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Physicochemical properties, volatile compound profile changes, and sensory evaluation of meatballs with the addition of different vegetable peels

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Abstract

This study aimed to determine the phenolic and antioxidant capacities of potato (*Solanum tuberosum* L.) and squash (*Cucurbita pepo* L.) peels, which are kitchen waste products, and to investigate their potential use in improving the physicochemical properties of meatballs, a meat product. Potato and squash peel powders were separately added to the meatball formulation at a rate of 6%. Meatballs with 6% breadcrumbs were used as the control group (C). Moisture content, color values (L*, a*, b*), pH, TBARS value, cooking loss, volatile compound profile, and sensory qualities of meatballs cooked in a pan with a small amount of olive oil were determined. When the color values of the meatballs were examined, the L* values of those containing vegetable peel powder (VPP) were lower than those of the control group. While the lowest average a* value was observed in the samples with squash peel powder, the highest average a* value was recorded in the control group. The pH of the meatballs with squash peel powder was higher than that of the other two groups. The TBARS values of the meatballs ranged between 0.30 and 1.80 mg MDA/kg, and increased with the addition of vegetable waste to the meatball formulation. The cooking loss values of the meatballs prepared with VPP were higher compared to those with breadcrumbs. As a result of GC-MS analyses, a total of 61 compounds were detected in the raw and cooked meatball samples. The number of compounds identified in cooked meatballs was lower than in the raw meatball dough. Among the compound groups in the meatballs, the highest number belonged to the terpene group, which included 19 compounds. Principal component analysis (PCA) clearly demonstrated that the volatile compound compositions of cooked and uncooked meatball samples differed. Based on the results obtained in this study, it can be concluded that the use of VPP in meatball production positively influenced the evaluated properties. VPP can serve as a substitute for breadcrumbs, thereby contributing to waste valorization and enhancing the waste utilization and sensory properties of the final product.

Keywords: color, meatball, peel, potato, sensory properties, squash, tbars, volatile compounds, waste

Introduction

The United Nations aims to end hunger, reduce food insecurity, and achieve better nutrition by 2030. To reach this goal, reducing the generation of edible food waste must be prioritized, as current food production is insufficient to meet the ever-increasing demand (Etuah *et al.*, 2023). At this point, sustainability and waste minimization are

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of great importance. Today, individuals should be more aware of the environmental and health implications of their food choices and consumption. For the future of our planet, it is essential to reduce the consumption of foods with a high negative environmental impact and to explore opportunities for utilizing waste and making it accessible for human use. Achieving this requires intensive research and investment in advanced waste management technologies.

Consumer awareness of the link between food and disease has increased significantly in recent years. Nutrition, a basic human need, is provided by food. Among food sources, meat holds an important place due to its advantages, such as high quantity and quality of protein, fat and fatty acid composition, and vitamin and mineral content (Savaş *et al.*, 2023). Meat is considered a priority food in terms of nutrition because of its high biological value protein, essential fatty acids, and rich vitamin and mineral profile (Turp, 2018; Karadağ *et al.*, 2019). Meatballs, one of the meat products, are defined as a ready-to-cook red or poultry meat mixture—or a cooked meat product—prepared in various ways by adding fats, flavorings, and one or more other food ingredients to a mixture made from one or more minced large or small cattle carcasses or poultry carcasses, in accordance with this communiqué and as specified by the Turkish Food Codex (Anonymous, 2019).

The addition of high levels of salt and oil to meat products such as meatballs—which already contain significant amounts of saturated fatty acids and cholesterol—during production may negatively impact health. In response to the growing demand for low-calorie, nutraceutical-effective foods essential for a healthy lifestyle, food manufacturers have prioritized the development of meat and meat products with reduced fat content (Karadağ *et al.*, 2019). To produce meat products that are both low in fat and possess functional properties, vegetables are often incorporated as fillers, binders, fat substitutes, dietary fiber sources, and natural antioxidants. These plant-based additions supply essential minerals and vitamins and are rich in natural antioxidants, dietary fiber, and phytochemicals. Furthermore, incorporating plant products into meat products can enhance their functional properties, reduce production costs, and either improve or maintain the nutritional and sensory qualities of the final product (Ergezer *et al.*, 2014; Bastos *et al.*, 2014). A review of the literature reveals that positive results have been observed in meat products enriched with plant parts that are typically considered waste. Examples include oat bran, rice bran, pea fiber, walnut fiber, olive oil production waste, rose hip (*Rosa canina* L.), *Ginkgo biloba* leaf, broccoli leaf, avocado seed, olive leaf, orange peel, pomegranate peel, pomegranate seed, artichoke vegetable waste, and artichoke fiber (Berry, 1997; Huang *et al.*, 2005; Anderson and Berry, 2000; Anderson and Berry, 2001; Sanchez-Zapata *et al.*, 2010; Karadağ *et al.*, 2019).

According to research, only the fleshy part of squash is utilized in the food processing sector, and approximately 18–21% of squash is wasted during production. Another commonly discarded part of the squash is its skin. Squash skin contains saponins, flavonoids, alpha-tocopherol, gamma-tocopherol, carotenoids, and amino acids such as histidine, arginine, leucine, glycine, isoleucine, methionine, alanine, valine, lysine, threonine, serine, tyrosine, phenylalanine, aspartic acid, and glutamic acid. Due to its component composition, it has been reported to exhibit burn and wound healing properties, as well as anti-neurotoxic, anti-helminthic, antioxidant, antibacterial, anti-proliferative, and antimicrobial effects (Shajan *et al.*, 2024). A review of the literature revealed studies in the baking industry regarding the use of squash seed flour as a substitute or supplement for wheat flour (Campos *et al.*, 2019; Saewan and George, 2020). However, no study was found on its application in meat products, except for Haque *et al.* (2024), who formulated buffalo meat sausage using ash gourd/white gourd (*Benincasa hispida*) peel powder.

Studies have shown that almost 50% of the phenolic compounds in potatoes are located in the peel and the tissues close to the peel (Al-Weshahy and Venket Rao, 2009; Albishi *et al.*, 2013; Akyol, 2017). In a study using extracts from potato peel and turmeric, these waste-derived extracts were added to sunflower oil, and the results indicated that potato peel extract exhibited higher antioxidant activity than turmeric extract alone, based on peroxide level analysis (Bozyokuş, 2019). Previous studies have also examined the functional properties of potato-derived ingredients—such as potato flour, mashed potato, dried potato extract, potato protein, and potato fiber—in meat products (Ali *et al.*, 2011; Uolanne and Ruusunen, 1983; Ergezer *et al.*, 2014; Colle *et al.*, 2019; Ikhlas *et al.*, 2011; Nieto *et al.*, 2009). Farvin *et al.* (2012) further suggested that potato peel extract could be used as a natural antioxidant. In light of these findings, the present study investigated the potential use of potato peels in the formulation of meatballs.

The literature review revealed that no studies have been conducted on the use of potato and squash peel powders as functional ingredients in meatball production. Meatballs are a popular meat product among consumers of all ages and are widely available both as ready-to-eat items and in traditional cuisine. Various non-meat components are incorporated during their production to enhance quality and develop healthier products (Akcan *et al.*, 2024). Among these, breadcrumbs are commonly used. Most commercially produced bread is made from refined wheat flour, as it yields a large loaf volume, light color, uniform crumb structure, and soft texture. In this study, breadcrumbs made from white flour were used. Despite their popularity, such breads lack essential nutrients—including vitamins, minerals, lysine, dietary fiber, and antioxidants. Moreover, they have a high glycemic index (Abedin *et al*., 2025) and contain gluten derived from refined wheat flour. Gluten, a storage protein found in cereals such as wheat, barley, and rye, forms the main structural component of bread and pasta. However, when consumed by genetically predisposed individuals, gluten proteins can trigger an immune-mediated enteropathy, resulting in intestinal damage (Allen and Orfila, 2018). Therefore, this study aimed to evaluate the potential of using potato and squash peel powders as substitutes for breadcrumbs to improve the functional properties of meatballs. Specifically, the study assessed the total phenolic content and antioxidant capacity of dried potato and squash peel powders, along with measurements of moisture content, color values (L*, a*, b*), pH, thiobarbituric acid reactive substances (TBARS), cooking loss after frying, volatile compound profile, and sensory properties of the meatballs.

Materials and Methods

Materials

Potatoes (*Solanum tuberosum* L.) and squash (*Cucurbita pepo* L.) purchased from a local market in Ağrı Province, Türkiye, were washed with tap water and peeled using a steel vegetable peeler to a thickness of approximately 0.1 mm. The collected peels were then dried by lyophilization (FDU-8612, OPERON, Korea) and ground into powder using a grinder. The total phenolic content and antioxidant properties of the potato and squash peel powders used in the study are presented in Table 1.

Lean meat and meat fat used in meatball production were obtained from the Ağrı Meat and Fish Institution. The meatballs were formulated in the laboratory to contain 15% fat. Other ingredients—olive oil, black pepper, cumin, onion, salt, and garlic—were purchased from a local market in Ağrı Province. The study was conducted using three different formulations: 6% breadcrumbs (control), 6% squash peel powder, and 6% potato peel powder. Each formulation was evaluated at two production stages (raw and cooked final product), with two replicates per sample. The data obtained from the study are presented in the corresponding tables within the relevant section.

Methods

Production of meatballs

In the study, three groups of meatballs were prepared using 15% fat-containing beef mince: a control group with breadcrumbs, and two experimental groups with either potato peel powder or squash peel powder. In the control group, 6% breadcrumbs were incorporated into the meatball dough, while in the experimental groups, potato and squash peel powders were added separately at the same ratio (6%) as substitutes for breadcrumbs. The meatball dough formulation for each group consisted of 87.75% minced beef (15% fat content), 6% breadcrumbs or peel powder (potato or squash), 0.25% black pepper, 0.5% cumin, 3.5% onion, 1.5% salt, and 0.5% garlic (Özdemir *et al*., 2014).

The meatball mixture was kneaded thoroughly and rested at +4 °C for 1 hour. After resting, the mixture was divided into round balls weighing 50 g each and shaped using ready-made molds (7 cm in diameter and 1 cm in thickness). The meatballs were then cooked in a non-stick pan with 25 ml of olive oil, with 4 meatballs placed in each pan. Once the oil temperature exceeded 80 °C, the meatballs were added to the pan. The cooking process was completed when the internal temperature of the meatballs, measured with an immersion food thermometer, reached 70 °C. During cooking, each surface of the meatballs was cooked for half of the total cooking time. The total cooking time was 6 minutes. The experiment was repeated twice, each time with different raw materials. Figure 1 shows images of the raw and cooked meatballs.

Determination of color intensity (L, a*, and b*) of meatballs*

The color intensities (L*, a*, and b*) of the samples were measured using a Minolta colorimeter (CR-400, Minolta Co., Osaka, Japan). The color measurements were performed according to the criteria of the International Commission on Illumination (CIE), based

Table 1. Total phenolic content and antioxidant properties of potato and squash peel powders.

Sample type	Total phenolic content (μg GAE/mg)	DPPH (IC_{50}, μg/mg)	ABTS (IC_{50}, μg/mg)
Butylated hydroxyanisole (BHA)	–	10.89±0.06	7.16±0.06
Potato peel	21.36±0.99	1567.67±22.72	1006.56±1.66
Squash peel	17.22±0.46	5067.94±16.46	1421.02±22.54

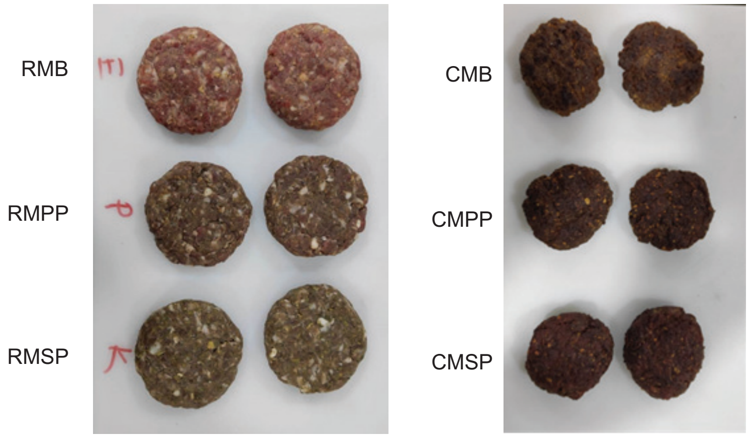

Figure 1. Raw and cooked meatballs. RMB, raw meatballs with breadcrumbs; CMB, cooked meatballs with breadcrumbs; RMPP, raw meatballs with potato peel powder; CMPP, cooked meatballs with potato peel powder; RMSP, raw meatballs with squash peel powder; CMSP. cooked meatballs with squash peel powder.

on three-dimensional color measurement. Specifically, L* represents darkness/lightness, with L* = 0 for black and L* = 100 for white; a* indicates the red-green spectrum, where +a* denotes red and -a* denotes green; and b* indicates the yellow-blue spectrum, where +b* represents yellow and -b* represents blue. The optical reader was placed in direct contact with the 1-2 mm thick sample surfaces, and color measurements were taken on the cross-sectional surface (Zor and Sengul, 2022).

Moisture analysis

Moisture analysis of the samples was performed using the drying method. A 5 g portion of each minced sample was placed in two parallel drying containers and dried in a drying cabinet at 100±2 °C until a constant weight was achieved. The dried samples were then cooled in a desiccator and weighed. The moisture content of the samples was determined by calculating the weight loss.

pH analysis

For pH analysis, 10 g of each sample were taken in triplicate, and 100 mL of pure water was added. The mixture was then homogenized for 1 minute using a mixer (Ultra-Turrax). The pH of the homogenates was measured using a pH meter.

Determination of cooking loss in meatballs

Cooking loss was calculated by considering the weight of the meatballs before and after cooking (Katmer, 2019). The meatballs were allowed to cool at room temperature for a specified period before measuring the cooking loss. The cooking loss values are expressed as percentages (%).

Determination of thiobarbituric acid reactive substances (TBARS) levels

TBARS analysis was used to determine lipid oxidation. The TBARS value was measured according to the method developed by Tarladgis *et al.* (1962) and modified by Lemon (1975). In this method, 1 g of the sample was taken, and 6 mL of trichloroacetic acid (TCA) solution (7.5% TCA, 0.1% EDTA, 0.1% propyl gallate; 1 g of propyl gallate dissolved in 3 mL of ethanol) was added. The mixture was homogenized for 15-30 seconds and filtered through Whatman No. 1 filter paper. From the filtrate, 1 mL was transferred into a tube, and 1 mL of 0.02 M TBA solution (2.9 g/L thiobarbituric acid) was added. This mixture was incubated in a boiling water bath for 40 minutes, cooled under tap water for 5 minutes, and then centrifuged at 2000 x g for 5 minutes. The absorbance of the samples was measured, and for the blank, 1 mL of TBA solution was added to 1 mL of TCA extract, following the same steps as for the samples. The TBARS value was calculated as μmol malondialdehyde (MDA) per kilogram of tissue using the following formula.

$$\text{TBARS} = \frac{\dfrac{\dfrac{\text{Absorbance}}{\text{K} \times 2} \times 6.8 \times 1000}{1000}}{\text{sample weight (g)}}$$

Determination of volatile compounds

A 2 g portion of each homogenized sample was weighed into 15 mL silicone septum vials. The vials were placed in a thermal block at 60 °C for 15 minutes to allow the sample to equilibrate. A CAR/PDMS fiber (75 μm fused silica, Supelco Ltd., Bellefonte, PA, USA) was then inserted into the vial to extract volatile compounds by solid-phase microextraction (SPME). The extraction process was completed by keeping the fiber in the vial at the same temperature for 30 minutes. Volatile compounds were identified using gas chromatography (GC, Shimadzu GC-2010) coupled with mass spectrometry (MS-QP2010, Shimadzu Corporation, Kyoto, Japan).

A Rxi-5Sil MS capillary column (30 m × 0.25 mm × 0.25 µm; Restek, Bellefonte, PA, USA) was used to separate the volatile compounds. The gas chromatography program began with an initial column temperature of 40 °C for 2 minutes, which was then gradually increased to 250 °C at a rate of 4 °C/min, held at 250 °C for 5 minutes, giving a total analysis time of 59.5 minutes. The temperature of the injection block and detector was set to 250 °C. Helium was used as the carrier gas at a flow rate of 1.6 mL/min. For compound identification, mass spectrometer libraries (NIST, WILEY, FFNSC) were used, and the results were expressed as area percentages (%) (Yılmazer *et al*., 2016).

Sensory analysis

For the sensory evaluation of the samples, a laboratory panel was used. The sensory analysis was conducted by a group of 10 panelists, consisting of academic staff from the Nutrition and Dietetics Department at the Faculty of Health Sciences, Ağrı İbrahim Çeçen University, Ağrı, Türkiye. The panelists were informed about the evaluation process beforehand. During the sensory evaluation, panelists were asked to rate the appearance, color, smell, taste, texture, and overall liking of the samples using a 9-point hedonic scale (9 = extremely like, 1 = extremely dislike).

Statistical analyses

The experiment was conducted with two replications, and the results are presented as mean ± standard deviation. One-way analysis of variance (ANOVA) was used to evaluate the results, and significant sources of variation were compared using Duncan's Multiple Comparison Test. The data were analyzed using SPSS 22.0 (IBM, USA), with comparisons made at a 0.05 significance level. The direction and strength of the linear relationship between variables were assessed using Pearson's correlation analysis. Additionally, principal component analysis (PCA) was performed to identify similarities and differences between the samples, using SIMCA-P+ 14.1 (UMETRICS).

Results and Discussion

Moisture content, color values, pH, and TBARS values of raw meatballs and cooked meatballs

The effect of substituting breadcrumbs with squash peel powder and potato peel powder on the moisture content of meatballs is shown in Table 1. Improving the water-holding capacity of meat products is a crucial factor, as water loss not only reduces yield but also leads to liquid accumulation in the packaging, affecting the color, texture, and overall acceptability of the product (Bastos *et al*., 2014). The addition of vegetable peel powders in place of breadcrumbs did not significantly affect the moisture content ($p > 0.05$). Akcan *et al*. (2024) observed that the moisture content of beef meatballs decreased in their raw form as the amount of acorn flour added increased. However, the same study reported no statistical difference in the moisture content of cooked patties, which aligns with the results of this study.

In contrast to the findings of the present study, several studies in the literature have reported that the addition of different flours increases the moisture content of meat products (De Oliveira *et al*., 2014; do Prado *et al*., 2019). Additionally, Elbir *et al*. (2023) found that the highest moisture content was observed in meatball samples with 0.5% chia seed addition, though the moisture content of other samples did not show significant changes. Similarly, Ali *et al*. (2011) examined the effect of potato flakes used as a fat substitute in low-fat beef meatballs and reported that moisture content increased with higher levels of potato flakes. Moisture content is a crucial parameter for microbial growth and significantly affects the shelf life of meatballs. The ingredients used in meatball production also influence moisture content. For instance, Khan *et al*. (2024) observed that using aloe vera gel in chicken meatballs increased the moisture content of the product. Furthermore, when comparing different stages of production, the moisture content of cooked meatballs decreased compared to the raw dough. This decrease was linked to the increased cooking temperature. Considering all the aforementioned studies, it is clear that the effects of various additives on the moisture content of meatballs can vary depending on their composition.

Cooking time and losses significantly impact various quality parameters of meat, including color, flavor, juiciness, tenderness, and micronutrient content (Savaş *et al*., 2023). When examining the color values of the meatballs produced, it was found that the addition of vegetable peel powders significantly affected the L^* and a^* values ($p<0.01$), but had no effect on the b^* values ($p>0.05$). The L^* values were lower in meatballs containing vegetable peel powder compared to those with breadcrumbs, indicating that the addition of vegetable peel powder caused a darkening of the color. The lowest mean a^* value was observed in the meatballs with squash peel powder, while the highest mean a^* value was found in the control group. The color properties of raw meat products can undergo significant changes during cooking, which is why the L^* and a^* values of the cooked meatballs decreased compared to the raw dough (Table 2). The color of meat and meat products is crucial for both quality and visual appeal, influencing consumer perception. Consequently,

Table 2. Moisture content (%), color values (L*, a*, and b*), pH, TBARS, and cooking loss of raw and cooked meatballs prepared with breadcrumbs and different vegetable peel additions.

Treatments	Moisture content (%)	L*	a*	b*	pH	TBARS (mg MDA/kg)	Cooking loss (%)
Control (Addition of breadcrumbs)	58.81±4.34^{a}	39.46±9.68^{a}	11.03±1.09^{a}	11.19±3.37^{a}	5.99±0.16^{b}	0.32±0.13^{c}	19.98±3.48^{b}
Addition of potato peel powder	58.01±3.80^{a}	36.15±8.44^{b}	7.61±1.09^{b}	10.16±2.75^{ab}	6.00±0.13^{b}	0.45±0.15^{b}	24.44±2.43^{a}
Addition of squash peel powder	57.42±3.56^{a}	37.35±7.98^{b}	6.59±2.73^{c}	10.42±1.93^{b}	6.31±0.05^{a}	1.78±0.47^{a}	23.58±1.64^{a}
Significance	ns	**	**	ns	**	**	*
Stage							
Raw	61.50±1.46^{b}	45.72±2.35^{a}	9.08±4.70^{a}	12.96±1.37^{a}	6.00±0.20^{b}	0.75±0.69^{b}	-
Cooked	54.66±1.54^{a}	29.58±1.38^{b}	7.74±1.09^{b}	8.22±0.82^{b}	6.20±0.11^{a}	0.95±0.79^{a}	-
Significance	**	**	**	**	**	**	-
TreatmentsxStage	ns	ns	**	**	**	ns	-

ns, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$.
a-c: Mean values with different letters are significantly different from each other.
TBARS, thiobarbituric acid reactive substances.

the a* value (which represents redness) is particularly important in evaluating meat color (Akcan *et al.*, 2024). The decrease in the a* value, which is an indicator of red coloration, suggests that the color of the meatballs became less red. Additionally, the b* value showed a significant decrease in cooked meatballs compared to the raw meatball dough (p<0.01).

The use of vegetable peel powders instead of breadcrumbs had a significant effect on the pH values (p<0.01). It was observed that the pH of the meatballs with squash peel powder was the highest (Table 2). This is likely due to the neutral compounds present in the squash peel. A significant difference (p<0.01) in pH was also observed between raw and cooked meatballs (Table 2). The pH of the meatballs increased during cooking, which may be attributed to the release of sulfhydryl, imidazole, and hydroxyl groups during the cooking process (Elbir *et al.*, 2023).

In addition to microbial spoilage, lipid oxidation is another common form of spoilage in meat and meat products. During lipid oxidation, malondialdehydes, which are decomposition products, are formed through the sequential oxidation of lipids by hydroperoxides from polyunsaturated fatty acids during storage. These malondialdehydes lead to the development of sensory off-flavors, negatively impacting the acceptability and quality of the products, thus limiting their shelf life. The TBARS (thiobarbituric acid-reactive substances) value is used to measure the amount of malondialdehyde, a secondary oxidation product, serving as a marker for lipid oxidation (Akcan *et al.*, 2024). The TBARS value of the minced meat used in the production of meatballs was found to be 0.11 mg MDA/kg (data not shown). The addition of ingredients during the production of meatballs led to an increase in the TBARS value compared to the minced meat. Specifically, the TBARS value significantly increased (p<0.01) when vegetable peel powders were incorporated into the meatball formulation. The TBARS values of the produced meatballs ranged from 0.30 to 1.80 mg MDA/kg (Table 2). The antioxidant activity of the compounds in the formulation had a notable effect on the TBARS values. The antioxidant activity of the potato and squash peel powders used in this study was relatively low compared to the standard. Additionally, potato peel powder exhibited higher antioxidant activity than squash peel powder. The TBARS value in processed meat products is typically expected to range between 1 and 2 mg MDA/kg, with sensory bitterness becoming apparent in products with TBARS values exceeding 2 mg MDA/kg (Gökalp *et al.*, 1995). Akcan *et al.* (2024) observed that TBARS levels increased during storage in uncooked meatball samples produced with medium-fat beef mince and acorn flour, suggesting that acorn flour was not effective in preventing lipid oxidation. Moreover, it was found that the TBARS value increased in cooked meatballs compared to the raw meatball dough. The cooking process significantly increases lipid oxidation in muscle tissue, leading to higher TBARS, peroxide, and free fatty acid values (Köseoğlu, 2014). Consistent with the findings of this study, Elbir *et al.* (2023) also observed that cooking elevated TBARS levels in meatballs with chia seed addition. In their study, the TBARS values of the meatballs ranged from approximately 0.6 mg MDA/kg, with changes in TBARS values depending on the chia seed usage rate; however, these changes were not statistically significant. Ilyasoglu (2014) investigated the TBARS values of raw and cooked meatballs prepared with four different formulations: no rosehip seed powder (RST) and 1%, 2%, and 4% RST. The study found that both raw and cooked meatballs containing 2% RST exhibited lower TBARS values at the end of storage compared to the control meatballs.

The denaturation of meat proteins during cooking results in a decrease in moisture content. Additionally, meatballs tend to shrink as they cook (Savaş *et al.*, 2023). This shrinkage is often associated with the loss of both water and fat. The use of vegetable peel powder instead of breadcrumbs in meatball formulations had a significant ($p<0.05$) effect on cooking loss. The cooking loss values for meatballs with vegetable peel powders were higher compared to those with breadcrumbs. This increase in cooking loss may be linked to fat loss, as no significant differences in moisture content were observed between the groups.

As a result of the GC-MS analyses, a total of 61 volatile compounds were detected in the raw and cooked meatball samples. Table 3 presents the percentages of volatile compounds found in dried breadcrumbs, squash peel powder, and potato peel powder when added to raw meatball dough and cooked meatballs. The breakdown of the number of compounds detected was as follows: breadcrumbs added to raw meatball dough (RMB) contained 48 compounds, breadcrumbs added to cooked meatball dough (CMB) contained 46 compounds, squash peel powder added to raw meatball dough (RMSP) contained 51 compounds, cooked meatballs with squash peel powder (CMSP) contained 47 compounds, potato peel powder added to raw meatball dough (RMPP) contained 49 compounds, and cooked meatballs with potato peel powder (CMPP) contained 50 compounds. When comparing the number of compounds detected, it was observed that the number of volatile compounds decreased in cooked meatballs (except for the potato peel powder group) compared to the raw meatball doughs. Among the various groups of compounds, terpenes were the most prevalent, with 19 compounds identified (Table 3). It has been reported that spices such as red pepper, black pepper, cumin, allspice, and garlic, commonly used in the production of sausages (a type of meat product), are significant sources of volatile compounds, with terpenes being an important class of these compounds (Şimşek *et al.*, 2023).

P-cymene (p-isopropyl toluene), a monocyclic monoterpene hydrocarbon, is a major compound found in the essential oils of various aromatic plants, including those from the genera *Artemisia* (Asteraceae), *Protium* (Burseraceae), *Origanum*, *Ocimum*, *Thymus* (Lamiaceae), and *Eucalyptus* (Myrtaceae). P-cymene is also naturally present in over 200 foods, such as cinnamon, carrots, orange juice, grapefruit, tangerines, raspberries, nutmeg, butter, cumin, and various other spices (Balahbib *et al.*, 2021). This compound exhibits a wide range of biological activities, including antioxidant, anti-inflammatory, antinociceptive, anxiolytic, anticancer, and antimicrobial effects (Marchese *et al.*, 2017). In the present study, p-cymene was detected in all meatball varieties. It was found in higher concentrations in meatballs cooked with squash peel powder compared to those cooked with breadcrumbs. Moreover, the percentage of p-cymene increased during cooking in the meatballs containing squash peel powder, while it decreased in those with potato peel powder (Table 3).

In addition to its anti-inflammatory and antioxidant properties, linalool also exhibits anti-cancer, sedative, anti-anxiety, and anticonvulsant effects. Clinical trials have confirmed the efficacy of dietary supplements containing (3R)-(-)-linalool in the treatment of anxiety disorders (Mączka *et al.*, 2022). In this study, the amount of linalool in all meatball samples decreased during cooking (Table 3).

Cumaldehyde, the main compound in the essential oil of cumin (de Mello *et al.*, 2023), exhibits anti-diabetic, anti-tumor, neuroprotective, anti-inflammatory, antimicrobial, and antifungal properties (Ebada, 2017). In this study, the percentage of cumaldehyde derived from cumin decreased in both breaded meatballs and meatballs with squash peel powder during cooking (Table 3).

Monoterpenes, a subclass of volatile plant compounds, are known for their pungent aromas and have been increasingly recognized for their biological and pharmacological activities. These activities include antioxidant, antiparasitic, anticancer, antiviral, and antinociceptive properties, contributing to the growing acceptance of herbal products. Gamma-terpinene, one of the most important monoterpenes, has notable antibacterial and secondary antioxidant effects (Nooshadokht *et al.*, 2022). In this study, the percentage of gamma-terpinene increased with the cooking process in meatballs with breadcrumbs, but decreased in meatballs with squash peel powder and potato peel powder. Additionally, alpha-terpinene, another compound detected, was found at lower levels in all cooked meatball samples compared to the raw meatballs (Table 3).

Limonene, a monoterpene from the Rutaceae family, exhibits a range of biological properties, including neuroprotective, antioxidant, anti-inflammatory, anticancer, antinociceptive, and gastroprotective effects (Eddin *et al.*, 2021). In this study, the percentage of limonene decreased during cooking in all meatball samples (Table 3).

Table 3. Volatile compound analysis results of raw and cooked meatballs prepared with breadcrumbs and different vegetable peels.

No	Compound	Compound group	RMB (%)	CMB (%)	RMPP (%)	CMPP (%)	RMSP (%)	CMSP (%)
1	Acetaldehyde	Aldehyde	0.23	0.42	nd	0.26	0.59	0.22
2	Methanethiol	Alkanethiol	nd	0.13	nd	nd	0.38	0.07
3	Ethanol	Alcohol	0.15	0.12	nd	0.09	nd	0.16
4	Propylene oxide	Epoxide	1.24	1.67	nd	0.18	1.17	2.01
5	2-Propanone	Ketone	nd	nd	1.30	1.19	nd	nd
6	Dichloromethane	Chloromethane	0.37	0.60	0.45	0.69	0.58	0.65
7	2-Methylpentane	Alkane	0.06	0.06	0.19	0.19	0.32	0.14
8	1-Bromopropane	Bromoalkane	0.31	0.34	0.43	0.54	0.11	0.39
9	Allyl mercaptan	Organosulfur	7.99	7.35	7.28	nd	5.39	nd
10	Hexane	Alkane	nd	nd	nd	4.71	nd	2.90
11	Ethyl acetate	Acetate ester	1.85	3.06	nd	4.12	1.01	3.41
12	Chloroform	Chloromethanes	1.00	1.95	1.73	2.10	1.01	1.52
13	3-Methylbutanal	Aldehyde	0.02	nd	0.24	0.20	3.09	0.35
14	2-Methylbutanal	Aldehyde	nd	nd	0.08	0.12	0.65	0.17
15	Allyl methyl sulphide	Organosulfur	0.27	nd	0.24	0.30	0.11	nd
16	Pentanal	Aldehyde	nd	0.44	nd	nd	0.14	1.30
17	Acetoin	Ketone	0.09	0.06	0.41	0.13	0.05	nd
18	Toluene	Toluenes	2.73	5.24	3.59	5.81	2.33	5.26
19	3-Methyl-1-butanol	Alcohol	nd	nd	0.11	nd	0.84	nd
20	Hexanal	Aldehyde	0.66	1.34	0.59	1.05	0.79	2.24
21	2-Methyl-2-pentenal	Aldehyde	nd	0.10	0.12	0.13	0.33	0.20
22	Allyl sulphide	Organosulfur	0.02	nd	0.02	nd	0.09	nd
23	Ethylbenzene	Alkylbenzene	0.51	0.82	0.40	0.61	0.27	0.65
24	p-Xylene	Aromatic hydrocarbon	nd	nd	nd	nd	0.35	0.63
25	Heptanal	n-alkanal	0.24	0.18	0.12	0.24	0.16	1.00
26	Methyl allyl disulphide	Organosulfur	0.27	0.41	0.15	0.29	0.27	0.19
27	α-Thujene	Thujene	0.11	0.14	0.21	0.16	0.09	0.23
28	α- Pinene	Terpene	0.32	0.40	0,60	0,43	0,27	0,35
29	β- Phellandrene	Terpene	0.12	0.18	0.24	0,18	0,15	0,21
30	β- Pinene	Terpene	2.46	3.11	3.79	3.07	2.08	3.01
31	1-Octen-3-ol	Alkenyl alcohol	nd	nd	0.27	0,05	nd	0.09
32	2,5-Octanedione	Ketone	nd	nd	0.50	0.03	0.03	0.86
33	β- Myrcene	Terpene	2.17	1.86	4.39	2.18	2.45	1.52
34	*l*-Phellandrene	Terpene	0.47	0.60	0.82	0.69	0.39	nd
35	δ.3-Carene	Terpene	1.66	1.86	3.43	2.14	1.46	1.87
36	α-Terpinene	Terpene	0.26	0.17	0.47	0.19	0.20	0.06
37	*p*-Cymene	Terpene	11.34	12.81	23.02	14.08	10.85	17.84
38	Limonene	Terpene	4.48	3.51	9.03	4.08	4.67	3.19
39	Eucalyptol (1.8-Cineole)	Terpene	0.41	0.12	1.21	0.16	0.56	0.21
40	cis-Ocimene	Terpene	0.04	nd	0.13	nd	0.03	nd
41	β-Ocimene	Terpene	0.07	0.02	0.16	nd	nd	nd
42	γ-Terpinene	Terpene	8.9	9.92	12.77	10.44	7.53	3.67
43	Allyl disulphide	Organosulfur	1.37	1.89	1.45	1.05	1.36	0.72
44	α- Terpinolene	p-menthadiene	0.21	0.16	0.35	0.18	0.20	nd
45	Diallyl tetrasulphide	Organosulfur	0.03	nd	nd	nd	0.10	nd
46	Allyl propyl disulphide	Organosulfur	nd	0.11	nd	0.06	nd	0.04
47	Diallyl disulphide	Organosulfur	0.07	nd	0.16	nd	0.18	nd

(*continues*)

Table 3. Continued.

No	Compound	Compound group	RMB (%)	CMB (%)	RMPP (%)	CMPP (%)	RMSP (%)	CMSP (%)
48	Linalool	Terpene	3.65	2.53	4.60	2.60	3.51	2.30
49	Nonanal	Aldehyde	nd	0.33	0.33	0.53	nd	0.92
50	Propyl disulphide	Organosulfur	0.24	0.03	nd	0.07	nd	nd
51	Camphor	Cyclic monoterpene ketone	nd	nd	0.07	nd	0.03	nd
52	Phellandral	Terpene	1.76	1.51	1.12	1.54	1.41	1.06
53	Dodecane	Alkane	0.1	0.12	0.08	0.18	nd	0.19
54	Cuminaldehyde	Benzaldehyde	32.69	25.82	29.47	23.85	34.39	20.29
55	2-Caren-10-al	Terpene	3.26	2.47	1.20	2.37	3.20	1.38
56	Phenylacetylcarbinol	Ketone	2.07	0.91	0.92	0.67	1.44	0.25
57	Tridecane	Alkane	0.06	nd	0.07	0.10	nd	0.12
58	δ-Elemene	Terpene	0.09	0.11	0.11	0.13	0.11	0.04
59	α-Copaene	Terpene	0.22	0.22	0.28	0.27	0.25	0.18
60	cis-Caryophyllene	Terpene	0.03	0.05	nd	0.10	0.08	0.05
61	Caryophyllene	β-caryophyllene	1.56	1.41	1.88	2.00	1.53	1.14

RMB; Raw meatballs with breadcrumbs, CMB; Cooked meatballs with breadcrumbs, RMSP; Raw meatballs with squash peel powder, RMPP; Raw meatballs with potato peel powder, CMPP; Cooked meatballs with potato peel powder, CMSP; Cooked meatballs with squash peel powder.

The reduction in limonene was more pronounced in meatballs with potato peel powder compared to those with breadcrumbs or squash peel powder.

In an in vitro study, allyl mercaptan, an organosulfur compound derived from garlic, was identified as the most potent histone deacetylase (HDAC) inhibitor among several organosulfur compounds in garlic. HDAC inhibitors have the potential to induce cell cycle arrest and apoptosis by reversing the repression of epigenetically silenced genes in cancer cells (Nian *et al*., 2008). In this study, the concentration of allyl mercaptan did not change significantly in meatballs made with breadcrumbs. However, its concentration could not be measured in meatballs made with crust powder, as it remained below the detectable level after cooking (Table 3).

1,8-Cineole is a compound that has garnered significant attention due to its various biological properties, including anti-inflammatory, antioxidant, mucolytic/secretolytic, bronchodilator, and antimicrobial effects. Recent studies have also emphasized its neuroprotective, analgesic, and proapoptotic properties, highlighting its potential therapeutic role in conditions such as Alzheimer's disease, neuropathic pain, and cancer (Hoch *et al*., 2023). In this study, 1,8-cineole was detected in all meatball formulations, both in their raw and cooked forms. A decrease in its concentration was observed after cooking, with the highest levels found in cooked meatballs with squash peel powder (CMSP).

Nine organosulfur compounds were detected in the meatballs: allyl mercaptan, allyl methyl sulphide, allyl sulphide, methyl allyl disulphide, allyl disulphide, diallyl tetrasulphide, allyl propyl disulphide, diallyl disulphide, and propyl disulphide (Table 3). These organosulphides are bioactive compounds primarily found in Allium plants such as garlic, onion, and leek. Organosulphides from garlic and onion are known for their potent antithrombotic, hypoglycemic, and lipid-lowering effects. They reduce cholesterol synthesis in hepatocytes by inhibiting HMG-CoA reductase, a key enzyme in the cholesterol biosynthetic pathway, lower blood pressure, and enhance non-specific immunity (Quesada *et al*., 2020).

Discrimination of samples with principal component analysis (PCA)

PCA was conducted to assess the differences in volatile compounds between raw and cooked meatball samples supplemented with breadcrumbs, potato, and squash powder. The results showed that the first principal component (PC1; 36.6%) and the second principal component (PC2; 29.4%) together explained 66% of the variation among the samples, indicating that the data were appropriate for PCA. A score scatter plot of the volatile compounds is shown in Figure 2A. The samples with squash peel powder (RMSP), breadcrumbs (RMB), and potato peel powder (RMPP) were positioned on the left side of the PCA plot, while the other meatball

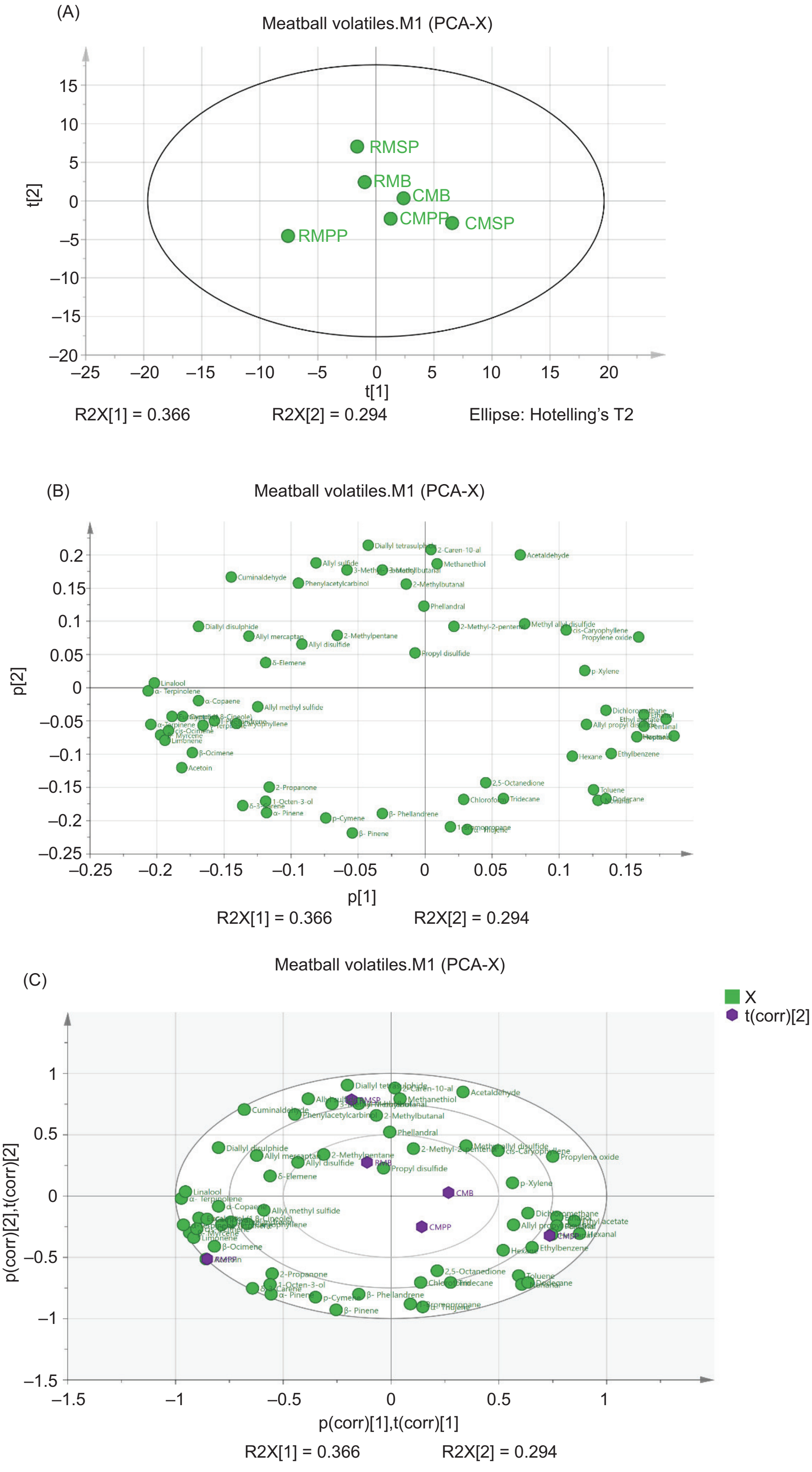

Figure 2. Principal component analysis (PCA) results of volatile compounds in meatball samples: (A) score scatter plot, (B) loading scatter plot, and (C) biplot (PC1 vs. PC2). RMB, raw meatballs with breadcrumbs; CMB, cooked meatballs with breadcrumbs; RMPP, raw meatballs with potato peel powder; CMPP, cooked meatballs with potato peel powder; RMSP, raw meatballs with squash peel powder; CMSP, cooked meatballs with squash peel powder.

samples appeared on the right side (Figure 2A). The distinct grouping of cooked meatball samples apart from the raw ones indicates that cooking significantly alters the volatile compound profile. The volatile compounds found in the upper right section of the loading scatter plot (Figure 2B), such as acetaldehyde and methanethiol ($r=0.861$, $p<0.01$), 2-methyl-2-pentenal and methanethiol ($r=0.821$, $p<0.01$), and 2-caren-10-al and phellandral ($r=0.862$, $p<0.01$), as well as those in the lower right section, including hexane and dodecane ($r=0.767$, $p<0.01$), hexane and ethyl acetate ($r=0.764$, $p<0.01$), ethylbenzene and ethyl acetate ($r=0.754$, $p<0.01$), ethylbenzene and toluene ($r=0.809$, $p<0.01$), ethylbenzene and allyl propyl disulphide ($r=0.893$, $p<0.01$), ethyl acetate and toluene ($r=0.813$, $p<0.01$), ethyl acetate and dodecane ($r=0.803$, $p<0.01$), pentanal and hexanal ($r=0.961$, $p<0.01$), pentanal and heptanal ($r=0.925$, $p<0.01$), hexanal and heptanal ($r=0.901$, $p<0.01$), hexanal and nonanal ($r=0.847$, $p<0.01$), toluene and chloroform ($r=0.867$, $p<0.01$), toluene and nonanal ($r=0.804$, $p<0.01$), toluene and dodecane ($r=0.869$, $p<0.01$), dodecane and 1-bromopropane ($r=0.810$, $p<0.01$), dodecane and nonanal ($r=0.828$, $p<0.01$), and nonanal and α-thujene ($r=0.851$, $p<0.01$), all showed strong positive correlations with each other. Likewise, a strong positive correlation exists among compounds in the upper left and lower left quadrants of the loading scatter plot (Figure 2B), such as allyl sulphide, 3-methyl-1-butanol, 3-methylbutanol, cuminaldehyde, phenylacetylcarbinol, 2-methylbutanal, allyl mercaptan, 2-methylpentane, allyl disulphide, eucalyptol, l-phellandrene, caryophyllene, gamma-terpinene, α-terpinene, cis-ocimene, β-myrcene, and limonene. In Figure 2C (biplot), the cooked meatball samples (CMB, CMPP, and CMSP), located to the right of PC1, are positioned closer to compounds such as p-xylene, 2-methyl-2-pentenal, methyl allyl disulphide, propylene oxide, acetaldehyde, methanethiol, 2-caren-10-al, dichloromethane, allyl propyl disulphide, ethyl acetate, hexanal, ethanol, ethylbenzene, pentanal, heptanal, toluene, dodecane, nonanal, 2,5-octanedione, chloroform, tridecane, 1-bromopropane, and α-thujene. This proximity suggests that these compounds are likely present at higher levels in the CMB, CMPP, and CMSP meatball groups compared to the other samples. A similar observation is seen with the compounds on the left side of PC1, which are associated with the raw meatball samples (RMB, RMPP, and RMSP). It is important to note, however, that any sample positioned on either side of PC1 is likely to contain higher concentrations of the volatile compounds to which it is closer. For instance, RMPP, located on the left side of PC1, shows higher levels of acetoin, β-ocimene, β-myrcene, l-phellandrene, α-terpinene, limonene, eucalyptol (1,8-cineole), cis-ocimene, γ-terpinene, and α-copaene compared to other cooked and raw meatball samples.

The results of the sensory evaluation are presented in Table 4. Panelists assessed the meatball samples based on appearance, color, odor, taste, texture, and overall acceptability. According to the sensory evaluation results, the control sample received the highest score, followed by meatballs with squash peel powder, while meatballs with potato peel powder received the lowest overall rating. Panelists noted that the taste of the meatballs with potato peel powder was relatively bland. The overall liking scores for meatballs with squash peel powder were similar to those of the meatballs with breadcrumbs. In contrast, Ali *et al.* (2011) investigated the effect of potato flakes on the quality characteristics of low-fat beef patties and found that the overall acceptability of patties formulated with potato flakes was high.

Conclusion

This study aimed to determine the phenolic and antioxidant capacities of potato and squash peels, which are often considered kitchen waste, and to explore their potential in enhancing the physicochemical properties of meatballs. The findings suggest that potato and squash peel powders can serve as viable alternatives to breadcrumbs in meatball production. Sensory and color analysis results indicate that meatballs made with squash peel powder received sensory scores similar to the control group, with a higher red color intensity compared to all other groups. This suggests that squash peel

Table 4. Sensory analysis results of raw and cooked meatballs prepared with breadcrumbs and different vegetable peels.

Treatment	Appearance	Color	Odor	Taste	Texture	Overall rating
Control (breadcrumbs added)	8.00±0.83^{a}	7.73±1.11^{a}	7.83±1.18^{a}	8.00±0.95^{a}	7.90±0.84^{a}	8.10±0.80^{a}
Potato peel powder added	6.83±1.23^{b}	6.55±1.28^{ab}	6.20±1.51^{b}	5.30±1.53^{c}	5.95±1.36^{c}	5.80±1.36^{c}
Squash peel powder added	7.35±0.86^{b}	7.20±0.83^{b}	7.30±1.26^{a}	7.00±1.56^{b}	7.10±1.29^{b}	7.25±1.37^{b}
Significant						
Treatment	ns	ns	ns	ns	ns	ns

*a-c: Mean values in the same column with different letters are significantly different from each other. ns, $P>0.05$; *, $P<0.05$; **, $P<0.01$.

powder could be a suitable replacement for breadcrumbs in meatball production, particularly from a consumer preference standpoint. Furthermore, the study found that vegetable peel powders had no significant impact on the moisture content of the meatballs. In terms of pH, the highest value was observed in meatballs with squash peel powder, and the cooking process led to an increase in pH across all groups. The addition of vegetable peel powder and cooking increased TBARS levels, indicating higher lipid oxidation.

Regarding cooking loss, meatballs with vegetable peel powder exhibited greater loss, likely due to fat loss during cooking. The cooking process also significantly impacted the volatile compound profile of the samples. This study highlights that vegetable peels, which are typically discarded despite their nutritional value, can be effectively utilized in meat products like meatballs. However, further research into sensory analysis and quality changes during storage would provide a more comprehensive understanding of how to optimize the use of these ingredients in processed meat products. Additionally, exploring the potential of powder or other products derived from vegetable waste in high-fat meat products could offer new avenues for sustainable food production. In conclusion, vegetable peel powders present a sustainable and nutritious alternative ingredient, positively influencing various physicochemical properties of meatballs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

Author Contributions

M.Z.: Writing—review & editing, methodology, investigation, formal analysis, project administration. E.E.: Writing—review and editing, formal analysis. K.F.: Formal analysis, and conceptualization. E.F.T.: Formal analysis and conceptualization. M.Ş.: Formal analysis, conceptualization.

Conflict of Interest

The authors declare no conflict of interests.

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