicochemical parameter that directly influences both the sensory properties (taste, freshness) and the technological characteristics (activation of leavening agents) of pastry products. The values obtained for the analyzed muffin batches ranged between 6.1 and 6.4 degrees of acidity (Figure 7).

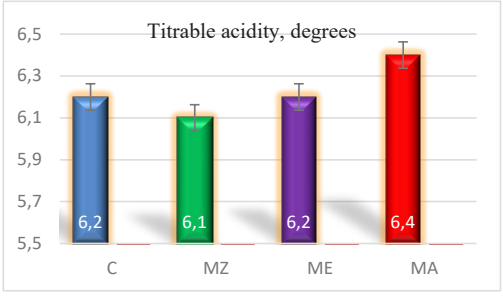


Figure 7. Titrable acidity

The comparative analysis of the samples reveals specific variations in acidity depending on the type of powder used; the MA (Apple) sample recorded the highest value of 6.4 degrees, a fact attributed to the presence of natural organic acids in the apple peel (primarily malic acid), which supplements the base acidity of the dough. In contrast, the Control sample (C) and the ME sample

presented identical values of 6.2 degrees, indicating that the addition of eggplant peel powder does not significantly alter the acid balance of the matrix compared to the standard recipe. At the opposite end, the MZ sample showed the lowest value of 6.1 degrees, suggesting either a slight acid-buffering capacity of the compounds in zucchini or a lower content of free acids in this specific by-product. A titratable acidity level within this range is considered optimal for savory pastry products utilizing fermented ingredients, such as telemea cheese. From a technological perspective, acidity plays a crucial role in activating sodium bicarbonate and baking powder. The resulting acid-base reaction releases carbon dioxide, the gas responsible for the superior porosity observed in our samples (52.82-53.14%).

According to the literature (Stojceska et al., 2009), an adequate level of acidity ensures an aerated alveolar structure, preventing the formation of a dense crumb. Furthermore, these acids enhance the flavor profile by potencying the lactic notes of the cheese and the freshness of the dill and green onions. In the case of the MA sample, the higher acidity aligns with reports by Alongi et al. (2019), who emphasize that fruit by-products can increase the concentration of organic acids, improving both the taste and the microbiological stability of the finished product. This optimal acidic balance explains the maximum sensory scores obtained for taste and overall acceptability, as it provides a necessary contrast to the richness of the lipids from the oil and cheese.

The moderate and constant range of acidity confirms that the partial replacement of flour with peel powders does not disturb the biochemical balance of the dough. On the contrary, the addition of apple peel powder (MA) optimizes acidity, contributing to an efficient release of fermentation gases and resulting in a fluffy muffin with a well-developed cellular structure, as confirmed by the porosity and moisture analyses.

Proximate chemical composition of muffins

The chemical composition analysis highlights the impact of fortification with vegetable by-product powders on the nutritional profile of the muffins. It is important to specify that while protein, carbohydrate, and lipid contents were calculated using specialized nutritional databases, the moisture and salt levels were both determined through experimental analysis. These experimental data were integrated to provide a comprehensive and verified overview of the products' functional value.

According to Figure 8, the moisture content determined by the oven-drying method ranged between 41.8% and 42.5%. The control sample (C) recorded the highest value (42.5%), followed by a progressive decline in the fortified samples: 42.1% (MZ), 41.9% (ME), and a minimum of 41.8% (MA).

This trend is generally attributed to the high water absorption capacity of the fibers within the peels, which alters the water release dynamics of the matrix during baking compared to pure wheat flour. In the food industry, savory muffins typically maintain a moisture level between 41-42% due to ingredients like telemea cheese and fresh vegetables. This level is considered ideal, as a content above 40% ensures the "moist" and succulent texture described in the sensory analysis, preventing premature drying.

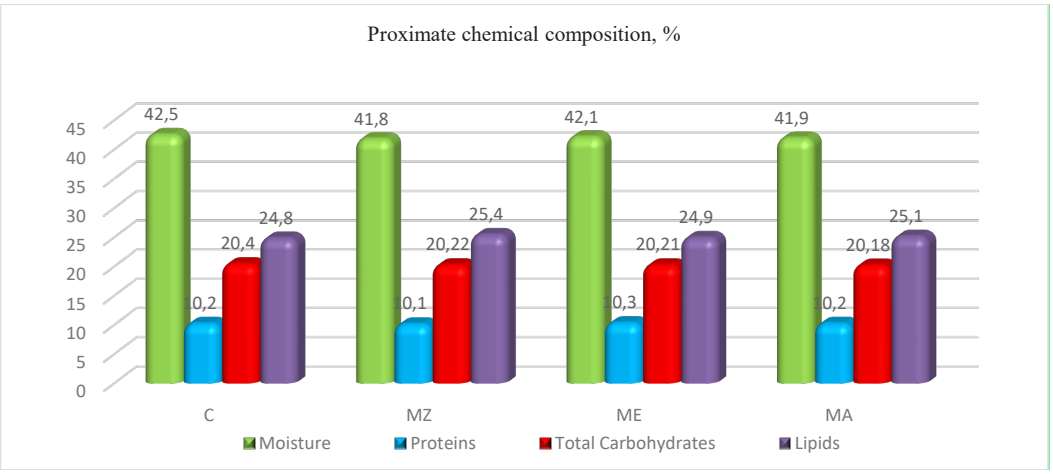


Figure 8. Proximate composition of the muffins

Our observations align with Alongi et al. (2019), who reported that apple-fortified muffins often exhibit lower final moisture than a control, likely because fibers disrupt the gluten network that typically "seals" moisture within the crumb. Furthermore, Henríquez et al. (2010b) demonstrated that apple peel powder reduces total moisture and water activity (a_w), providing a functional advantage by enhancing shelf-life and reducing microbial risk. Despite this decrease, the literature suggests that a lower moisture content is often compensated by a softer crumb, as fibers retain water in a bound form, providing a persistent sensation of freshness.

Regarding macronutrients, proteins (~10.2%), total carbohydrates (~20.3%), and lipids (~25%) remained relatively constant across samples. The significant lipid level is justified by the oil and telemea cheese, essential for the savory profile. However, a marked increase in fiber was observed: from 0.98% (C) to a peak of 1.38% (ME), confirming the success of the upcycling process. Henríquez et al. (2010a) noted that such increases in insoluble and soluble fibers have a major technological impact. For instance, Lucera et al. (2012) observed that certain vegetable fibers stabilize gas bubbles, explaining why our ME sample achieved the highest porosity (53.14%) despite its lower moisture, as the eggplant fibers supported superior alveolar expansion.

Salt values also rose slightly from 0.77% (C) to 0.947% (ME) and 0.936% (MZ), reflecting the natural mineral contribution of the peels. A salt content below 1% is considered moderate and balanced for savory bakery products, complementing the cheese and dill flavors without becoming overwhelming. This correlation is supported by Stojceska et al. (2009), who found that vegetable by-products are rich in mineral salts, contributing to the electrolytic profile of the finished product without the need for additional refined salt.

Antiradical activity: DPPH radical scavenging capacity of muffins

The comparative analysis of the antioxidant activity (Figure 9) demonstrates a significant increase in the radical scavenging capacity of the fortified muffins compared to the control sample (C - 5.01%). The highest inhibition was observed in the muffins enriched with apple peel flour (MA - 11.14%), followed by the zucchini variant (MZ - 10.04%) and the eggplant variant (ME - 8.76%). An increase in the antioxidant capacity of muffins supplemented with eggplant powder was also reported by Mirani & Goli (2021). Although the raw functional flours exhibited very high inhibition percentages - ranging from 76.86% to 82.09% at a 1:100 dilution - the values recorded for the finished products are lower.

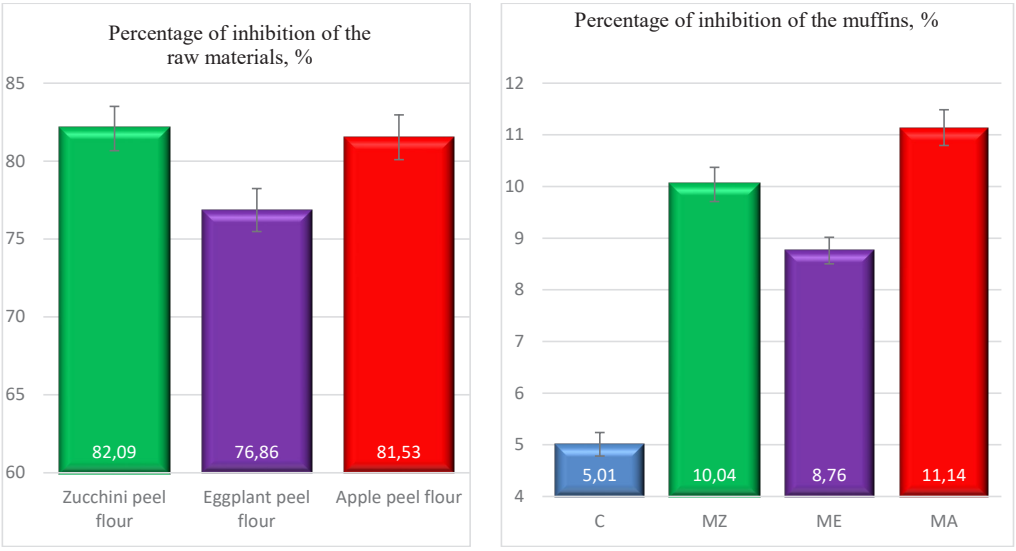


Figure 9. DPPH radical scavenging activity of muffins and raw materials

This trend is standard in bakery science, being attributed to the dilution of the functional ingredient within the complex food matrix and the thermal degradation of polyphenols during the baking process (typically at 180°C). Notably, the incorporation of these vegetable by-products successfully doubled the antioxidant potential of the final product.

The retention of approximately 10% inhibition in the final product, despite the harsh thermal treatment, is consistent with findings by Lucera et al. (2012), who noted that while heat decreases raw antioxidant power, the resulting functional bread or pastry remains significantly more protective than standard versions.

Furthermore, these results can be correlated with other physicochemical parameters determined in this study.

The MA sample, which exhibited the highest acidity (6.4 degrees), also showed the strongest antioxidant activity. This suggests that the acidic environment provided by the malic acid in the apple peel may have helped stabilize certain heat-sensitive antioxidants during baking.

Despite the slight decrease in moisture compared to the control (41.8-42.1% vs. 42.5%), the high fiber content in the MA and ME samples supported a superior alveolar structure. This indicates that the antioxidant-rich powders did not interfere with the leavening agents, allowing for a high porosity (over 52%) and an aerated volume.

The increased salt levels in the MZ and ME samples (0.936-0.947%) reflect the high mineral density of the peels, which typically accompanies the polyphenol complexes responsible for the observed DPPH inhibition. This aligns with Stojceska et al. (2009), who emphasized that vegetable by-products enhance the overall electrolytic and bioactive profile of baked goods.

CONCLUSIONS

The present study explored an innovative direction in food technology, responding to the current consumer trend of reducing the carbohydrate content of foods. In this context, the most effective strategy identified in the literature is the reduction of free sugar content, an aspect that formed the basis for the development of these savory muffins. Parallel to nutritional optimization, the research addressed major concerns regarding the valorization of food by-products within the framework of the circular economy, transforming often-ignored resources into high-value-added ingredients. The main achievements of the study include a successful nutritional reformulation where, by partially substituting wheat flour with powders obtained from zucchini, eggplant, and apple peels, the

goal of reducing carbohydrate density was achieved without compromising the product's structure. This integration effectively transformed the conventional muffin into a functional food.

Furthermore, the study highlighted a significant bioactive retention; although the baking process diminishes the raw antioxidant potential of the materials, the finished product offers a level of protective compounds and DPPH inhibition capacity significantly higher than the standard recipe, doubling the antioxidant potential in the case of the apple sample. From a technological standpoint, it was demonstrated that the use of by-products maintains an optimal physicochemical balance between the titratable acidity required for leavening, appropriate moisture levels between 41.8% and 42.5%, and a superior structural porosity of over 52%.

Beyond the technical parameters, the sensory acceptability of these muffins was remarkably high, proving that the use of these by-products results in a gourmet-quality product where expectations regarding health and taste are effectively satisfied simultaneously. In conclusion, the integration of apple, zucchini, and eggplant peel powders transforms the classic muffin into an innovative product capable of providing enhanced levels of protective compounds and fiber while maintaining an excellent sensory profile. The results confirm that the valorization of vegetable peels represents a sustainable solution for the modern food industry, offering products that do not compromise between nutritional benefits and the pleasure of taste.

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