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Physicochemical, textural, sensory, and environmental impact assessment of muffins enriched with black chokeberry pomace

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Abstract. As healthy lifestyles and functional foods become essential priorities, the food industry is increasingly focusing on developing products with additional nutritional benefits. The incorporation of black chokeberry pomace powder into baked products, such as muffins, provides an effective approach to enhancing their nutritional profile while maintaining acceptable sensory attributes, including taste and appearance. The main purpose of this paper is to analyze the effects of adding black chokeberry powder on the physical, chemical, textural, and sensory qualities of muffins. Also, the environmental impacts associated with muffin production were determined by applying life cycle assessment (LCA) methodology. Four muffin formulations were prepared: three samples containing 5%, 10%, and 20% black chokeberry pomace, and a control sample without pomace addition. The results showed that incorporating high-fiber pomace powder into muffins reduced the volume of the dough due to increased resistance and decreased moisture content. The water activity (a_w) in the muffin samples ranged from 0.790 to 0.881, the pH decreased from 7.90 (control sample) to 7.08 (sample with 20% chokeberry pomace), while the titratable acidity increased with the increase in pomace content in the muffin samples. There is a major difference in color between the muffin samples, and texture parameters (especially hardness) were also influenced by the addition of pomace. Although higher levels of pomace incorporation were associated with increased environmental impact, the contribution was mainly linked to energy consumption rather than to the production process itself. However, adding chokeberry pomace is one of the solutions for utilizing by-products from the fruit juice industry, thus contributing to the circular economy.

***Keywords*:** bakery products; chokeberry by-products; fruit pomace; life cycle; sensory quality; texture.

1. Introduction

Food waste is generated in large quantities, in the EU approximately 130 kg of food waste per person were generated in 2023 [1]. This means that over 58 million tons of food waste (fresh weight) was generated, of which less than 11 million tons of waste was produced during food processing and manufacturing [1]. Most of the food waste generated is disposed of in landfills and has a negative impact on the environment [2]. Waste and by-products from fruit processing has high technological potential and can be used as functional ingredients in food [3]. Pomace, fruit peels, and seeds are rich in polyphenols, vitamins, and dietary fiber, which have beneficial effects on human health [2]. Fruit pomace has antioxidant and anti-inflammatory properties, antidiabetic potential, and antibacterial properties [4]. It is a by-product of juice extraction, resulting in large quantities, which represents an economic and microbiological challenge [4]. First, the wet fruit pomace is dried (to increase microbiological safety, to facilitate storage and transportation, to minimize food waste) and then it can be used in various food products [5].

Recently, one of the most popular and widely used berries has been chokeberry [6], which is rich in anthocyanins, flavonols, flavanols, proanthocyanidins, and phenolic acids [7]. The food industry produces the following products from chokeberry: syrups, juices, jellies, nectars, wines, fruit teas, and food supplements [7,8]. Chokeberry pomace obtained as a by-product of fruit processing is rich in anthocyanins, accounting for more than 50% of the total anthocyanin content of the fruit, as well as dietary fiber, which represents approximately 60% of the fruit's total composition [9]. Due to its properties, chokeberry pomace can be used in various food products (bread [10-12], muffins [3, 13], meat products [14, 15], dairy products [16, 17] and others), to improve their nutrient content, intensify color, and add antioxidant, antimicrobial anti-inflammatory properties that are beneficial to health [14, 18, 19].

Muffins are one of the most popular baked goods consumed worldwide [20] and are generally made from white flour, fat, and sugar [3]. In recent years, various studies have been conducted to replace white flour rich in gluten with raw materials that do not contain this protein, due to increased consumer interest in gluten-free products, but this can lead to a decrease in the quality of the final products [3, 21].

Numerous studies have demonstrated that partially replacing (up to 30%) wheat flour in food products (like muffins) with fruit powder obtained from by-products is feasible [3, 22]. The use of chokeberry powder, obtained by drying pomace, in the production of muffins is in line with the principles of the circular economy, promoting

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sustainability using by-products from fruit juice production [3]. This contributes to reducing food waste by utilizing pomace and promoting sustainable production practices. It also results in new food products that are nutritionally improved due to the addition of polyphenols and fibers present in pomace.

The aim of this study was to investigate the physicochemical, textural and sensory properties of muffins enriched with black chokeberry pomace (5, 10 and 20%) and to determine the environmental impact associated with production of these muffins.

2. Experimental

2.1. Materials and muffins preparation

White flour, sugar, coconut oil, coconut milk, eggs, and baking powder were purchased from a Romanian supermarket. Black chokeberry pomace (powder) was obtained from a natural products store. The dry ingredients (flour, black chokeberry powder, baking powder and salt) are mixed in a bowl. The next step was to separate the eggs. The egg whites were beaten until they became a dense white foam, approximately doubling their volume through aeration. Following foam formation, sugar was added progressively to the egg whites until a firm and stable structure was achieved. Simultaneously, the egg yolks were blended with coconut oil and coconut milk to obtain a homogeneous mixture of lighter appearance. The two mixtures were gradually combined by gently incorporating the yolk mixture into the whipped egg whites in order to preserve foam aeration. Once fully incorporated, the dry ingredients were also added, which had been sifted beforehand to avoid the formation of small, compact flour lumps. The batter was divided gravimetrically, with approximately 45-50 g of batter allocated to each muffin prior to baking. The composition was dosed into specific muffin molds and placed in the oven preheated to 180 °C for 30 min. After baking, the muffins were removed from the oven and left to cool to ambient room temperature for 2 hours, after which they were analyzed (Figure 1). The culinary formulation, expressed as proportional parts by mass of white flour, sugar, eggs, coconut milk, coconut oil, and baking powder, was 5.17:4.33:3.50:2.50:1:0.17, respectively. The control sample (S1) did not contain black chokeberry pomace, while samples S2, S3, and S4 contained 5%, 10%, and 20% black chokeberry pomace, respectively. These percentages represent the substitution of wheat flour by black chokeberry pomace. Figure 2 shows the resulting muffin samples, both whole and in vertical-section.

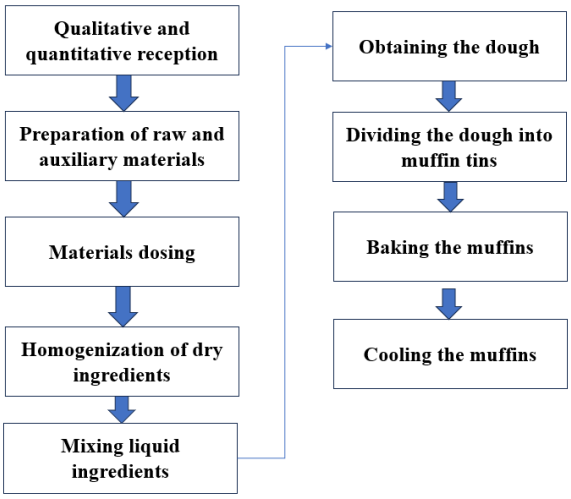


Figure 1. Steps for obtaining muffins with black chokeberry pomace

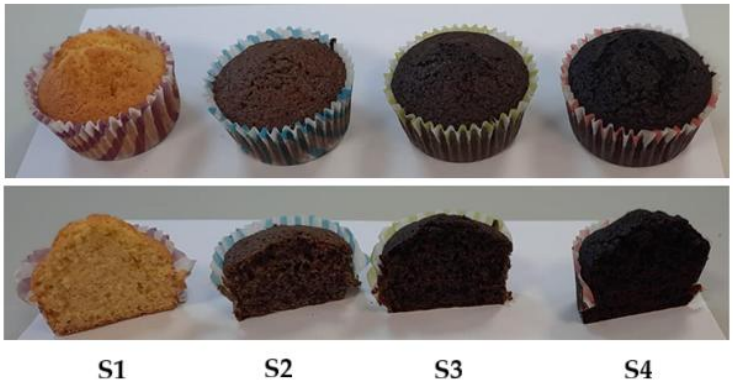


Figure 2. Muffin samples (S1 – control sample; S2 – 5% black chokeberry pomace sample; S3 – 10% black chokeberry pomace sample; S4 - sample with 20% black chokeberry pomace)

2.2. Determination of the muffins' properties

Extract preparation: 5 g of muffin sample was added to 50 cm^3 of distilled water. This content was heated on a boiling water bath for 30 min. The extract was then cooled, made up to 250 cm^3 of distilled water and filtered [23].

pH determination. An aliquot of 10 cm^3 of the prepared extract was transferred into a beaker. The pH electrode was inserted into the beaker with the extract and the pH value was read on the pH meter screen [24].

Determination of titratable acidity. A volume of 50 cm^3 of the previously prepared extract was measured and placed in an Erlenmeyer flask [25]. After adding a few drops of 1% phenolphthalein solution, it was titrated with 0.1N NaOH solution until a faint pink color appeared, which persisted for 2-3 minutes. The equation for calculating titratable acidity is as follows (Eq. 1) [24]:

$$\%\ acid = \frac{C_{NaOH} * V_{NaOH} * Ge_{acid}}{V_e * 1000} * 100 \qquad (1)$$

where: C_{NaOH} – concentration of NaOH solution (mEq/mL; V_{NaOH} – volume of NaOH used in titration (mL); Ge_{acid} – equivalent weight of the predominant acid (malic) (mg/mEq); V_e – volume of extract (mL); 1000 - factor relating to the conversion of mg to g (mg/g).

Determination of moisture content was carried out using the oven drying method, 5 g of each muffin sample was dried (at 105 °C) to constant weight [26].

The moisture content was calculated according to Equation (2):

$$\%\ M = \frac{W_{ws} - W_{ds}}{W_{ws}} \times 100 \qquad (2)$$

where: M – moisture (%); W_{ws} – mass of the wet sample (g); W_{ds} – mass of the sample after drying (g).

Water activity determination: Water activity (a_w) was determined using a Lab Touch-a_w water activity meter. Approximately 3 g of sample were placed in the cuvette, and the water activity was subsequently measured and displayed by the instrument.

Muffins color determination. Minolta Chroma Meter CR-400 (Minolta Co. Ltd., Osaka, Japan) was used to determine the color of the black chokeberry pomace muffins. The color parameters determined were: L* (lightness/darkness), a* (red/green), and b* (yellow/blue). Three readings were taken per sample at different points on the surface of the muffin (in section and above). The parameter L* varies in the range 0÷100 from black to white, the parameter a* varies on a scale from -a* to +a* from green to red, and b* on a scale from -b* to +b* from blue to yellow [26]. The total color differences (ΔE*) between the control muffins and the test muffins (with black chokeberry pomace) were calculated using Equation (3) [27]:

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \qquad (3)$$

where L^*, a^* and b^* are the color parameters of the black chokeberry pomace muffins, while L_0^*, a_0^* and b_0^* are the color parameters of the control muffins.

Textural properties of muffins. The Perten TVT 6700 texturometer was used to determine the textural characteristics (hardness, adhesiveness, cohesiveness, stickiness, elasticity, gumminess and chewiness) of black chokeberry pomace muffins. The center of the muffins was cut into cube-shaped blocks with dimensions of 2.5 cm × 2.5 cm × 2.5 cm, and the samples were placed on the test table. The sample height was 25 mm, the compression was 7 mm, the holding time was 32 s, the trigger force was 5 g, the initial speed was 2 mm/s, the test speed was 1 mm/s and the withdrawal speed was 10 mm/s [28].

All determinations were performed in triplicate.

Sensory analysis. The sensory analysis was performed by 7 experienced food industry engineers using the nine points of the standard hedonic scale, where 9 denotes "I like it extremely much", 5 "I neither like it nor dislike it", and 1 indicates "I dislike it extremely much". The sensory attributes investigated were: external appearance, cross-sectional appearance, core color, taste, smell, and overall acceptance [28].

2.3. Life cycle methodology

Goal, system boundaries, and functional unit. LCA analysis was applied to model the environmental impact of the muffins, and GaBi software was used to determine the values of the impact categories. The functional unit (FU) used was 982 g of muffin dough, from which 23 (from the control sample) and 20 (from each of the other three samples) muffins were obtained. The four scenarios considered for the LCA analysis correspond to the four muffin samples. The scenarios included: muffin production stages, wheat flour production, black chokeberry flour production, production of electricity necessary for the processes, and wastewater treatment.

Inventory analysis. The input data related to muffin production were the ingredients (eggs, white wheat flour, sugar, coconut milk, crude coconut oil, baking powder, and black chokeberry pomace), electricity, and water.

The electricity necessary for this step was estimated at 1.88 kWh based on the considering that the mixer consumes 0.15 kWh per 30 min, while the electric oven consumes 1 kWh per 30 min, and the dishwasher 0.73 kWh per one washing cycle. The water consumption required for dishwashing was set at 9.5 L per wash cycle, and the dishwashing detergent consumed per wash cycle was 20 g. Inventory data related to functional unit are presented in Table 1.

Impact assessment. CML2001 - Jan 2016 method was selected for the impact assessment stage. Environmental impact categories considered in this study are: Abiotic Depletion (ADP fossil), Acidification Potential (AP), Eutrophication Potential (EP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Global Warming Potential (GWP 100 years), excluding biogenic carbon, Human Toxicity Potential (HTP), and Photochemical Ozone Creation Potential (POCP).

Table 1. Inventory data related to functional unit

Process	GaBi database
Muffins production	**Inputs**
	Eggs [RO animal production] [a]
	White wheat Flour [GLO Materials from renewable raw materials] [b]
	Sugar (crystal sugar) [GLO Materials from renewable raw materials] [b]
	Coconut milk [GLO Materials from renewable raw materials] [b]
	Crude coconut oil [GLO Materials from renewable raw materials] [b]
	Baking powder [GLO chemicals] [b]
	Water (tap water) [EU-28 Operating materials] [b]
	Electricity [RO Electric power] [b]
	Detergent [RO Operating materials] [a]
	Outputs
	Muffin [RO processing] [a]
	Baking losses [RO processing] [a]
	Waste water [GLO Production residues in life cycle] [b]
White wheat flour production	**Inputs**
	Wheat grains dried [GLO Materials from renewable raw materials] [b]
	Electricity [RO Electric power] [b]
	Outputs
	White wheat Flour [GLO Materials from renewable raw materials] [b]
	Wheat Bran (14-17% CP) [GLO Materials from renewable raw materials] [b]
	Waste (solid) [GLO Waste for disposal] [b]
Black chokeberry flour production	**Inputs**
	Black chokeberry pomace [RO Production residues in life cycle] [a]
	Electricity [RO Electric power] [b]
	Outputs
	Black chokeberry flour [RO Material recovery] [a]
Electricity production	RO: Electricity grid mix process [b]
Waste water treatment	EU28: Waste water treatment process [b]

a—User-defined process (RO – Romania). b—Process already existing in the database (EU-28; GLO—Global).

2.4. Data statistical analysis

The physicochemical, textural and sensory analyses results were statistically evaluated (ANOVA and Tukey's test) with Minitab version 17 (State College, PA, USA). Also, principal component analysis (PCA), and Pearson's correlation were conducted.

3. Results and discussion

3.1. Physico-chemical characteristics of black chokeberry pomace muffins samples

The physico-chemical properties of black chokeberry pomace muffins samples are presented in Table 2.

The weight of the muffin samples before baking was: 45.82±2.48 g (S1), 43.83±2.89 g (S2), 46.2±3.3 g (S3), and 53.05±4.6 g (S4). After baking, the control sample (S1) exhibited an average weight of 40 g and a height of 5.0 cm. In comparison, muffins enriched with black chokeberry pomace showed average weights and heights of 37.6 g and 3.5 cm (S2), 39.2 g and 4.2 cm (S3), and 43.4 g and 4.5 cm (S4), respectively. Compared to the control sample (S1), a reduction in weight was observed for muffin samples S2 and S3, in which wheat flour was partially replaced with 5% and 10% chokeberry pomace, respectively, whereas an increase in weight was recorded for the sample containing 20% chokeberry pomace (S4).

Table 2. Physico-chemical characteristics of black chokeberry pomace muffins samples

Samples	Weight (g)	Height (cm)	Moisture (%)	Water activity (a_w)	Titratable acidity (% malic acid)	pH
S1	40.23±0.25 [b]	5.1±0.1 [a]	21.86±0.03 [a]	0.881±0.01 [a]	0.0013±0.00 [d]	7.90±0.06 [a]
S2	37.60±0.10 [d]	3.5±0.2 [c]	21.04±0.05 [c]	0.790±0.01 [d]	0.0026±0.00 [c]	7.57±0.02 [b]
S3	39.17±0.06 [c]	4.2±0.1 [b]	21.43±0.02 [b]	0.813±0.00 [c]	0.0040±0.00 [b]	7.37±0.04 [c]
S4	43.37±0.15 [a]	4.5±0.2 [b]	21.51±0.01 [b]	0.836±0.00 [b]	0.0053±0.00 [a]	7.08±0.01 [d]

S1 – control sample, S2 – 5% black chokeberry pomace sample, S3 – 10% black chokeberry pomace sample, S4 - sample with 20% black chokeberry pomace. Values with different letters within one column are significantly different ($p < 0.05$).

The height of all samples of black chokeberry pomace muffins fell below 5 cm. The incorporation of water-absorbing ingredients instead of gluten results in a more compact structure, which ultimately leads to a reduction in the final product [3]. Similarly, Nath *et al.* [29] reported an increase in the specific gravity of samples compared to the control sample when black chokeberry pomace was added to muffins. Black chokeberry powder has different densities compared to other ingredients such as flour, sugar, and eggs. When these powders were added to the batter, they altered the overall appearance, density of the mixture, leading to changes in specific gravity. The black chokeberry powder added to the muffins may have induced additional moisture, and this made the batter denser, potentially increasing the specific gravity. Changes in specific gravity can affect the distribution of air bubbles in the dough, which can lead to variations in the crumb

structure [30]. Adding high-fiber flour reduces the volume of the dough due to increased strength and, consequently, reduced gas cells. Katina *et al.* [31] concluded that the addition of fiber to bakery products can cause technological quality problems, resulting in a decrease in CO_2 gas retention in the dough matrix. Walker *et al.* [32] observed similar effects for the fortification of bread, muffins, and brownies made with red grape pomace. From Table 2 it can be seen that the moisture content of the muffin samples decreased for the muffin samples with pomace (between 21.04 and 21.51%) compared to the control sample (21.86%). Among the samples of muffins with pomace, an increase in moisture is observed with increasing pomace content. Moisture decreases when black chokeberry pomace is added due to the presence of fibers in the pomace [33]. In terms of moisture, the samples with higher addition of black chokeberry powder recorded significantly higher values than the control group. This may be due to the high-water content of berries. These berries have high levels of sugars that typically act as humectants. This may influence the greater interaction with water within the muffin matrix. The higher moisture content of these fruits can lead to changes in the texture of the muffins, affecting their overall quality. Increased moisture levels may result leading to a softer texture, potentially improving the perceived freshness and moistness of the muffins [30].

Water activity (a_w) is the ratio of the vapor pressure of food to the vapor pressure of pure water and is a determining factor in food spoilage. Muffins are semi-perishable foods with an a_w range of 0.50-0.80 [34]. For baked muffins the water activity is around and below 0.80-0.82 which ensures sufficient resistance to microbiological growth for this type of product [35]. In this study a_w ranged from 0.790 to 0.881 (Table 2). Javed *et al.* [34] reported a_w values between 0.56 and 0.65 for muffins supplemented with mulberry powder.

The pH of any food system is an indication of product stability. It varies depending on the change in respiration and microbial activities [34]. The pH of the muffin samples ranged from 7.08 (S4) to 7.90 (S1), and it decreased with increasing black chokeberry pomace content in the samples. The decrease in pH of muffins supplemented with mulberry powder (from 7.3 to 5.61) was also observed by Javed *et al.* [34]. Malic and quinic acids, but especially citric acid, are the main acids found in berries, being responsible for most of the changes in pH and acidity in bakery products such as muffins. Also, sugars in berry-enriched muffins may contribute to higher acidity during baking, as they undergo reactions at high temperatures, releasing acidic substances [30]. According to Baldán *et al.* [36], the pH trend in muffins decreases as the grape marc powder content increases (increasing acidity). Low pH values (acidic) can help preserve food by inhibiting microbial growth [30]. The results showed that pH and acidity were significantly different ($p < 0.05$) by adding black chokeberry powder, with pH values decreasing and acidity values increasing. The pH of the 5% enriched muffins measuring 7.57 and acidity reaching 0.0026% indicated a notable impact of the extracts on the overall acidity level of the products, presenting results comparable to the control samples. Hardness and gumminess as the main texture properties showed a notable increase with the addition of black chokeberry powders [30].

The titratable acidity expressed in % malic acid ranged between 0.0013% (S1) and 0.0053% (S4). The titratable acidity of the muffins increases with the increase in the percentage of black chokeberry pomace added to the muffins.

In general, the color of baked goods is the result of various chemical reactions that occur during baking, including the Maillard reaction and caramelization [37]. The Maillard reaction occurs through the condensation of a carbonyl compound (such as a reducing sugar) with an unprotonated amine (from an amino acid), leading to the formation of brown or black pigments with high molecular weight [38]. Thus, it is expected that the brightness will decrease and the a* and b* parameters will approach reddish/yellowish tones, regardless of the addition of substitution ingredients. Consumers consider darker muffins to be healthier than lighter ones. The highest brightness values were recorded for the control muffins, with L* values of 26 for the top view and 24.43 for the cross-sectional view. In contrast, muffins enriched with chokeberry pomace exhibited lower brightness, with L* values of 16.93 (S2) and 9.91 (S4) for the top view, and 12.82 (S2) and 7.30 (S4) for the cross-sectional view, respectively (Figures 3 and 4).

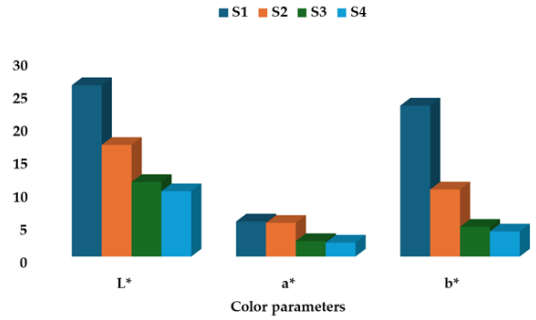


Figure 3. Color parameters of muffin samples (top view): S1 – control sample, S2 – 5% black chokeberry pomace sample, S3 – 10% black chokeberry pomace sample, S4 - sample with 20% black chokeberry pomace

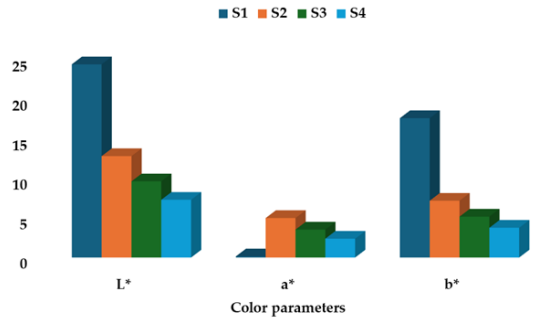


Figure 4. Color parameters of muffin samples (in section): S1 – control sample, S2 – sample with 5% black chokeberry pomace, S3 – sample with 10% black chokeberry pomace, S4 - sample with 20% black chokeberry pomace

The brightness of the samples darkened with the increase in the percentage of black chokeberry pomace in the muffins. The muffin samples were darker in cross-section. The values of the parameter a* are positive, meaning that the muffin samples are reddish in color,

and the values of the parameter b* are positive for all samples, meaning that they are yellow in color.

The addition of black chokeberry pomace influences the color of muffin samples; the values of the color parameters decrease with increasing added pomace content. For all samples of muffins with chokeberry pomace powder ΔE > 3 which means major color differences. Thus, for the top view the following color differences were determined: ΔE = 15.62 (S2), ΔE = 23.72 (S3) and ΔE = 25.19 (S4). Regarding the color differences of the samples in section, the values obtained were: ΔE = 16.35 (S2), ΔE = 19.64 (S3) and ΔE = 22.15 (S4).

3.2. Textural properties of black chokeberry pomace muffins samples

The results regarding the textural parameters of the black chokeberry pomace muffin samples are presented in Table 3.

Table 3. Textural parameters of black chokeberry pomace muffin samples

Muffin sample	Hardness	Adhesives	Stickiness	Cohesion	Gumminess	Chewability
S1	414±0.6 ^{d}	-0.21±0.1 ^{a}	-0.88±0.5 ^{a}	0.692±0.02 ^{a}	287±0.5 ^{d}	287±0.5 ^{d}
S2	429±0.1 ^{c}	-0.12±0.1 ^{a}	-1.00±0.7 ^{a}	0.740±0.03 ^{a}	317±0.2 ^{c}	317±0.2 ^{c}
S3	658±0.7 ^{a}	-0.12±0.1 ^{a}	-1.00±0.0 ^{a}	0.715±0.02 ^{a}	370±0.7 ^{b}	370±0.7 ^{b}
S4	519±0.9 ^{b}	-0.95±0.9 ^{a}	-2.46±1.2 ^{a}	0.698±0.05 ^{a}	457±0.3 ^{a}	457±0.3 ^{a}

Values with different letters within one column are significantly different ($p < 0.05$).

The hardness of the samples ranged between 414 (control sample) and 519 g (sample with 20% black chokeberry pomace) and an increase in hardness values was observed with the increase in the amount of pomace added. This may be due to the higher fiber content of these samples, which increased the density of the dough and reduced air incorporation during baking. Thus, the resulting samples were more compact, which increased the force required to compress them [39]. Fibers also influenced cohesiveness: values decreased as the percentage of pomace product added increased. The desegregating effect of fiber is reflected in a lower energy requirement when performing a second compression [39].

The parameters of gumminess (mechanical attribute of texture related to the cohesion of a soft product and is related to the force required in the mouth to disintegrate the product to the ideal point for swallowing), chewability (mechanical attribute of texture related to cohesion and the time spent, or the number of bites required for a solid product to be ready to swallow) are directly related to the texture characteristics perceived by consumers during chewing and swallowing a product [38]. In this study, the values of the two parameters increased with the increase in the amount of pomace added (Table 3).

3.3. Sensory attributes of black chokeberry pomace muffins samples

Figure 5 illustrates the effect of black chokeberry pomace on the sensory attributes of the muffin samples.

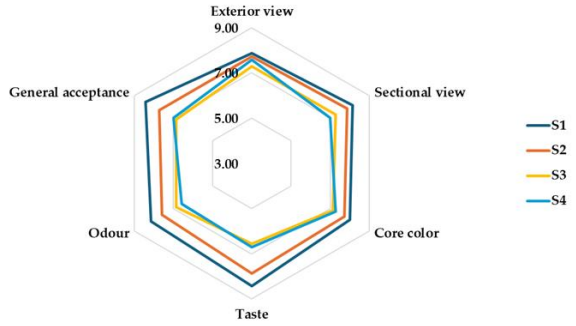


Figure 5. Sensory attributes of black chokeberry muffin samples

The control sample (S1) received the highest scores, being particularly appreciated for taste, smell and appearance in section. Of all the samples of black chokeberry pomace muffins, the sample with 5% pomace received the highest scores, being most appreciated for taste and appearance in the section. Samples S3 and S4 received lower scores, but were appreciated for their external appearance, cross-sectional appearance and core color. These samples were not appreciated for taste because sample S3 leaves a slight sandy sensation after consumption, and sample S4, in addition to this sensation, also has a slightly bitter taste and even gives a slight astringency after consumption. Therefore, the incorporation of the black chokeberry product significantly reduced the overall appreciation.

3.4. Environmental impacts of black chokeberry pomace muffins samples

The results indicated that HTP and FAETP are the main impact categories affected by the process of obtaining muffins. Figure 6 shows that the contribution of the processes involved in obtaining black chokeberry muffins to environmental impact categories increased (with increasing chokeberry content) compared to the contribution of the process involved in obtaining the control sample (S1).

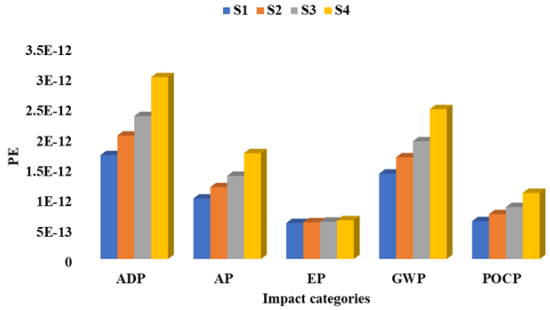


Figure 6. Normalized values (Europe) of environmental impacts obtained by applying CML2001-Jan2016 (PE-person equivalents)

After comparing the results obtained between the control sample (S1) and the black chokeberry muffin samples (S2, S3, and S4), increases of 19% (S2), 38% (S3), and 75% (S4) were observed for the environmental

impact categories ADP, AP, GWP, and POCP. For the FAETP environmental category, no differences were observed between the contributions of the muffin making processes, and for HTP the increase was only 1% for all samples. In the case of the EP category, very small increases of 2% were observed in the case of S2, 4% for S3 and 8% for S4.

The process of obtaining muffins does not have a direct impact on the environment, the impact associated with this process is indirectly due to the consumption of electricity, water and the wastewater treatment stages. Electricity generation, water treatment, and wastewater treatment resulting from the process are the stages that have a direct impact on the environment, and the percentage contribution of these stages to the impact categories has been calculated (Figure 7).

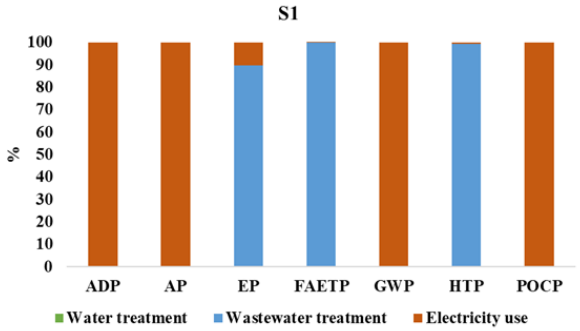


Figure 7. Contribution of different stages to impact categories included in CML2001 - Jan 2016

It was observed that the use of electricity (*i.e.*, its production) contributes over 99% to the following impact categories: ADP, AP, GWP, and POCP due to emissions resulting from electricity production, while wastewater treatment contributes over 99% to the HTP and FAETP categories and over 89% to EP. Electricity is consumed during the baking of muffins and in the processes of drying and grinding chokeberry powder and grinding wheat flour. Electricity grid mix in Romania included hydro, nuclear, hydrocarbons and others energy sources [40].

Wastewater from bakeries mainly originates from cleaning operations (equipment and floors), contains flour, oil, fats, and sugar, and is mainly acidic. The resulting wastewater is biodegradable and biological treatment can be used to remove organic substances from it [41]. Water treatment contributes very little to all impact categories (below 0.5%).

3.5. Principal component analysis

The relationship between the physicochemical, textural, sensory and environmental parameters of the muffins is illustrated in Figure 8.

The primary component (PC1) and secondary component (PC2) accounted for 74.1% and 20.7% of the total variation, respectively. Weight (-0.108), TA (-0.244), a* (-0.119) and all environmental impact categories had negative loadings, while the others parameters had positive loadings on PC1. pH (0.049), a* (0.409), sectional view (0.102), taste (0.028), odor (0.046) and HTP (0.080) had positive loadings on PC2, while the remaining parameters had negative loadings.

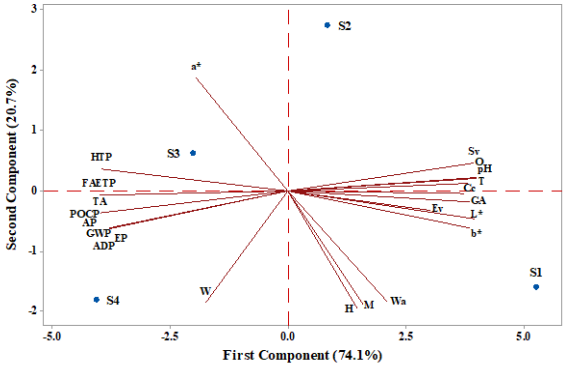


Figure 8. Principal component analysis (PCA) biplot depicting the relationship between parameters of muffins samples (W - weight, H - height, M - moisture, Wa - water activity, TA - titratable acidity; L*, a*, and b* - color parameters; Ev - Exterior view, Sv - Sectional view, Cc - core color, T- taste, O - odor, GA - general acceptance (sensory parameters); ADP, AP, GWP, HTP, FAETP and POCP (environmental impact categories))

Figure 8 shows that sample S1 had positive scores for PC1 and negative scores for PC2, sample S2 had positive scores for both PC1 and PC2, sample S3 had negative scores for PC1 and positive scores for PC2, while samples S4 had negative score for both PC1 and PC2. The analyzed parameters, such H-height, M-moisture, Wa - water activity, b*, L*, exterior view (Ev), and general acceptance (GA) were more representative for sample S1, a*, HTP and FAETP were grouped around sample S3, while titratable acidity (TA), weight (W), AP, ADP, EP, GWP, POCP were more representative for sample S4.

4. Conclusions

The results obtained from the experiments revealed that the incorporation of black chokeberry powder into the muffin dough significantly influences the physicochemical and sensory parameters of the final product. The pH of the muffins decreased progressively with the increase in the percentage of black chokeberry powder, from values close to 6 for the control, to 4.5–5.0 in the samples with high addition. This phenomenon is explained by the high content of organic acids and phenolic compounds in the pomace. The weight and height of the muffins were slightly reduced in samples containing black chokeberry pomace, likely due to the effect of the pomace powder on gluten network formation and gas retention during baking. The muffins became denser, with a more compact texture. Moisture analysis showed an increased water retention capacity in the black chokeberry samples, due to the high soluble fiber content, but also a reduction in water loss during baking. The results of the textural analysis indicated that the hardness of the muffin samples increased with the amount of pomace added, due to the higher fiber content of these samples. Sensory evaluations showed that samples with up to 5÷7.5% black chokeberry powder were well accepted by consumers. Slightly sour flavors, intense purple color, and specific texture were appreciated, while higher concentrations (10% or above) were perceived as too intense or slightly bitter.

Compared to the control sample, muffins enriched with black chokeberry powder may be classified as functional bakery products, as they combine acceptable sensory attributes with enhanced nutritional benefits.

LCA results showed that electricity consumption during the muffin production is the main contributor to environmental impact categories like ADP, AP, GWP and POCP, while wastewater treatment contributes mainly to HTP, FATEP and EP.

This research highlights promising opportunities for the development of innovative bakery products with functional and ecological attributes, contributing both to the diversification of the food supply and to the sustainable use of natural resources.

Conflict of interest

Authors declare no conflict of interest.

References

[1]. Eurostat, Food waste and food waste prevention estimates, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Food_waste_and_food_waste_prevention_estimates.

[2]. P. Skwarek, M. Karwowska, Fruit and vegetable processing by-products as functional meat product ingredients-a chance to improve the nutritional value, LWT 189 (2023) 115442. Doi: 10.1016/j.lwt.2023.115442

[3]. A. Zbikowska, P. Lukasiak, M. Kowalska, A. Lukasiak, M. Kozłowska, K. Marciniak-Lukasiak, Incorporation of Chokeberry Pomace into Baked Products: Influence on the Quality of the Dough and the Muffins, Applied Sciences 14 (2024) 9675. Doi: 10.3390/app14219675

[4]. E. Raczkowska, P. Serek, Health-promoting properties and the use of fruit pomace in the food industry—A Review, Nutrients 16 (2024) 2757. Doi: 10.3390/nu16162757

[5]. F. Thomas, G. Abebe, C. Emenike, A. Martynenko, Sustainable utilization of apple pomace: Technological aspects and emerging applications, Food Research International 220 (2025) 117149. Doi: 10.1016/j.foodres.2025.117149

[6]. Ľ. Gurčík, Z. Bajusová, J. Ladvenicová, J. Palkovič, K. Novotná, Cultivation and processing of modern superfood - *Aronia melanocarpa* (Black Chokeberry) in Slovak Republic, Agriculture 13 (2023) 604. Doi: 10.3390/agriculture13030604

[7]. O. Tasinov, I. Dincheva, I. Badjakov, C. Grupcheva, B. Galunska, Comparative phytochemical analysis of *Aronia melanocarpa* L. fruit juices on Bulgarian market, Plants 11 (2022). 1655. Doi: 10.3390/plants11131655

[8]. A. Wójtowicz, M. Combrzyński, B. Biernacka, R. Różyło, M. Bąkowski, K. Wojtunik-Kulesza, J. Mołdoch, I. Kowalska, Fresh chokeberry (*Aronia melanocarpa)* fruits as valuable additive in extruded snack pellets: Selected nutritional and physiochemical properties, Plants 12 (2023) 3276. Doi: 10.3390/plants12183276

[9]. T. Witczak, A. Stępień, D. Gumul, M. Witczak, G. Fiutak, T. Zięba, The influence of the extrusion process on the nutritional composition, physical properties and storage stability of black chokeberry pomaces, Food Chemistry 334 (2021) 127548. Doi: 10.1016/j.foodchem.2020.127548

[10]. G. Cacak-Pietrzak, D. Dziki, U. Gawlik-Dziki, N. Parol-Nadłonek, S. Kalisz, A. Krajewska, S. Stępniewska, Wheat bread enriched with black chokeberry (*Aronia melanocarpa* L.) pomace: Physicochemical properties and sensory evaluation, Applied Sciences 13 (2023) 6936. Doi: 10.3390/app13126936

[11]. G. Adamczyk, Z. Posadzka-Siupik, I. Bobel, P.Ł. Kowalczewski, A. Szwengiel, Impact of chokeberry (*Aronia melanocarpa* L.) extracts on the physicochemical properties of wheat bread, Applied Sciences 15 (2025) 12633. Doi: 10.3390/app152312633

[12]. A. Pecyna, M. Krzywicka, A. Buczaj, A. Blicharz-Kania, Z. Kobus, The effect of fruit pomace addition on the color, texture and sensory properties of gluten-free bread, Scientific Reports 15 (2025) 24510. Doi: 10.1038/s41598-025-10077-z

[13]. J. Rutkowska, A. Antoniewska, M. Martinez-Pineda, A. Nawirska-Olszańska, A. Zbikowska, D. Baranowski, Black chokeberry fruit polyphenols: A valuable addition to reduce lipid oxidation of muffins containing xylitol, Antioxidants 9 (2020) 394. Doi: 10.3390/antiox9050394

[14]. A. Cegiełka, J. Piątkowska, M. Chmiel, E. Hać-Szymańczuk, S. Kalisz, L. Adamczak, Changes in quality features of pork burgers prepared with chokeberry pomace during storage, Applied Sciences 15 (2025) 2337. Doi: 10.3390/app15052337

[15]. L. Yang, S. Chen, N. Ma, W. Chen, Z. Zhang, H. Zhang, Effect of gelatin edible coating with *Aronia melanocarpa* pomace polyphenols on the cold storage of chilled pork, Meat Science 219 (2025) 109677. Doi: 10.1016/j.meatsci.2024.109677

[16]. S. Pădureț, C. Ghinea, A.E. Prisacaru, A. Leahu, Physicochemical, textural, and antioxidant attributes of yogurts supplemented with black chokeberry: fruit, juice, and pomace, Foods 13 (2024) 3231. Doi: 10.3390/foods13203231

[17]. I.C. Crivei, I.D. Veleșcu, A.B. Balint, F. Stoica, F.D. Lipșa, M.G. Usturoi, R.N. Rațu, Aronia enhanced caciotta as a dairy alternative with improved functional properties, Scientific Papers. Series D. Animal Science 68 (2025) 405-413.

[18]. D. Wieloch, D. Konopacka, Black chokeberry extracts (*Aronia melanocarpa*) as an ingredient of functional food - potential, challenges and directions of development, Molecules 30 (2025) 4237. Doi: 10.3390/molecules30214237

[19]. J. Xu, F. Li, M. Zheng, L. Sheng, D. Shi, K. Song, A comprehensive review of the functional potential and sustainable applications of *Aronia melanocarpa* in the food industry, Plants 13 (2024) 3557. Doi: 10.3390/plants13243557

[20]. S. Mildner-Szkudlarz, J. Bajerska, P. Górnaś, D. Segliņa, A. Pilarska, T. Jesionowski, Physical and bioactive properties of muffins enriched with raspberry and cranberry pomace powder: A promising application of fruit by-products rich in biocompounds, Plant Foods for Human Nutrition 71 (2016) 165-173. Doi: 10.1007/s11130-016-0539-4

[21]. Y. Wang, C. Jian, Sustainable plant-based ingredients as wheat flour substitutes in bread making, npj Science of Food 6 (2022) 49. Doi: 10.1038/s41538-022-00163-1

[22]. L. Benvenutti, F.M. Moura, G. Zanghelini, C. Barrera, L. Seguí, A.A.F. Zielinski, An upcycling approach from fruit processing by-products: Flour for use in food products, Foods 14 (2025) 153. Doi: 10.3390/foods14020153

[23]. J.H. Lee, Y.Y. Shim, M.J.T. Reaney, J.A. Yoon, The impacts of standardized flaxseed meal (XanFlax) on the physicochemical, textural, and sensory properties of muffins, Foods 12 (2023) 4085. Doi:10.3390/foods12224085

[24]. G.D. Sadler, P. Murphy, pH and Titratable Acidity, in: S.S. Nielsen (Ed.), Food Analysis, 4th Edition, Springer, New York, USA, 2010, pp. 219–238.

[25]. C. Ghinea, A.E. Prisacaru, A. Leahu, Physico-chemical and sensory quality of pasteurized apple juices extracted by blender and cold pressing juicer, Ovidius University Annals of Chemistry 33 (2022) 84-93. Doi: 10.2478/auoc-2022-0012

[26]. C. Ghinea, A. Leahu, A.E. Prisacaru, M. Cojocaru, V. Ladariu, Physico-chemical and sensory analyzes of muffins obtained with almond flour and coconut oil, International Multidisciplinary Scientific GeoConference: SGEM 19 (2019) 165-172. Doi: 10.5593/sgem2019V/6.3/S08.022

[27]. S. Xiong, Y. Li, G. Chen, H. Zou, Q. Yu, J. Si, H. Yang, Incorporation of Huangjing flour into cookies improves the physicochemical properties and in vitro starch digestibility, LWT 184 (2023) 115009. Doi: 10.1016/j.lwt.2023.115009

[28]. A. Leahu, C. Ghinea, S. Ropciuc, in: H.N. Costin, R. Magjarević, G.G. Petroiu, (Eds), Apple Pomace: Influence on the Physico-Chemical and Textural Characteristics of Gluten-Free Biscuits. Advances in Digital Health and Medical Bioengineering. EHB 2023. IFMBE Proceedings, Cham: Springer Nature Switzerland, pp. 542-550. Doi:10.1007/978-3-031-62520-6_60

[29]. P. Nath, S.J. Kale, C. Kaur, O.P. Chauhan, Phytonutrient composition, antioxidant activity and acceptability of muffins incorporated with red capsicum pomace powder, Journal of Food Science and Technology 55 (2018) 2208-2219. Doi:10.1007/s13197-018-3138-6

[30]. N. Gashi, E. Hasani, S. Salihu, Quality evaluation of muffins enriched with blueberry and cranberry powders, International Journal of Food Science 2024 (2024) 7045401. Doi: 10.1155/2024/7045401

[31]. K. Katina, M. Salmenkalio-Martila, R. Partanen, P. Forssell, K. Autio, Effects of sourdough and enzymes on staling of high-fibre wheat bread, LWT 39 (2005) 479–491. Doi: 10.1016/j.lwt.2005.03.013

[32]. R. Walker, A. Tseng, G. Cavender, A. Ross, Y. Zhao, Physicochemical, nutritional, and sensory qualities of wine grape pomace fortified baked goods, Journal of Food Science 79 (2014) S1811–S1822. Doi: 10.1111/1750-3841.12554

[33]. Z. Kırbaş, S. Kumcuoglu, S. Tavman, Effects of apple, orange and carrot pomace powders on gluten-free batter rheology and cake properties, Journal of Food Science and Technology 56 (2019) 914-926. Doi: 10.1007/s13197-018-03554-z

[34]. M.S. Javed, A. Amjad, R. Suleman, A. Siraj, S. Sabir, Physicochemical characterization of mulberry-supplemented muffins, International Journal of Food Science and Nutrition 7 (2022) 55-62.

[35]. I. Sopotenska, V. Chonova, Application of chickpea and chestnut flour in the production of gluten-free cookies and muffins, Scientific Works of UFT-Plovdiv 65 (2018) 11-17.

[36]. Y. Baldán, M. Riveros, M.P. Fabani, R. Rodriguez, Grape pomace powder valorization: A novel ingredient to improve the nutritional quality of gluten-free muffins, Biomass Conversion and Biorefinery 13 (2023) 9997-10009. Doi: 10.1007/s13399-021-01829-8

[37]. M. Mohammadi, M. Salami, M. Yarmand, Z. Emam-Djomeh, D.J. McClements, Production and characterization of functional bakery goods enriched with bioactive peptides obtained from enzymatic hydrolysis of lentil protein, Journal of Food Measurement and Characterization 16 (2022) 3402-3409. Doi: 10.1007/s11694-022-01416-z

[38]. E.C. De Souza, D. A. Cordeiro, B.S. Silva, N. de Andrade Neves, M. Schmiele, Development of muffin with the incorporation of olive pomace flour, extra virgin olive oil and hydrolyzed soy protein, Research, Society and Development 11 (2022) e58511226012-e58511226012. Doi: 10.33448/rsd-v11i2.26012

[39]. M. Ortega-Heras, I. Gómez, S.de Pablos-Alcalde, M. L. González-Sanjosé, Application of the just-about-right scales in the development of new healthy whole-wheat muffins by the addition of a product obtained from white and red grape pomace, Foods 8 (2019) 419. Doi: 10.3390/foods8090419

[40]. C. Ghinea, A. Leahu, Life cycle assessment of sheep cheese production in a small dairy factory from Romanian rural area, Environmental Science and Pollution Research 30 (2023) 6986-7004. Doi: 10.1007/s11356-022-22644-2

[41]. J. Struk-Sokolowska, J. Tkaczuk, Analysis of bakery sewage treatment process options based on COD fraction changes, Journal of Ecological Engineering 19 (2018) 226–235.

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