

Article

Sustainable Utilization of Black Chokeberry Pomace in Beef Burgers: Implications for Quality and Storage Stability

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Abstract

The sustainable management and valorization of agri-food by-products is a key challenge in the development of circular and resource-efficient food systems. This study aimed to evaluate the effect of incorporating varying amounts of black chokeberry (*Aronia melanocarpa*) pomace, a fruit-processing by-product, on the quality of beef burgers. Pomace was incorporated at levels of 0.0%, 0.5%, 1.0%, 2.0%, and 3.0%. The burgers were baked, vacuum-packed, and stored at 4 °C for 14 days. On the production day, cooking properties and chemical composition were determined, while during storage, pH, shear force, color parameters (CIEL*a*b*), organoleptic attributes, and microbiological quality were assessed. The results showed that increasing the pomace level from 0% to 3.0% increased ($p < 0.05$) the thermal loss and diameter shrinkage by 5.6 and 2.9 percentage points, respectively. In contrast, shear force was lower in burgers containing 3.0% pomace than in the control burgers, by 3.76 N on day 1 and by 5.11 N on day 14. Burgers supplemented with chokeberry pomace were significantly ($p < 0.05$) darker and exhibited lower redness and yellowness values than the control samples. Organoleptic evaluation showed that burgers containing 0.5–1.0% pomace achieved scores comparable to those of the control group across most evaluated attributes, indicating that 1.0% was the highest inclusion level that maintained acceptable organoleptic characteristics under the conditions of this study. Furthermore, chokeberry pomace supplementation did not adversely affect the microbiological quality of the burgers during storage, with mesophilic aerobic microorganism counts remaining below 5 log CFU/g in all treatments throughout the 14-day storage period. These findings demonstrate that low levels of shredded black chokeberry pomace, particularly 1.0%, can be incorporated into beef burger formulations without substantial deterioration of quality attributes, suggesting that the valorization of this fruit-processing by-product may offer opportunities to support more sustainable food production practices.



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1. Introduction

Food production is among the sectors exerting a substantial environmental impact. Consequently, the utilization of agricultural by-products has become increasingly important in the development of new food products, including meat products. This approach is consistent with the European Union's Farm to Fork Strategy, a key component of the European Green Deal, which promotes sustainable food production and processing, circular economy principles, more efficient resource use, and waste reduction [1,2]. The transition toward responsible and transparent food production is further driven by consumer expectations [3]. These issues are particularly relevant to the meat sector, which is frequently criticized for its environmental footprint and intensive use of natural resources. Accordingly, the incorporation of agri-food industry by-products into meat product formulations is increasingly explored as sustainable processing strategy [4,5].

The development of meat products enriched with agricultural by-products requires consideration of technological, environmental, and regulatory aspects. Such products should demonstrate adequate sensory acceptability and comply with food safety requirements established under applicable European Union (EU) legislation, including Commission Regulation (EC) No. 2073/2005 on microbiological criteria for foodstuffs [6]. Although detailed mandatory quality criteria for technological and sensory attributes have not been established at the EU level for all product categories, the voluntary Polish standard PN-A-82010:1997 [7] may serve as a useful benchmark for assessing the technological quality of fully heat-treated burgers.

Beef burgers, also known as hamburgers or hamburger steaks, are popular meat-based fast-food products generally prepared from ground beef shaped into patties, with the possible addition of salt, spices, or other food ingredients [8,9]. Within the European Union, beef burgers are classified as “meat preparations”, as the technological processes applied do not substantially alter the internal structure of muscle fibers [10]. The proportions of meat, fat, and functional ingredients significantly influence the physicochemical, sensory, and microbiological quality of the final product [11]. Despite their popularity, beef burgers are criticized for their relatively high fat and energy content [12–14].

In recent years, various strategies have been proposed to enhance the quality features and consumer perception of beef burgers, including the incorporation of vegetable oils [14], pea fiber [11], *Chlorella vulgaris* powder [15], and brown flaxseed powder [16]. An alternative and increasingly promoted approach is the valorization of plant-derived agri-food by-products in meat product formulations, which supports food waste reduction, improved resource utilization, and the development of value-added products [17,18].

Fruit and vegetable by-products are rich sources of dietary fiber and bioactive compounds. Their incorporation into meat products may affect physicochemical, sensory, and microbiological quality; depending on the type of by-product, processing form, level of addition, and product matrix [19,20]. Various fruit and vegetable by-products have already been used in beef burgers, including dried tomato peels [21], dried papaya peels [22], freeze-dried carrot pomace [23], and dried grape pomace [24]. Similar strategies have also been reported for pork burgers using Kinnow mandarin pomace powder [25] and freeze-dried berry pomace [26]. According to data collected by Ueda et al. [27], the annual by-products generation ranges from 13.5 million tons for pea processing and 19–25 million tons for pineapple processing, to 228 million tons for beet processing and 368 million tons for potato processing. The efficient utilization of plant by-products is justified by the large quantities generated globally each year, which, if poorly managed, may cause environmental and economic losses.

Among fruit-processing by-products, black chokeberry (*Aronia melanocarpa*) pomace is of particular interest. Poland is among the leading producers of this crop [28], and more

than 90% of domestic chokeberry production is processed, generating substantial quantities of pomace [29]. Black chokeberry pomace is rich in bioactive compounds, particularly anthocyanins, catechins, and phenolic acids, and also contains dietary fiber, making it a potentially valuable functional ingredient for food applications, including comminuted meat products [30–34]. However, fresh chokeberry pomace has a limited shelf life due to its high moisture content and therefore requires immediate utilization or stabilization [35].

Common valorization methods for chokeberry pomace include drying, extrusion, extraction of bioactive compounds, and microencapsulation of anthocyanin-rich extracts [36–39]. Although these methods may improve functional properties of pomace, they often require additional energy inputs and investment costs, potentially limiting their industrial scalability and sustainability [20,40], and inappropriate processing or storage conditions may lead to the degradation of valuable bioactive compounds [35]. Previous studies have shown that black chokeberry pomace can be incorporated into comminuted meat products, including hamburger-type products and pork burgers, in a shredded, non-dried form [41,42]. However, published data on the direct application of shredded, non-dried black chokeberry pomace in beef burgers remain scarce. Beef burgers represent a different meat matrix from pork products, with product-specific raw material composition, color characteristics, fat/protein structure, and technological behavior during heat treatment and re-frigerated storage. Therefore, the effects observed in pork products cannot be directly extrapolated to beef burger formulations. This lack of data on beef burger formulations represents the main research gap addressed in the present study.

The aim of this study was to evaluate the effects of incorporating shredded black chokeberry (*Aronia melanocarpa*) pomace at varying levels (0–3%) on the physical, chemical, sensory, and microbiological quality of beef burgers during refrigerated storage (1–14 days). The study also sought to identify the level of pomace addition that allows for the maintenance of selected technological properties, organoleptic and microbiological quality during refrigerated storage.

2. Materials and Methods

2.1. Materials

The production of black chokeberry pomace and the production and quality assessment of beef burgers were conducted at the Institute of Food Sciences, Warsaw University of Life Sciences (WULS—SGGW).

The experimental material consisted of beef burgers with the addition of various amounts of black chokeberry pomace. The raw materials of animal origin—meat trimmings from beef forequarters and beef fat—were sourced from the meat processing plant located in central-eastern Poland (Zakład Mięśny „Zychowicz”, Daleszyce, Poland). The raw meat and fat were purchased in quantities sufficient to experiment with two separate series. They were transported to the laboratory by a delivery truck from a meat processing plant under controlled cold conditions ($+4\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$).

For the production of pomace from black chokeberry (*Aronia melanocarpa*), the cultivar ‘Galicjanka’ was used. The fruit was sourced from a conventional plantation in eastern Poland (Lublin Voivodeship) and harvested in mid-September 2024. Approximately 10 kg of chokeberry fruit was purchased one day after harvesting and transported to the WULS-SGGW laboratory under refrigerated conditions ($+4\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$). Upon arrival, the fruits were washed with running water and then pressed using a laboratory hydraulic press (BUCHER Unipektin AG HPL 14; Bucher Unipektin AG, Niederweningen, Switzerland), which was equipped with a drainage filter recommended for berry and stone fruit processing. The pressing was conducted in three cycles at a pressure of 5 bar. Between the pressing cycles, the plant material was loosened to enhance juice yield and reduce the moisture

content of the resulting pomace. The hydraulic press and fresh black chokeberry pomace are presented in Figure S1. During juicing, the fruit underwent enzymatic treatment with Brent Pect Acid Colors (Brenntag GmbH, Essen, Germany), an enzyme preparation that does not degrade anthocyanins. Used enzyme dose was 100 microliters per kg. Enzymatic processing time was one hour at 50 °C. The treatment was applied to promote pectin degradation and increasing the efficiency of juice extraction. The pomace was divided into portions of approximately 0.5 kg each and vacuum-packed in 0.70 mm PA/PE bags using a Multivac C200 packaging machine (Multivac, Wolfertschwenden, Germany). The packaged chokeberry pomace was subsequently frozen and stored at $-60\text{ °C} \pm 1\text{ °C}$ for 30 days. On the day of burger production, the required amount of pomace was thawed in a microwave oven for 4 min at 900 W. It was then shredded to a paste-like consistency using a Thermomix® (Vorwerk, Warsaw, Poland) at a knife speed of 4000 rpm for 5 min, with the maximum processing temperature limited to 37 °C. The appearance of the shredded black chokeberry pomace is shown in Figure S2.

2.1.1. Analysis of the Antioxidant Properties of Chokeberry Pomace

Shredded chokeberry pomace was evaluated for its potential usefulness in the production of processed meat products. The total content of polyphenols and anthocyanins in the chokeberry pomace was determined, and its antioxidant activity was assessed.

Analyses conducted on pomace were preceded by the preparation of extracts from this by-product. Extracts from shredded pomace were prepared according to the method described by Grobelna et al. [43] with slight modifications regarding sample type (pomace instead of berry puree) and sample weight (0.5 g vs. 2.5 g). The extraction solvent contained 20% distilled water and 80% methanol, which was acidified with 1 mL HCl per litre of solution. Centrifuge tubes were weighed with an accuracy of 0.01 g, after 0.5 g of shredded pomace. The extraction mixture was then added to each sample tube up to a volume of 12 mL and placed in an ultrasonic cleaner (Sonoswiss SH-3H, Ramsen, Switzerland) for 3 min to increase the extraction efficiency. The prepared samples were centrifuged in a laboratory centrifuge (MPW-350R, Warsaw, Poland) (10,000 rpm/min, 10 min). The steps were repeated until the samples were completely discolored. The extracts were collected into 100 mL volumetric flasks in which the extraction mixture was added.

The total polyphenol content was determined using the Folin-Ciocalteu reagent, following the guidelines outlined by Gao et al. [44]. The results were expressed in milligrams per 100 grams of fresh pomace weight and were calculated as gallic acid equivalents.

The anthocyanin content in the chokeberry pomace extracts was determined using high-performance liquid chromatography with a diode-array detector (HPLC-PDA) method, following the methodology established by Grobelna et al. [43]. This analysis utilized Shimadzu equipment (Kyoto, Japan). The total anthocyanin content was expressed in milligrams per 100 grams of fresh pomace and was calculated as cyanidin 3-O-glucoside.

Additionally, the antioxidant activity of the chokeberry pomace extracts was evaluated using the Trolox equivalent antioxidant capacity (TEAC) with DPPH (2,2-diphenyl-1-picrylhydrazyl) radicals. The TEAC assay was conducted according to the method described by Chen and Yen [45]. The results were expressed as micromoles of Trolox equivalents ($\mu\text{M TE}$) per 1 gram of fresh pomace weight.

Following reagents used in this study (Folin-Ciocalteu reagent, sodium carbonate, sodium hydroxide, gallic acid, formic acid, Trolox and DPPH) were reagent grade. Acetonitrile and methanol used in the study were of HPLC grade. All chemicals were purchased from one vendor (Merck KGaA, Darmstadt, Germany). For HPLC analysis ultra-pure water of 18.2 M Ω cm resistivity was used (Milli-Q® system, Merck Millipore, Darmstadt, Germany).

2.1.2. Production of Beef Burgers with Varying Amounts of Added Chokeberry Pomace

The beef burgers were produced by grinding of 20 kg of beef and 5 kg of beef tallow using a Mesko WN40 laboratory grinder (Mesko-AGD Sp. z o.o., Skarżysko-Kamienna, Poland) fitted with a 4.5 mm plate. The ground meat and fat were subsequently mixed at an 80:20 ratio using a Mainca RM-40 paddle mixer (Equipamientos cárnicos, S.L. MAINCA, Barcelona, Spain) to obtain a uniform meat-fat batter. Five variants of beef burgers were manufactured, each differing in the amount of black chokeberry pomace added, as outlined in Table 1. The incorporation of pomace in burger variants B0.5–B3 did not replace meat and fat raw materials; instead, it was added as an extra ingredient in the recipe. As a result, the total weight of the burger batters increased compared to the BC burgers. This increase in the mass of burger batters B0.5–B3 was considered when calculating the amount of table salt added, ensuring that the intended percentage of salt in the final mixture was maintained. Burger formulations expressed in g/kg of meat batter are provided in Table S1.

Table 1. Recipe of beef burgers.

Burger Variant ¹	Meat-Fat Raw Materials [%]	Chokeberry Pomace ² [%]	Table Salt (NaCl) ³ [%]
BC		0.0	
B0.5		0.5	
B1	100	1.0	1.5
B2		2.0	
B3		3.0	

¹ Explanation of burger variant codes: BC/0.5/1/2/3—beef burger variants with 0/0.5/1/2/3% addition of chokeberry pomace. ² The amount of pomace added was calculated in relation to the weight of the meat and fat raw material. ³ The amount of NaCl added was calculated in relation to the weight of the meat and fat raw material and black chokeberry pomace.

Meat batters for BC–B3 burgers were prepared using Kenwood Major laboratory mixers (Kenwood Ltd., Havant, UK). Initially, meat-fat batter and table salt were mixed for 10 min. In the B0.5–B3 variants, shredded chokeberry pomace was subsequently incorporated into the meat batter, followed by an additional 5 min of mixing to ensure uniform distribution of this plant material. The batters were then formed into flat, round patties with a target mass of 120 g ± 2 g using a manual molding device (Hendi BV, Rhenen, the Netherlands). The burgers were baked in a convection–steam oven (Rational SCC WE61; Rational AG, Landsberg am Lech, Germany) at 180 °C and 10% relative humidity until a core temperature of 80 °C was reached, with the burgers turned during heat treatment. After baking, the burgers were cooled at ambient temperature (approximately 18 °C) for 30 min. The appearance of the baked beef burgers is shown in Figure S3. The burgers of each variant were then divided into four batches, each containing 16 pieces. One batch was analyzed on the day of production, while the remaining batches were vacuum-packed in 0.70 mm PA/PE bags using a Multivac packaging machine and stored at 4 °C ± 1 °C under dark conditions for 1, 7, and 14 days, respectively. Samples intended for microbiological analysis were packaged separately.

2.1.3. Experimental Procedure

Five variants of beef burgers were produced. On the day of production, the burgers were assessed for thermal loss and diameter reduction (shrinkage) following heat treatment, as well as the content of selected chemical components. Additional quality characteristics of burgers, including pH, color, texture, organoleptic properties, and microbiological quality, were evaluated after 1, 7, and 14 days of refrigerated storage. The study was carried out in two independent experimental series. The experimental design took into account organizational factors and the availability of laboratories. Approximately 60 hamburgers of each

product variant were produced in the experiment. The sample size (n) for each analysis was calculated as the product of the number of experimental batches and the number of burgers analyzed within each batch or individual evaluations in the organoleptic assessment.

2.2. Methods

2.2.1. Cooking Characteristics of Beef Burgers

The cooking characteristics of burgers were evaluated according to the methods described by Basiri et al. [16]. For each product variant, three burgers were randomly selected in each of two independent experimental series and evaluated for weight and diameter before and after heat treatment, resulting in six independent observations per variant ($n = 6$). The thermal loss of burgers was measured gravimetrically and calculated using Equation (1):

$$\text{Thermal loss} = (\text{weight of raw burger [g]} - \text{weight of baked burger [g]}) / \text{weight of raw burger [g]} \times 100\% \quad (1)$$

To measure the diameters of burgers, an electronic caliper was utilized. The reduction in the diameter of the burgers following heat treatment (shrinkage) was calculated using Equation (2):

$$\text{Shrinkage} = (\text{diameter of raw burger [mm]} - \text{diameter of baked burger [mm]}) / \text{diameter of raw burger [mm]} \times 100\% \quad (2)$$

2.2.2. Analysis of the Chemical Composition of Beef Burgers and the Moisture Content in Pomace

The content of selected chemical components in beef burgers, including water, protein, fat, and sodium chloride, was analyzed in heat-treated products. The procedure followed the guidelines of the PN-A-82109:2010 standard [46]. Measurements were conducted using a FoodScan™2 near-infrared spectrometer (Foss Analytical A/S, Hillerød, Denmark), operating in the wavelength range of 850–1500 nm and employing an artificial neural network model for meat product analysis. For each product variant in each experimental series, two samples were prepared by grinding three randomly selected burgers using a grinder (Diana 886.8, Zelmer, Rzeszów, Poland) equipped with a 2 mm mesh. The sample was ground twice, thoroughly mixed, and placed in the measuring cuvette. The measurement was then initiated, and chemical composition was automatically determined, with results displayed on a computer monitor. For each burger variant, measurements were performed in two samples within each experimental series, and mean values were reported as the final results ($n = 4$).

The moisture content of the pomace was determined gravimetrically. A sample ($2 \text{ g} \pm 0.001 \text{ g}$) was dried in successive stages at 70 °C (40 min), 90 °C (40 min), and 95 °C (30 min), with cooling in a desiccator between stages. Drying was continued until constant weight was attained, as indicated by a mass difference of $\leq 0.001 \text{ g}$ between consecutive measurements. The analysis was performed in duplicate.

2.2.3. Measurement of pH of Beef Burgers and Chokeberry Pomace

The pH of the beef burgers was measured on days 1, 7, and 14 using a portable pH meter, the Testo 206-pH2 (Testo SE and Co. KGaA, Titisee-Neustadt, Germany). Before taking the measurements, the device was calibrated with buffer solutions at pH 4.0 and 7.0. For each product variant, a representative test sample was prepared by grinding three burgers twice through a meat grinder with a 2 mm plate. Then, $10 \text{ g} \pm 0.01 \text{ g}$ of the ground sample was mixed with 30 mL of distilled water in glass beaker. The pH was determined

by immersing the electrode directly into the prepared sample. For each burger variant, three independent samples, each prepared from a separate burger, were analyzed in each experimental series. The resulting data from six independent observations ($n = 6$) were used for statistical analyzes. On the day of burger production, the pH of chokeberry pomace was also measured. The samples were prepared in the same manner as the burgers.

2.2.4. Measurement of Color Parameters in Beef Burgers

The color parameters of beef burgers were evaluated on days 1, 7, and 14 of refrigerated storage. Color measurements were performed on the burgers' surface using a Minolta® CR-200 colorimeter (Minolta, Tokyo, Japan) operating with a D65 illuminant, a 10° standard observer, and an 8-mm measurement aperture. Color was expressed according to the CIEL*a*b* color space using the parameters: L* (lightness), a* (red–green component), and b* (yellow–blue component). Before measurements, the instrument was calibrated using a standard white calibration plate ($L^* = 97.83$, $a^* = +0.45$, $b^* = +1.88$), and the vacuum-packaged burgers were conditioned for 60 min at ambient temperature (approximately 18 °C). In each experimental series, six individual burgers were randomly selected from each treatment variant for color analysis. Each burger was measured separately, yielding six independent observations per variant per series and a total of twelve observations across both experimental series ($n = 12$). Mean values were then used for subsequent statistical analyses. To evaluate the effect of adding black chokeberry pomace on the color changes of beef burgers on days 1, 7, and 14 of refrigerated storage, total color difference (ΔE) was calculated according to the method described by Mokrzycki and Tatol [47] and the equation:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (3)$$

where: ΔL^* , Δa^* , and Δb^* represent the differences in color parameters between the control product (BC) and burgers with the addition of black chokeberry pomace (B0.5, B1, B2, and B3).

2.2.5. Measurement of Shear Force in Beef Burgers

The shear force of beef burgers was determined on days 1, 7, and 14 of refrigerated storage. The shear force was measured using a Zwicky 1120® universal testing machine (Zwick GmbH & Co., Ulm, Germany) equipped with a flat cutting blade. The shear force was defined as the maximum force recorded during cutting. Measurements were taken at a blade speed of 50 mm/min, with a pre-load force of 0.5 N and a force deactivation threshold set at 50% of the maximum recorded force. Before analysis, vacuum-packed burgers were kept for 60 min at ambient temperature (approximately 18 °C). Cuboid-shaped test samples measuring 90 mm × 30 mm × 7 mm were then prepared. In each of the independent production series, six samples prepared from six different burgers were analyzed for each burger variant, resulting in 12 independent observations per variant ($n = 12$). Final results were expressed as arithmetic means.

2.2.6. Evaluation of the Organoleptic Quality of Beef Burgers

The organoleptic evaluation of beef burgers focused on the following quality attributes: appearance and color, aroma, taste, and texture. The criteria for assessing individual quality attributes, developed for the purposes of this study, were established based on the relevant literature [48] and are presented in Table 2. Evaluation sessions were conducted under laboratory conditions on days 1, 7, and 14 of the burgers' storage. The evaluation was performed in a laboratory room dedicated to product assessment, free from chemical reagents and foreign odors. The room temperature during evaluation was approximately 20 °C. Prior to evaluation, the burgers were removed from their packaging and heated on an

electric grill (Stalgast, Warsaw, Poland) to approximately 60 °C. After heating, each burger was cut into four equal portions. The samples were served to the panelists on white plates and identified using random three-digit codes. The order of sample presentation was randomized across panelists. The sensory panel consisted of ten panelists recruited voluntarily from food technology students and staff members of the Institute of Food Science. Panelists had basic knowledge and/or experience in food quality assessment and were familiarized with the evaluation procedure, the five-point rating scale, and the quality criteria presented in Table 2 before the assessment. One training session was conducted before the experiment began. The training procedure included an explanation of the study's aim and a discussion on the flow of the experiment. The panelists evaluated the organoleptic attributes using a five-point rating scale, where scores were defined as follows: 1—poor quality (does not meet established criteria), 2—sufficient quality (noticeable deviations from criteria that do not disqualify the product), 3—satisfactory quality (persistent noticeable deviations), 4—good quality (minor deviations), and 5—very good quality (no deviations from the established requirements). Half-scores were not permitted. Panelists were provided with evaluation forms, still water, and wheat bread for palate cleansing, and were allowed to record additional observations regarding specific quality characteristics of the samples. Participation in the organoleptic examination was voluntary, and participants could withdraw from the study at any time. Prior to the organoleptic evaluation, the panelists were informed that the burger samples contained chokeberry pomace. Before participation in the organoleptic evaluation, all panelists provided written informed consent (Figure S4). The consent form was created in line with the guidelines established by the Rector's Committee on Ethics in Research Involving Human Subjects at the WULS—SGGW. The design of the organoleptic tests received a positive opinion of the Rector's Committee for Ethics of Scientific Research Involving Human Participation at the Warsaw University of Life Sciences (resolution no 32/RKE/2026/U).

Table 2. Organoleptic quality attributes for beef burgers [established by the authors].

Organoleptic Quality Attribute	Description of Organoleptic Quality Criteria
Appearance and color	Surface clean, no cracks, product does not fall apart; color characteristic of the raw materials used and the technological process applied, from brown to dark brown, unacceptable color indicating product deterioration during storage.
Aroma	Aroma characteristic of the raw materials used and the technological process employed; unacceptable is a musty, unusual, foreign, or stale odor of the product.
Taste	Taste is characteristic of the raw materials used and the technological process employed; an unacceptable taste is musty, unusual, or foreign, indicating that the product is not fresh.
Texture	Homogeneous structure, uniform degree of grinding of meat and fat raw materials; consistency sufficiently firm, not falling apart; a piece of product that can be easily broken up in the mouth and swallowed; unacceptable consistency, very hard, crumbling, rubbery.

In each experimental series, 10 panelists evaluated samples prepared from individual burgers of each variant. Thus, a total of 20 individual sensory scores were obtained for each organoleptic attribute across the two experimental series ($n = 20$).

2.2.7. Evaluation of the Microbiological Quality of Beef Burgers

The microbiological quality of beef burgers was assessed on days 1, 7, and 14 of refrigerated storage. Burger packages intended for microbiological evaluation were opened under aseptic conditions. Sample preparation was conducted following the Polish Standard PN-EN ISO 6887–2:2017 [49]. Microbiological analyses included the determination of the

total count of mesophilic aerobic microorganisms [50], psychrotrophic bacteria [51], lactic acid bacteria (LAB) [52], Enterobacteriaceae [53], and *Escherichia coli* [54]. Microbial counts were expressed as colony-forming units per gram of product (log CFU/g). For results below the detection limit, values were reported as “<1.00 log CFU/g”. Censored observations were handled as described in the statistical analysis section. Detailed procedures for the microbiological assessment have been reported previously [55,56]. For each burger variant and storage day, microbiological analyses were conducted on two independent samples in each of two independent experimental series, resulting in a total of four independent observations ($n = 4$). Additionally, the microbiological quality of chokeberry pomace was assessed by measuring the total count of mesophilic aerobic microorganisms, psychrotrophic bacteria, LAB, Enterobacteriaceae, and yeasts and molds [57].

2.2.8. Statistical Analysis of Results

Statistical analysis was conducted using Statistica® software (version 13.0; StatSoft Inc., Tulsa, OK, USA). Two separate one-way analyses of variance (ANOVA) were performed: (a) to evaluate the effect of black chokeberry pomace level on selected quality parameters of the burgers, and (b) to assess the effect of storage time within each burger variant. Normality of data distribution was assessed using the Shapiro–Wilk test, and homogeneity of variances using Levene’s test. When significant effects were observed, differences between means were identified using Tukey’s honestly significant difference (HSD) test. Statistical significance was set at $\alpha \leq 0.05$.

In this study, two separate one-way ANOVAs were conducted, as our primary objective was to evaluate the main effects of each factor (pomace inclusion level and storage time) independently rather than their interaction. Preliminary data analysis indicated no significant interaction between the two factors.

3. Results

3.1. Antioxidant Properties of Chokeberry Pomace

The chokeberry pomace incorporated into beef burgers was characterized by a high total polyphenol content of 1417.31 ± 7.97 mg GAE/100 g fresh weight, including anthocyanins at a concentration of 207.04 ± 7.37 mg/100 g fresh weight. Moreover, this plant material exhibited an antioxidant activity of 11.90 μ M TE/1 g fresh pomace weight. The anthocyanin profile was predominantly composed of cyanidin-3-galactoside, which accounted for 66.8% of the total anthocyanins, followed by cyanidin-3-arabinoside (27.9%), cyanidin-3-xyloside (2.9%), and cyanidin-3-glucoside (2.5%).

3.2. Cooking Characteristics of Beef Burgers

Weight loss in beef burgers following heat treatment ranged from 29.9% to 35.5% (Figure 1), with significant differences ($p < 0.05$) depending on the level of chokeberry pomace added. The control burgers (BC) exhibited the lowest thermal loss. In contrast, burgers B1 and B2, containing 1% and 2% pomace, respectively, showed a significant increase ($p < 0.05$) in weight loss compared with the control. The highest thermal loss ($p < 0.05$) was observed in burger B3, which contained the greatest amount of chokeberry pomace (3.0%).

Thermal processing of beef burgers resulted not only in weight loss but also in a reduction in diameter. The extent of shrinkage increased with higher levels of chokeberry pomace, corresponding to the observed weight losses. Diameter reduction ranged from 20.6% in control (BC) burgers to 23.5% in B3 burgers (Figure 1). Burgers with the highest chokeberry pomace content (B2 and B3) exhibited significantly greater shrinkage ($p < 0.05$) compared with the control burgers (BC).

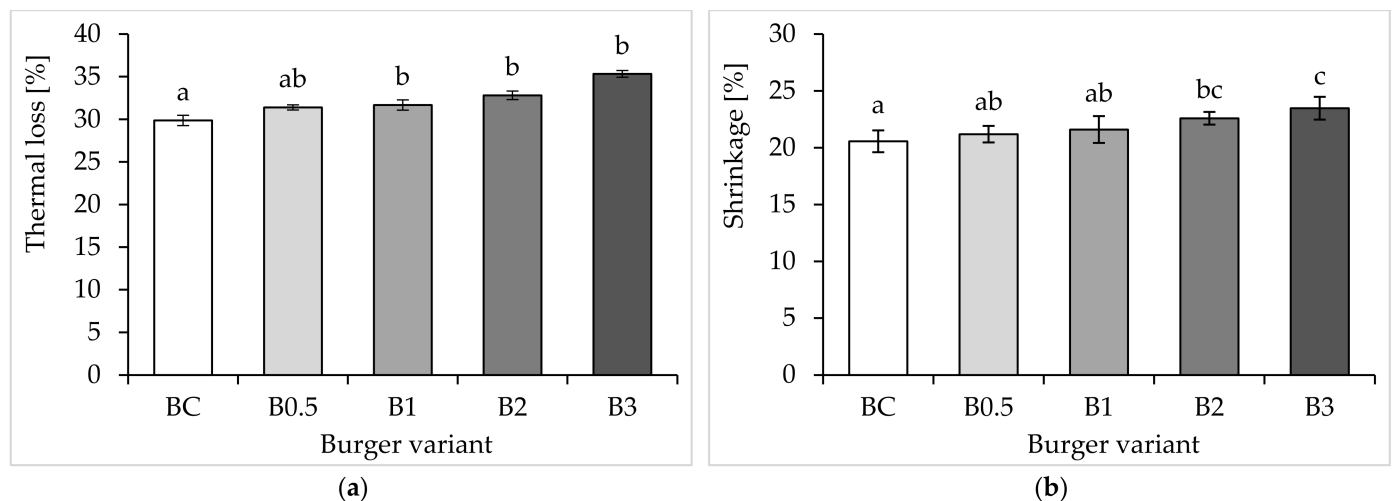


Figure 1. Thermal loss (a) and the shrinkage (b) of beef burgers with varying amounts of black chokeberry pomace added. Notes: Explanation of burger variant codes: BC/0.5/1/2/3—beef burger variants with 0/0.5/1/2/3% addition of chokeberry pomace; a–c—mean values (for the given quality feature) marked with different letters differ significantly ($p < 0.05$).

3.3. Chemical Composition of Beef Burgers

The content of the basic chemical components in beef burgers is presented in Table 3. The mean water content ranged from 54.50% in product B3 to 57.06% in product BC. Protein content varied from 24.20% in BC to 25.89% in B3, while NaCl content ranged from 1.29% in BC to 1.36% in B0.5.

Table 3. Content of selected chemical components in beef burgers with varying amounts of black chokeberry pomace added (mean value $\pm$ standard deviation).

Feature	BC	B0.5	B1	B2	B3	<i>p</i> -Value
Water content [%]	57.06 ^a $\pm$ 1.47	54.75 ^a $\pm$ 1.89	54.16 ^a $\pm$ 0.09	54.66 ^a $\pm$ 0.68	54.50 ^a $\pm$ 2.05	0.3843
Protein content [%]	24.20 ^a $\pm$ 0.18	24.47 ^a $\pm$ 1.15	25.48 ^a $\pm$ 0.31	25.42 ^a $\pm$ 0.01	25.89 ^a $\pm$ 0.60	0.1383
Fat content [%]	16.15 ^b $\pm$ 0.01	16.01 ^b $\pm$ 0.08	15.89 ^b $\pm$ 0.18	14.96 ^a $\pm$ 0.28	14.67 ^a $\pm$ 0.06	0.0007
NaCl content [%]	1.36 ^a $\pm$ 0.04	1.36 ^a $\pm$ 0.04	1.33 ^a $\pm$ 0.02	1.30 ^a $\pm$ 0.01	1.29 ^a $\pm$ 0.05	0.2447

Notes: Explanation of burger variant codes: BC/0.5/1/2/3—beef burger variants with 0/0.5/1/2/3% addition of chokeberry pomace; a–b—mean values in the same row marked with different letters differ significantly ($p < 0.05$).

The addition of shredded chokeberry pomace (0.5–3.0%) did not significantly affect ($p > 0.05$) the water, protein, or NaCl content of the burgers after heat treatment. However, a trend toward lower water and NaCl content, accompanied by higher protein content, was observed with increasing levels of pomace.

Significant differences ($p < 0.05$) were observed only in fat content. Specifically, burgers containing the highest levels of pomace (B2 and B3) exhibited significantly lower fat content compared with the control (BC).

The fresh chokeberry pomace used in this study was characterized by the moisture content of 67.20%. Nevertheless, incorporation of chokeberry pomace into the beef burger formulation at concentrations of up to 3.0% did not significantly affect ($p > 0.05$) the water content of the burgers after baking. These findings suggest that changes in the concentrations of the analyzed chemical constituents were influenced to a greater extent by weight loss occurring during thermal processing than by the moisture introduced with the pomace itself.

3.4. pH Value of Beef Burgers

The average pH of beef burgers ranged from 6.09 to 6.27. The lowest and highest values were recorded in burgers B3 (day 14) and BC (days 1 and 7), respectively (Table 4). Although the maximum difference between the variants was only 0.18 pH units, a significant ($p < 0.05$) effect of both the addition of black chokeberry pomace and storage time on this parameter was demonstrated. Increasing the share of black chokeberry pomace in the recipe led to a gradual decrease in the pH of the burgers, and regardless of storage time, the lowest values were significantly ($p < 0.05$) recorded in burgers B3, which contained the highest pomace addition.

Table 4. Changes in pH values of beef burgers with varying amounts of black chokeberry pomace added during storage under refrigeration (mean value $\pm$ standard deviation).

Storage Time [Days]	BC	B0.5	B1	B2	B3	<i>p</i> -Value
1	6.27 ^{cA} $\pm$ 0.05	6.23 ^{bA} $\pm$ 0.01	6.21 ^{bB} $\pm$ 0.02	6.19 ^{bB} $\pm$ 0.01	6.12 ^{aB} $\pm$ 0.01	<0.0001
7	6.27 ^{dA} $\pm$ 0.02	6.21 ^{cA} $\pm$ 0.02	6.19 ^{bcA} $\pm$ 0.02	6.18 ^{bB} $\pm$ 0.01	6.10 ^{aAB} $\pm$ 0.02	<0.0001
14	6.27 ^{dA} $\pm$ 0.01	6.21 ^{cA} $\pm$ 0.01	6.18 ^{bA} $\pm$ 0.01	6.16 ^{bA} $\pm$ 0.01	6.09 ^{aA} $\pm$ 0.01	<0.0001
<i>p</i> -Value	0.1944	0.1944	0.0038	0.0017	0.0355	

Notes: Explanation of burger variant codes: BC/0.5/1/2/3—beef burger variants with 0/0.5/1/2/3% addition of chokeberry pomace; a–d—mean values (in the same row) marked with different letters differ significantly ($p < 0.05$) between burger treatments on a given day of storage; A–B—mean values of a given burger treatment (in the same column) marked with different letters differ significantly ($p < 0.05$) between storage days.

During the 14-day storage period, a general decline in pH was observed across all burger variants, however, significant changes ($p < 0.05$) were identified specifically in products containing 1.0% to 3.0% chokeberry pomace (B1–B3). The reduction in pH observed in burgers enriched with chokeberry pomace (B0.5–B3) may be attributed to differences in the acidity of the raw materials used. The pH of the meat and fat components was measured at 6.39, whereas the chokeberry pomace exhibited a substantially lower pH value of 3.75.

3.5. Color Parameters of Beef Burgers

Significant differences ($p < 0.05$) in all color parameters (L^* , a^* , b^*) were observed among the analyzed beef burgers, depending on both the level of chokeberry pomace addition and the duration of storage (Table 5).

The highest lightness (L^*) value was observed in the control burgers (BC), reaching 43.80 on the first day after production. In contrast, the lowest L^* value (34.74), indicating the darkest color, was recorded for burgers containing the highest level of chokeberry pomace (B3), also on day 1. The L^* value decreased progressively with increasing levels of chokeberry pomace, reflecting a gradual darkening of the product surface. Throughout the storage period, burgers containing 2% and 3% pomace (B2 and B3) remained significantly darker ($p < 0.05$) than the control (BC). Over time, the L^* values of BC and B1 samples remained relatively stable, whereas the remaining treatments exhibited a slight but statistically significant ($p < 0.05$) increase in this parameter.

The mean a^* values of the refrigerated beef burgers ranged from 6.12 for sample B3 on day 1 to 8.39 for the control sample (BC) on day 14. On day 1, the control burgers exhibited significantly higher redness compared to burgers containing chokeberry pomace (B0.5–B3) ($p < 0.05$). On days 7 and 14, the BC burgers continued to show the highest a^* values ($p < 0.05$), whereas samples B1 and B2 displayed significantly lower redness ($p < 0.05$).

Over time, a gradual and significant increase ($p < 0.05$) in a^* values was observed in samples BC, B0.5, and B3. In contrast, no significant changes ($p > 0.05$) in redness were detected for samples B1 and B2 over the storage period.

The b^* parameter of beef burgers was most strongly influenced by the pomace addition. The highest b^* value (+5.81) was recorded on day 1 for the control sample (BC), whereas the lowest value (−2.06) was observed for sample B3 on day 14. Increasing the proportion of chokeberry pomace resulted in a significant ($p < 0.05$) decrease in the b^* parameter, with values shifting from positive (BC, B0.5), indicative of yellow tones, to negative (B2, B3), corresponding to blue hues. Furthermore, a decreasing trend in b^* values was observed over the storage period for all burger variants, however, statistically significant changes ($p < 0.05$) were detected only in samples B1 and B2.

Table 5. Changes in color parameters L^* , a^* and b^* of beef burgers with varying amounts of black chokeberry pomace added during storage under refrigeration (mean value $\pm$ standard deviation).

Storage Time [Days]	BC	B0.5	B1	B2	B3	<i>p</i> -Value
L^* (lightness)						
1	43.80 ^{cA} $\pm$ 2.03	42.63 ^{cA} $\pm$ 1.11	39.56 ^{bA} $\pm$ 1.46	36.11 ^{aA} $\pm$ 1.06	34.74 ^{aA} $\pm$ 1.32	<0.0001
7	44.75 ^{dA} $\pm$ 2.57	43.27 ^{dAB} $\pm$ 1.32	40.09 ^{cA} $\pm$ 0.76	37.59 ^{bB} $\pm$ 1.39	34.96 ^{aA} $\pm$ 1.17	<0.0001
14	45.84 ^{cA} $\pm$ 1.72	44.07 ^{cB} $\pm$ 1.26	40.10 ^{bA} $\pm$ 0.52	38.81 ^{bB} $\pm$ 1.19	36.93 ^{aB} $\pm$ 2.63	<0.0001
<i>p</i> -Value	0.0792	0.0265	0.3249	<0.0001	0.0110	
$+a^*/-a^*$ (redness/greenness)						
1	7.54 ^{bA} $\pm$ 0.76	6.70 ^{aA} $\pm$ 0.66	6.13 ^{aA} $\pm$ 0.31	6.15 ^{aA} $\pm$ 0.30	6.12 ^{aA} $\pm$ 0.41	<0.0001
7	8.17 ^{cAB} $\pm$ 0.76	7.33 ^{bB} $\pm$ 0.62	6.18 ^{aA} $\pm$ 0.52	6.29 ^{aA} $\pm$ 0.62	7.57 ^{bcB} $\pm$ 0.50	<0.0001
14	8.39 ^{cB} $\pm$ 0.87	7.59 ^{bB} $\pm$ 0.50	6.22 ^{aA} $\pm$ 0.41	6.41 ^{aA} $\pm$ 0.65	7.61 ^{bB} $\pm$ 0.76	<0.0001
<i>p</i> -Value	0.0389	0.0028	0.0866	0.5170	<0.0001	
$+b^*/-b^*$ (yellowness/blueness)						
1	5.81 ^{dA} $\pm$ 1.65	3.03 ^{cA} $\pm$ 0.59	0.72 ^{bB} $\pm$ 0.68	−0.17 ^{abB} $\pm$ 0.88	−1.17 ^{aA} $\pm$ 1.01	<0.0001
7	5.50 ^{dA} $\pm$ 1.21	2.23 ^{cA} $\pm$ 1.12	0.61 ^{bB} $\pm$ 0.80	−0.73 ^{abAB} $\pm$ 1.02	−1.61 ^{aA} $\pm$ 1.72	<0.0001
14	4.73 ^{dA} $\pm$ 0.93	2.20 ^{cA} $\pm$ 1.13	−0.25 ^{bA} $\pm$ 0.91	−1.29 ^{abA} $\pm$ 0.85	−2.06 ^{aA} $\pm$ 0.72	<0.0001
<i>p</i> -Value	0.1245	0.0655	0.0104	0.0202	0.2227	

Notes: Explanation of burger variant codes: BC/0.5/1/2/3—beef burger variants with 0/0.5/1/2/3% addition of chokeberry pomace; a–d—mean values (in the same row) marked with different letters differ significantly ($p < 0.05$) between burger treatments on a given day of storage; A–B—mean values of a given burger treatment (in the same column) marked with different letters differ significantly ($p < 0.05$) between storage days.

The total color difference (ΔE) values indicate a pronounced effect of chokeberry pomace incorporation on the color of beef burgers relative to the control sample (Table 6). In most cases, ΔE values exceeded 3.5, suggesting that color differences between the control (BC) and pomace-enriched burgers were perceptible. The burger treatment with 0.5% chokeberry pomace exhibited the lowest ΔE values, regardless of the storage day. A noticeable increase in ΔE was observed with increasing levels of the chokeberry by-product in burgers' recipes. ΔE values exceeding 5.0, recorded for samples B1, B2, and B3 irrespective of storage time, indicate that the color differences compared to the control burgers were readily noticeable to consumers.

Table 6. Total color difference (ΔE) for beef burgers with different amounts of black chokeberry pomace added during storage.

Storage Time [Days]	ΔE			
	BC–B0.5	BC–B1	BC–B2	BC–B3
1	3.1	6.8	9.8	11.5
7	3.7	7.0	9.7	12.1
14	3.2	7.9	9.5	11.2

Notes: Explanation of burger variant codes: BC/0.5/1/2/3—beef burger variants with 0/0.5/1/2/3% addition of chokeberry pomace.

3.6. Shear Force of Beef Burgers

The mean shear force values of the beef burgers ranged from 17.88 to 23.21 N, with the difference between the extreme values not exceeding 23%. The lowest shear force was recorded for sample B3 on day 1 of storage, whereas the highest value was observed for the control sample (BC) on day 14 (Figure 2). An inverse relationship was identified between the proportion of chokeberry plant by-product incorporated into the meat batter and the shear force values. On day 1, the addition of pomace did not significantly affect shear force ($p > 0.05$). However, by day 7, the control burgers (BC) exhibited higher shear force compared to samples B2 and B3. This pattern persisted through day 14 of refrigerated storage, with shear force decreasing further as the pomace content increased. Despite differences in burgers' formulation (BC–B3), storage time did not significantly influence burger texture, as indicated by the slight ($p > 0.05$) increase in shear force over time.

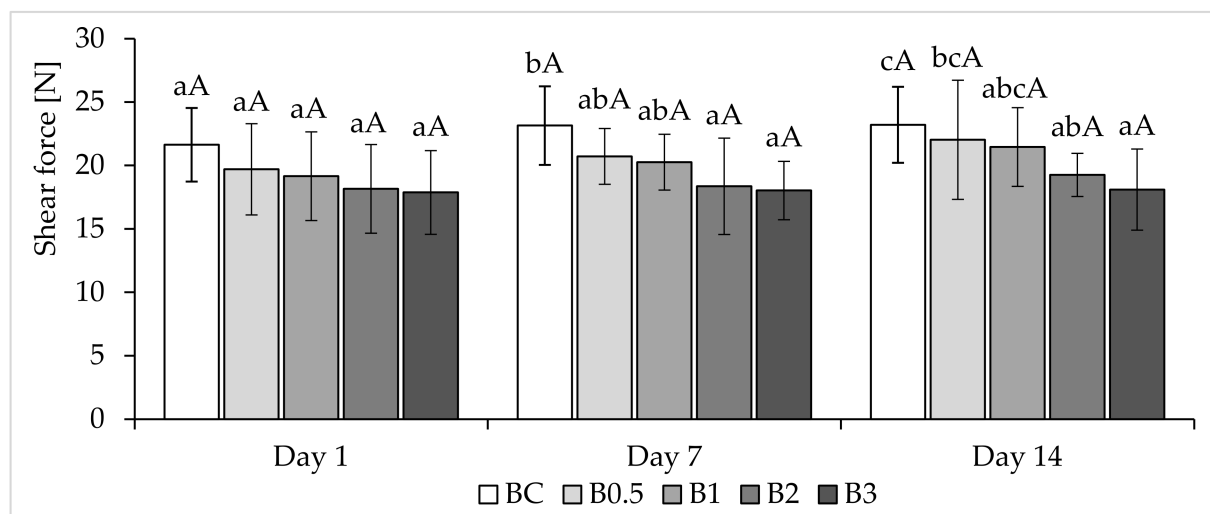


Figure 2. Changes in shear force of beef burgers with varying amounts of black chokeberry pomace added during storage under refrigeration. Notes: Explanation of burger variant codes: BC/0.5/1/2/3—beef burger variants with 0/0.5/1/2/3% addition of chokeberry pomace; a–c—mean values marked with different letters differ significantly ($p < 0.05$) between burger treatments on a given day of storage; A—mean values of a given burger treatment (for the same bar pattern) marked with different letters differ significantly ($p < 0.05$) between storage days.

3.7. Organoleptic Properties of Beef Burgers

The results of the organoleptic evaluation of beef burgers supplemented with varying levels of chokeberry pomace indicate that the mean scores for all assessed quality attributes remained high throughout the 14-day refrigerated storage period, with none falling below 3.3 on a five-point scale (Table 7). The organoleptic properties of the burgers were significantly ($p < 0.05$) influenced by the level of ground chokeberry pomace addition. In contrast, storage time did not significantly affect these attributes ($p > 0.05$). For most evaluated organoleptic parameters, only slight, non-significant decreasing trends were observed over the storage period.

Increasing the proportion of chokeberry pomace in the formulation resulted in lower scores for the appearance and color of the burgers. However, a significant deterioration ($p < 0.05$) in these attributes, relative to the control sample (BC), was observed only in products with the highest pomace content (B2 and B3). The color of these burgers was perceived as excessively dark and did not fully meet the established quality criteria (Table 2). Additionally, some panelists noted that burger B3 appeared “overcooked.”

Similar trends were identified in the aroma assessment. Irrespective of storage duration, samples BC and B0.5 received the highest scores, significantly outperforming sample

B3 ($p < 0.05$). The aroma of burger B3 was rated as only “moderately acceptable” according to the evaluation criteria. Furthermore, several panelists reported a perceptible “fruity note” in the aroma of burgers containing higher levels of chokeberry pomace.

Table 7. Changes in organoleptic properties of beef burgers with varying amounts of black chokeberry pomace added during storage under refrigeration (mean $\pm$ standard deviation).

Storage Time [Days]	BC	B0.5	B1	B2	B3	<i>p</i> -Value
Appearance and Color						
1	4.9 ^{bA} $\pm$ 0.31	4.8 ^{bA} $\pm$ 0.41	4.7 ^{bA} $\pm$ 0.47	3.9 ^{aA} $\pm$ 0.55	3.6 ^{aA} $\pm$ 0.50	<0.0001
7	4.8 ^{bA} $\pm$ 0.41	4.7 ^{bA} $\pm$ 0.47	4.6 ^{bA} $\pm$ 0.50	3.9 ^{aA} $\pm$ 0.31	3.6 ^{aA} $\pm$ 0.50	<0.0001
14	4.8 ^{bA} $\pm$ 0.41	4.7 ^{bA} $\pm$ 0.47	4.4 ^{bA} $\pm$ 0.50	3.7 ^{aA} $\pm$ 0.47	3.3 ^{aA} $\pm$ 0.47	<0.0001
<i>p</i> -Value	0.6315	0.7220	0.1549	0.2837	0.0929	
Aroma						
1	4.9 ^{bA} $\pm$ 0.31	4.8 ^{bA} $\pm$ 0.41	4.7 ^{abA} $\pm$ 0.47	4.6 ^{abA} $\pm$ 0.50	4.4 ^{aA} $\pm$ 0.50	0.0072
7	4.8 ^{bA} $\pm$ 0.41	4.7 ^{abA} $\pm$ 0.47	4.6 ^{abA} $\pm$ 0.50	4.6 ^{abA} $\pm$ 0.50	4.3 ^{aA} $\pm$ 0.47	0.0180
14	4.8 ^{bA} $\pm$ 0.41	4.7 ^{bA} $\pm$ 0.47	4.6 ^{abA} $\pm$ 0.50	4.5 ^{abA} $\pm$ 0.51	4.2 ^{aA} $\pm$ 0.41	0.0012
<i>p</i> -Value	0.6314	0.3280	0.2750	0.7717	0.3987	
Taste						
1	4.9 ^{bA} $\pm$ 0.31	4.9 ^{bA} $\pm$ 0.31	4.4 ^{abA} $\pm$ 0.68	4.2 ^{aA} $\pm$ 0.70	4.0 ^{aA} $\pm$ 0.79	<0.0001
7	4.9 ^{bA} $\pm$ 0.31	4.8 ^{bA} $\pm$ 0.41	4.3 ^{aA} $\pm$ 0.80	4.1 ^{aA} $\pm$ 0.55	3.9 ^{aA} $\pm$ 0.31	<0.0001
14	4.9 ^{cA} $\pm$ 0.31	4.8 ^{cA} $\pm$ 0.41	4.3 ^{bA} $\pm$ 0.66	4.0 ^{aA} $\pm$ 0.46	3.8 ^{aA} $\pm$ 0.41	<0.0001
<i>p</i> -Value	0.6315	0.6314	0.8782	0.5430	0.5154	
Texture						
1	4.9 ^{cA} $\pm$ 0.31	4.9 ^{cA} $\pm$ 0.31	4.5 ^{bcA} $\pm$ 0.51	4.2 ^{abA} $\pm$ 0.62	3.9 ^{aA} $\pm$ 0.72	<0.0001
7	4.9 ^{cA} $\pm$ 0.31	4.9 ^{cA} $\pm$ 0.31	4.4 ^{bA} $\pm$ 0.50	4.1 ^{abA} $\pm$ 0.55	3.8 ^{aA} $\pm$ 0.41	<0.0001
14	4.9 ^{cA} $\pm$ 0.31	4.9 ^{cA} $\pm$ 0.31	4.4 ^{bA} $\pm$ 0.50	4.0 ^{aA} $\pm$ 0.46	3.8 ^{aA} $\pm$ 0.62	<0.0001
<i>p</i> -Value	0.6315	1.0000	0.7717	0.5154	0.8290	

Notes: Explanation of burger variant codes: BC/0.5/1/2/3—beef burger variants with 0/0.5/1/2/3% addition of chokeberry pomace; a—c—mean values (in the same row) marked with different letters differ significantly ($p < 0.05$) between burger treatments on a given day of storage; A—mean values of a given burger treatment (in the same column) marked with different letters differ significantly ($p < 0.05$) between storage days.

In the taste assessment conducted on days 1, 7, and 14 of storage, significant differences ($p < 0.05$) were identified between samples BC and B0.5, which constituted a single homogeneous group, and samples B2 and B3. The lower taste scores assigned to burgers with higher levels of chokeberry pomace were attributed to the presence of “sour” and “fruity” notes, which were perceived by the panelists as atypical for this type of meat product.

The incorporation of chokeberry pomace also adversely affected the texture of the beef burgers, resulting in consistently lower scores for samples B0.5–B3 compared to the control (BC). Moreover, variation in texture ratings among the different formulations of burgers increased over the storage period. On day 1, the texture of samples B2 and B3 was rated significantly lower ($p < 0.05$) than that of BC and B0.5. On day 14, significant differences ($p < 0.05$) were observed among all tested burger variants (BC, B0.5, B1, B2, and B3). Panelists suggested that the reduced texture in burgers with higher pomace content may be associated with the presence of fine particles perceived during mastication, as well as a slight reduction in juiciness, potentially related to increased thermal losses observed in these products.

It should be noted that the sensory evaluation performed in the present study was based on a relatively small trained panel and was intended primarily for product characterization. Therefore, the obtained results reflect differences in sensory quality between burger formulations rather than consumer preferences or market acceptance. Further studies involving larger consumer panels are required to determine the acceptability of beef burgers enriched with chokeberry pomace under real consumption conditions.

3.8. Microbiological Quality of Beef Burgers

The microbiological quality of chokeberry pomace was characterized by the counts of selected microbial groups. The total count of mesophilic aerobic microorganisms was 3.63 log CFU/g, while lactic acid bacteria (LAB) and yeasts and molds were detected at 2.28 log CFU/g and 2.46 log CFU/g, respectively.

Under the conditions adopted in this study, the addition of chokeberry pomace to the beef burger formulation did not adversely affect microbiological quality and helped maintain acceptable microbiological status during 14 days of refrigerated storage (Table 8). While reductions in the counts of certain microbial groups were observed in samples containing chokeberry pomace, these changes were not consistently related to the level of pomace addition. The counts of mesophilic aerobic microorganisms ranged from below the detection limit (<1.00 log CFU/g; product B3, day 1) to 4.25 log CFU/g (product BC, day 14). On day 1, significant differences between treatments were already observed ($p < 0.05$), however, the changes were not dose-dependent. Similar observations were made on days 7 and 14, where several pomace-containing variants showed lower microbial counts than the control, although a consistent relationship between pomace level and microbial reduction was not evident. Although several differences between treatments were statistically significant, the magnitude of these changes did not exceed approximately 1 log CFU/g in most cases. Therefore, their biological relevance in terms of product safety and shelf-life should be interpreted with caution, as they may partially reflect natural variability of microbial populations in complex food systems.

Table 8. Changes in microbial quality of beef burgers with varying amounts of black chokeberry pomace added during storage at refrigeration temperature (mean value $\pm$ standard deviation).

Storage Time [Days]	BC	B0.5	B1	B2	B3	<i>p</i> -Value
Mesophilic aerobic microorganisms [log CFU/g]						
1	1.32 $\pm$ 0.28 ^{aA}	1.30 $\pm$ 0.01 ^{aA}	2.26 $\pm$ 0.05 ^{bA}	2.25 $\pm$ 0.05 ^{aA}	<1.00 ^{aA}	<0.0001
7	2.71 $\pm$ 0.14 ^{bA}	2.28 $\pm$ 0.13 ^{aA}	2.36 $\pm$ 0.05 ^{aA}	2.94 $\pm$ 0.04 ^{cB}	1.77 $\pm$ 0.06 ^{aA}	<0.0001
14	4.26 $\pm$ 0.02 ^{cB}	4.02 $\pm$ 0.02 ^{dB}	3.03 $\pm$ 0.03 ^{aB}	3.55 $\pm$ 0.04 ^{bC}	3.75 $\pm$ 0.03 ^{cB}	<0.0001
<i>p</i> -Value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	
Psychrotrophic bacteria [log CFU/g]						
1	2.97 $\pm$ 0.07 ^{bA}	1.89 $\pm$ 0.11 ^{aA}	2.23 $\pm$ 0.22 ^{aA}	1.48 $\pm$ 0.16 ^{aA}	<1.00 ^{aA}	<0.0001
7	3.10 $\pm$ 0.05 ^{cAB}	1.97 $\pm$ 0.03 ^{abA}	2.33 $\pm$ 0.05 ^{abA}	2.39 $\pm$ 0.08 ^{bB}	1.53 $\pm$ 0.21 ^{aA}	<0.0001
14	3.15 $\pm$ 0.06 ^{cB}	3.00 $\pm$ 0.03 ^{bB}	3.37 $\pm$ 0.04 ^{dB}	2.59 $\pm$ 0.11 ^{aB}	2.47 $\pm$ 0.21 ^{aB}	<0.0001
<i>p</i> -Value	0.0302	<0.0001	<0.0001	0.0012	0.0039	
Lactic acid bacteria [log CFU/g]						
1	2.12 $\pm$ 0.05 ^{cA}	2.04 $\pm$ 0.04 ^{bcA}	2.13 $\pm$ 0.16 ^{cA}	1.46 $\pm$ 0.15 ^{aA}	1.67 $\pm$ 0.06 ^{abA}	0.0008
7	2.16 $\pm$ 0.11 ^{bA}	2.31 $\pm$ 0.02 ^{cA}	2.21 $\pm$ 0.02 ^{bcA}	1.68 $\pm$ 0.03 ^{aA}	1.72 $\pm$ 0.13 ^{aA}	<0.0001
14	3.12 $\pm$ 0.03 ^{bB}	3.35 $\pm$ 0.04 ^{cB}	3.38 $\pm$ 0.03 ^{cB}	1.62 $\pm$ 0.28 ^{aA}	2.50 $\pm$ 0.16 ^{aB}	<0.0001
<i>p</i> -Value	<0.0001	<0.0001	<0.0001	0.3649	0.0019	
Enterobacteriaceae [log CFU/g]						
1	<1.00	<1.00	<1.00	<1.00	<1.00	-
7	<1.00	<1.00	<1.00	<1.00	<1.00	-
14	<1.00	<1.00	<1.00	<1.00	<1.00	-
Escherichia coli [log CFU/g]						
1	<1.00	<1.00	<1.00	<1.00	<1.00	-
7	<1.00	<1.00	<1.00	<1.00	<1.00	-
14	<1.00	<1.00	<1.00	<1.00	<1.00	-

Notes: Explanation of burger variant codes: BC/0.5/1/2/3—beef burger variants with 0/0.5/1/2/3% addition of chokeberry pomace; a–e—mean values (in the same row) marked with different letters differ significantly ($p < 0.05$) between burger treatments on a given day of storage; A–C—mean values of a given burger treatment (in the same column) marked with different letters differ significantly ($p < 0.05$) between storage days.

A greater reduction in psychrotrophic bacterial counts was observed for psychrotrophic bacteria. On day 1, burgers containing pomace (B0.5–B3) showed significantly lower counts compared to the control ($p < 0.05$). The lowest counts were consistently recorded in product B3, containing the highest level of pomace. In this variant, psychrotrophic bacteria were below the detection limit on day 1 and reached 2.50 log CFU/g after 14 days. As with mesophilic microorganisms, a significant increase in counts over time was observed in all samples ($p < 0.05$).

Lactic acid bacteria were present in all variants, with counts ranging from 1.46 log CFU/g (B2, day 1) to 3.38 log CFU/g (B1, day 14). On day 1 after production, burgers containing 2% chokeberry pomace (B2) exhibited significantly lower ($p < 0.05$) lactic acid bacteria counts than BC–B1 burgers. On days 7 and 14, significantly lower LAB counts were observed in burgers containing 2% and 3% chokeberry pomace (B2 and B3, respectively) compared with the other variants. However, the observed differences were not consistently related to the level of chokeberry pomace addition, indicating the absence of a clear dose-dependent effect throughout storage. Enterobacteriaceae and *Escherichia coli* were not detected in any of the analyzed beef burger variants (<1.00 log CFU/g).

Overall, the results indicate that the incorporation of chokeberry pomace did not compromise the microbiological quality of beef burgers during refrigerated storage. Although certain pomace-containing treatments exhibited lower microbial counts than the control, the observed effects were not consistently dose-dependent across microbial groups and storage periods. Therefore, the findings support the maintenance of acceptable microbiological quality rather than a definitive antimicrobial effect of chokeberry pomace.

4. Discussion

The use of shredded, non-dried black chokeberry pomace has previously been investigated in pork burgers [42], whereas the present study evaluated the use of the same by-product in beef burgers. Due to differences in composition, color, protein-fat structure, and technological behavior between pork and beef, the results cannot be directly extrapolated to beef burger formulations. In both products, pomace addition reduced pH, darkened color, and was more acceptable organoleptically at lower inclusion levels. However, matrix-dependent effects were observed. In beef burgers evaluated in this study, increasing pomace levels increased thermal loss and shrinkage while reducing shear force, suggesting different interactions between pomace components and the meat matrix.

4.1. Properties of Chokeberry Pomace

Black chokeberry is a rich source of bioactive compounds exhibiting antioxidant, antimicrobial, and health-promoting properties. Since a considerable proportion of these constituents remains in the pomace following juice extraction, this by-product can serve as a valuable ingredient in food production, the use of which will be in line with the idea of "less-waste" food production and the idea of a circular economy [33,58].

Previous studies have demonstrated considerable variability in the concentration of individual bioactive compounds in chokeberry fruits, depending on cultivar, agronomic practices, and harvesting conditions. The total polyphenol content in chokeberry fruits has been reported to range from 778 mg GAE/100 g fresh mass [58] to 2340 mg GAE/100 g fresh mass [59], whereas in chokeberry pomace it may reach up to 6310 mg GAE/100 g fresh weight. Furthermore, according to Vagiri and Jensen [60], the anthocyanin content in chokeberry pomace varies from 114.4 to 1221.1 mg/100 g fresh mass. Therefore, the values obtained in the present study fall within the ranges previously reported in the literature.

4.2. Cooking Characteristics of Beef Burgers

Thermal processing of meat burgers, which determines their suitability for consumption, induces physicochemical transformations of muscle proteins, leading to modifications in the structure of the product matrix. These changes may affect cooking losses [11]. Cooking characteristics such as cooking loss and product shrinkage are important indicators of burger quality, as they can influence juiciness and texture [24]. In the analyzed beef burgers, an increased proportion of chokeberry pomace with relatively high acidity resulted in greater mass loss and shrinkage after baking. Although the mechanisms underlying these changes were not investigated in the present study, similar observations have been reported in pork burgers enriched with dried plums [61]. As noted by de Alencar et al. [24], the interactions between plant-derived ingredients and the meat matrix, as well as their effects on cooking losses and textural properties, require further investigation.

There are relatively few reports in the literature concerning the use of raw, shredded fruit pomace in the development of more sustainable meat products. Previous studies have shown that the addition of fresh chokeberry pomace [42] and freeze-dried and rehydrated apple pomace [62] may increase cooking losses and intensify changes in burger geometry. However, the underlying mechanisms remain unclear and were not examined in the present study.

More extensively, the effects of dried fruit and vegetable by-products on the quality of ground beef products such as burgers have been investigated, including raspberry and blackberry pomace [63], tomato peel flour [21], dried papaya peel [22], and freeze-dried carrot pomace [23]. Depending on the type and level of addition, these ingredients may influence the physicochemical and technological properties of meat products. However, findings regarding cooking losses and burger shrinkage remain inconsistent: de Alencar et al. [24] reported an increase in cooking losses following the addition of grape skin flour, whereas Peiretti et al. [26] did not observe significant changes in the shrinkage of pork patties containing dried blueberry pomace.

4.3. Chemical Composition of Beef Burgers

The chemical composition of meat products, including beef burgers, is primarily determined by the relative proportions of water, protein, and fat. Analysis of the water, protein, fat, and NaCl contents demonstrated that all examined beef burger samples (BC–B3) complied with the quality requirements specified in the Polish Standard PN-A-82010 Meat and Meat Products–Hamburgers [7]. According to this standard, the contents of water, fat, and sodium chloride should not exceed 64%, 20%, and 2.5%, respectively, while the protein content should be maintained at a minimum level of 15%.

The nutritional value of beef burgers can be modified through the incorporation of plant-based components into the formulation, such as pea fiber [11], tomato peel flour [21], freeze-dried carrot pomace [23], or grape skin flour [24]. The application of chokeberry pomace in beef burgers may likewise affect their nutritional profile, which is attributable, among other factors, to the physicochemical characteristics of this raw material. According to Kulling and Rawel [64], chokeberry pomace is characterized by a high dry matter content (17–29%), in which carbohydrates predominate. Cegiełka et al. [42] reported that the dry matter content of comminuted chokeberry pomace was 26.6%, indicating a high moisture fraction in this by-product. The effect of fruit and vegetable pomace on the chemical composition of ground meat products depends on both the form and the level of this material incorporated into the formulation. Pork burgers containing comminuted chokeberry pomace (2–5%) were characterized by a significantly ($p < 0.05$) lower water content, accompanied by an increase in protein and fat levels with increasing pomace addition. This phenomenon was interpreted by the authors as a result of enhanced cooking

losses [42]. Different trends were observed in the case of freeze-dried carrot pomace (1.0–4.2%) incorporated into raw beef burgers, where no significant ($p > 0.05$) effect on protein and fat content was found, and only a decreasing tendency in these components was noted [23]. In contrast, the observed reduction in water content in beef burgers resulted from the substitution of meat with a plant-based component containing less water than meat, which simultaneously enabled enrichment of the product with dietary fiber. Similar relationships were reported by Karslıoğlu et al. [21] in beef burgers containing dried tomato peels (1–4%). Gracey et al. [65], in a study on the quality of beef meatballs supplemented with rehydrated apple pomace (10% and 20% w/w), demonstrated that increasing the proportion of this by-product in the formulation resulted in higher moisture and dietary fiber contents, alongside a reduction in protein content, without a significant effect on fat levels in the beef meatballs.

4.4. pH of Beef Burgers

The incorporation of plant-derived components into meat product formulations may lead to a reduction in pH, resulting from the introduction of acidic compounds into the meat matrix. This relationship has been confirmed, among other factors, in studies on the quality of beef burgers, in which the addition of açai and sea buckthorn juices caused a significant decrease in pH [66]. A similar trend to that observed in the present study was reported for pork burgers containing shredded chokeberry pomace, where its inclusion at levels of 2–5% significantly ($p < 0.05$) lowered pH values compared with the control sample [42]. This effect may be attributed to the presence of organic acids characteristic of chokeberry, such as neochlorogenic, cryptochlorogenic, chlorogenic, and galacturonic acids [30,67].

The use of dried fruit and vegetable processing by-products in meat processing may also significantly contribute to a decrease in pH. For example, Karslıoğlu [21] demonstrated that the addition of dried tomato pomace (1–4%) significantly ($p < 0.05$) lowered the pH value of beef burgers, which was attributed to the presence of tartaric and citric acids in the plant material. A similar effect was observed when beef in burger formulations was replaced with dried papaya peel at levels ranging from 1% to 3% [22]. However, in contrast to the findings of the present study, a slight but significant increase in pH was observed in these meat products over the storage period.

According to the other study [63], the addition of dried raspberry and blackberry pomace (at levels of 1–5%) to beef patties resulted in a significant ($p < 0.05$) reduction in pH compared to the control sample. This change was already noticeable by day 3 of storage, but it was only observed at the highest pomace addition level (5%). The authors suggested that this effect resulted from the release of organic acids, such as citric, malic, tartaric, and oxalic acids, during storage. In contrast, the incorporation of freeze-dried carrot pomace at levels up to 4.2% did not significantly affect the pH of beef burgers ($p > 0.05$), despite an observed decreasing tendency [23].

In light of the mentioned evidence, fruit and vegetable by-products, including pomace, appear to be promising ingredients for processed meat products. However, the optimal inclusion level should be determined on a case-by-case basis, taking into account its impact on the quality attributes of the final product.

4.5. Color Parameters of Beef Burgers

The color of meat products is primarily determined by the muscle pigment myoglobin and its transformations during meat processing, which are highly influenced by such technological factors as the addition of sodium nitrite and thermal processing [68]. Furthermore, modifications of the formulation composition, particularly the incorporation

of plant-derived ingredients rich in natural pigments, may substantially affect the color of meat products. Consequently, the application of fruit and vegetable by-products, including pomace, should be carefully optimized, as their pigmentation can influence the color and appearance of the final product [23].

In the present study, the addition of chokeberry pomace was shown to significantly affect the color of beef burgers, resulting in darker coloration, a decrease in the contribution of the yellow component (b^*), and a modification of the intensity of the red component (a^*). The obtained results are consistent with previous reports [42], in which the application of fresh comminuted chokeberry pomace (2–5%) in pork burgers led to a significant ($p < 0.05$) decrease in L^* and b^* values and an increase in the a^* parameter compared with the control sample. Additionally, during refrigerated storage (days 7 and 14), negative b^* values were observed at higher levels of chokeberry pomace addition (3.5% and 5%), indicating a pronounced shift in color toward blue hues. The observed changes in burger color parameters may be associated with the presence and transformations of bioactive compounds in chokeberry, particularly anthocyanins. These compounds, responsible for colors ranging from red to purple, may reduce the contribution of yellow coloration (b^*) and influence other color components of meat [69]. At the same time, as phenolic compounds with strong antioxidant properties, anthocyanins may inhibit the oxidation of myoglobin to metmyoglobin, thereby contributing to the retardation of unfavorable color changes in meat products [70]. However, it should be emphasized that the effect of these compounds on the a^* parameter is complex and depends on both the level of addition and processing conditions. In studies on beef burgers supplemented with açai berry juice, variability in a^* values was attributed to transformations and degradation of plant pigments occurring during thermal processing [66].

The effect of plant-based by-products on the color of ground beef products remains inconclusive and depends on both their type and form of processing. In the study by López-Parra et al. [71], the addition of freeze-dried cherry extract (2–10%) to hamburgers resulted only in a significant ($p < 0.05$) decrease in L^* values. Similarly, the incorporation of grape skin powder (up to 2%) resulted in progressive darkening of burger color during refrigerated storage, which was attributed to the presence of anthocyanins, including malvidin [24]. In contrast, increasing the proportion of tomato peel powder to 4% in beef burgers led to a decrease ($p < 0.05$) in L^* values and an increase in b^* values [21]. Somewhat different results from those obtained in the present study were reported by Babaoğlu et al. [72], who found no significant effect ($p > 0.05$) of water extracts from berry fruit pomace on the lightness of beef burger color, while observing that changes in a^* and b^* parameters depended on both the level of addition and the storage time.

4.6. Shear Force of Beef Burgers

Texture constitutes a key quality attribute of meat products, contributing to their sensory attractiveness. It is defined as the rheological and structural properties of food resulting from the spatial arrangement and interactions of its components [68]. Studies have demonstrated that the texture parameters of ground meat products are strongly determined by raw material composition and may be modified by the incorporation of plant-based ingredients, which influence the structure of the meat matrix [2,73].

Concerning the effect of comminuted chokeberry pomace on the textural properties of burger-type products, previous studies [42] reported a significant increase ($p < 0.05$) in the shear force of pork burgers with increasing levels of shredded chokeberry pomace (2–5%) in the formulation, as well as during 14 days of refrigerated storage, irrespective of the formulation composition. The increase in shear force and the development of a more compact structure were attributed to greater losses of water and fat during cooking, as

well as a higher degree of thermal shrinkage in burgers containing chokeberry pomace compared with the control sample.

A contrasting trend was observed in the application of apple pomace (10% and 20%) in beef meatballs, where no significant differences ($p > 0.05$) were found in hardness, cohesiveness, or chewiness [65]. In contrast, the incorporation of freeze-dried grape pomace (0.5–2.0%) into beef burgers resulted in a significant increase in instrumental hardness, which—according to the authors—was due to the fiber components present in the pomace, particularly cellulose and lignin [24].

According to the literature, the texture parameters of burgers are determined not only by the presence of plant-based components but also, to a large extent, by the type of meat used as the raw material [2]. Studies on beef and pork burgers supplemented with apple fiber preparation (1.5% and 3.0%) demonstrated that product hardness was significantly influenced ($p < 0.05$) by the type of meat. Regardless of the level of fiber addition, beef burgers exhibited lower hardness compared with pork burgers, which was attributed to the greater water-binding capacity of beef within the structure of the final product.

In texture profile analysis (TPA) of pork burgers, the substitution of lean meat with dried kinnow mandarin pomace powder (4% and 6%) resulted in a significant increase ($p < 0.05$) in product hardness compared with the control sample [25]. This effect was linked to improved binding properties of the meat batter after thermal processing, associated with an increased content of dietary fiber. A similar relationship was reported for beef burgers containing dried tomato pomace (2–4%), where a significant increase ($p < 0.05$) in hardness and chewiness was observed [21]. According to other researchers [74], the increase in hardness of meat products formulated with plant-based additives may be attributed not only to dietary fiber fractions but also to plant proteins, which promote the formation of a more compact protein network.

4.7. Organoleptic Properties of Beef Burgers

From a sustainability perspective, the utilization of fruit and vegetable processing by-products, such as pomace, in meat product formulations offers an opportunity to valorize underutilized biomass and promote circularity within agri-food systems. Nevertheless, as with other quality attributes, the incorporation of such plant-derived ingredients may substantially influence the sensory properties of meat products, necessitating case-specific assessment [40,75]. Available evidence suggests that the magnitude and direction of these effects depend on the type of meat product, the characteristics of the plant ingredient, its form (e.g., fresh, dried, extract), and the inclusion level [23,73].

The findings of this study align with the observations reported by Gracey et al. [65] regarding the effects of apple pomace, a by-product of apple juice production, on the sensory attributes of beef meatballs. According to the authors, sensory evaluations conducted with 104 participants revealed no significant differences ($p > 0.05$) in appearance, aroma, flavor, mouthfeel, or overall liking between the control meatballs and those containing 10% or 20% apple pomace.

In studies focusing on the optimization of freeze-dried carrot pomace addition to beef patties, it was demonstrated that a 3% inclusion level did not result in significant differences ($p > 0.05$) in sensory attributes, however, increasing the addition to 4.2% led to a decrease in flavor scores, which was attributed to the presence of undesirable plant-derived notes [23]. Karşlıoğlu et al. [21] similarly reported that the maximum acceptable level of tomato peel flour in beef burgers should not exceed 2%, beyond which a deterioration in sensory characteristics is observed.

In turn, the application of water extracts from fruit pomace (blackberry, chokeberry, blueberry, blackcurrant) in beef burgers did not significantly ($p > 0.05$) affect most sensory

parameters during the initial stage of storage, except for taste [72]. During refrigerated storage, a significant ($p < 0.05$) decline in sensory quality was observed in the control sample, associated with lipid oxidation processes and microbial growth. In contrast, the addition of pomace extracts slowed these changes, thereby maintaining the stability of sensory scores ($p > 0.05$) up to day 6 of storage.

4.8. Microbial Quality of Beef Burgers

The results obtained in this study indicate a moderate level of microbiological contamination of the tested plant by-product, which was chokeberry pomace. According to data reported by other authors [76], the microbiological safety of by-products derived from fruit and vegetable processing represents an important consideration for their utilization as food ingredients, particularly in the context of circular economy strategies aimed at the valorization of agri-food waste streams. Currently, however, neither the European Union nor Polish food legislation establishes specific microbiological limits for fruit pomace [6]. Therefore, the microbiological quality and safety of fruit pomace intended for human consumption must be assessed within the framework of general food safety requirements and HACCP-based procedures.

The results of the present study also indicate that adding chokeberry pomace up to 3% did not adversely affect the microbiological quality of beef burgers during refrigerated storage (Table 8). All burger variants, regardless of the chokeberry pomace concentration, maintained satisfactory microbiological quality throughout the storage period. The absence of Enterobacteriaceae and *Escherichia coli* in 0.1 g of all analyzed beef burger samples indicates the high microbiological quality of the raw materials used and confirms the implementation of appropriate hygienic practices during production and packaging. With regard to the microbiological requirements established by European Union and Polish food legislation for fully cooked minced meat products placed on the market, such as the burgers evaluated in the present study, Commission Regulation (EC) No. 2073/2005 [6] does not define limits for total viable counts or other general indicators of microbiological quality for this product category. Nevertheless, products of this type, which are generally classified as ready-to-eat foods, should comply with applicable food safety criteria and be subject to an appropriate microbiological safety assessment.

In summary, the observed microbiological effects in the burger samples can likely be attributed to the presence of antibacterial compounds in chokeberry pomace. Although these compounds were not identified or quantified in the present study, previous research has reported the occurrence of various phytochemicals in chokeberry and chokeberry-derived products that may contribute to the inhibition of microbial growth [27,77]. Nevertheless, the findings of this study should be considered preliminary and may partly reflect inherent experimental variability. Therefore, further research is required to comprehensively evaluate the impact of chokeberry pomace on the microbiological quality and safety of ground meat products.

Microbial contamination remains one of the major concerns in food safety. Natural antimicrobial ingredients are increasingly used in meat products to improve safety and extend shelf life, as meat is highly susceptible to microbial spoilage. Product stability also depends on processing parameters, particularly thermal treatment, and storage conditions, including packaging. Growing consumer demand for clean-label foods has intensified research into natural preservation methods consistent with circular economy principles. Plant extracts and essential oils are of particular interest to scientists due to their multifaceted effects, i.e., antioxidant and antimicrobial activities. Black chokeberry fruits are a rich source of polyphenols, mainly anthocyanins, flavonoids, and phenolic acids (e.g.,

chlorogenic and neochlorogenic acids), with the highest concentrations found in the peel, the major component of pomace [27,33,34,77,78].

The mechanism by which active phytochemicals present in fruits and plant-derived preparations—including chokeberry—affect bacterial cells has not been yet fully elucidated. Research highlights that fruits and vegetables contain a wide range of antimicrobial compounds, which may operate through various mechanisms. These mechanisms include disrupting cell membranes, affecting nucleic acid processes, and causing depletion of adenosine triphosphate (ATP) [27,77]. Data presented by Ghanbari et al. [78] on the potential application of black chokeberry against human bacterial pathogens, including foodborne pathogens, indicate that various chokeberry constituents inhibit the growth of Gram-positive bacteria and, to a lesser extent, Gram-negative bacteria. This difference may be attributed to the outer membrane of Gram-negative bacteria, which acts as a natural barrier to hydrophilic compounds, including the flavonoids present in chokeberry. Nevertheless, the antimicrobial activity of chokeberry phytochemicals is significantly enhanced through synergistic interactions among individual bioactive compounds. Consistent with these findings, Efenberger-Szmechtyk et al. [79] suggested that the antimicrobial effect of chokeberry results from the synergistic action of multiple constituents, whereas individual compounds may exhibit less pronounced activity when acting alone.

Literature data on the antimicrobial effects of raw comminuted chokeberry pomace in meat products are limited. In agreement with the findings of the present study, Cegińska et al. [42] demonstrated that its addition (2–5%) to pork burgers did not deteriorate microbiological quality during 14 days of refrigerated storage. On days 1 and 7 of storage, no significant differences ($p > 0.05$) were observed in the number of tested microbial groups between the control sample and the burgers containing pomace. However, in the final stage of storage, a moderate antimicrobial effect of the pomace was observed, manifested by significantly ($p < 0.05$) lower counts of lactic acid bacteria and *Pseudomonas* spp. in samples with pomace addition compared with the control. During the 14-day storage of pork burgers, no Enterobacteriaceae, yeasts, or molds were detected, regardless of the level of pomace incorporation.

The effect of chokeberry pomace on the microbiological quality of meat products has also been investigated using it in a valorized form. In raw beef patties containing water extracts from berry fruits, including black chokeberry, an increase in the counts of mesophilic bacteria, psychrotrophic aerobic bacteria, lactic acid bacteria, staphylococci, and coliform bacteria was observed during nine days of storage. However, within the first six days, products containing fruit pomace extracts exhibited improved microbiological quality than the control sample [72]. The lack of significant differences ($p > 0.05$) in microbiological quality between beef patties observed on day 9 of storage was attributed to reduced antimicrobial activity of the extracts, likely due to degradation of bioactive compounds. In another study [80], it was demonstrated that the antimicrobial efficacy of chokeberry pomace extracts depends on the method of their preparation, particularly the solvent used. In pork burgers, ethanolic extracts showed stronger inhibitory effects against Gram-positive bacteria (e.g., *Leuconostoc mesenteroides*, *Weissella viridescens*, *Brochothrix thermosphacta*, *Listeria monocytogenes*) and Gram-negative bacteria (e.g., *Campylobacter jejuni*, *Pseudomonas putida*) than aqueous extracts.

It should be noted that the present study did not include an energy balance, economic assessment, or life-cycle analysis, therefore, the sustainability-related interpretation of using shredded, non-dried chokeberry pomace should be understood primarily in terms of by-product valorization rather than as direct evidence of lower environmental impact compared with alternative valorization routes.

5. Conclusions

The results of this study indicate that shredded black chokeberry pomace may be used as a plant-derived by-product in beef burger formulation, however, its technological effects should be considered dose-dependently. Increasing the pomace level significantly increased cooking loss and diameter shrinkage, indicating a negative effect on cooking properties, particularly at higher inclusion levels. At the same time, pomace addition reduced shear force and modified the color of burgers, producing darker products with lower redness and yellowness compared with the control.

From a practical perspective, the most favorable levels of black chokeberry pomace were 0.5% and 1.0%. Samples enriched with these concentrations generally achieved organoleptic scores similar to the control for most evaluated attributes in the trained-panel assessment, although the burgers with a 1.0% pomace addition received significantly lower scores for certain organoleptic characteristics, particularly taste and texture. Nevertheless, the incorporation of black chokeberry pomace at these levels enabled the valorization of fruit-processing by-products while maintaining overall good organoleptic quality. The results indicated that 1.0% was the highest pomace concentration that preserved acceptable organoleptic characteristics under the tested conditions. In contrast, higher additions, especially 2.0% and 3.0%, caused more pronounced changes in cooking characteristics and color, which may limit their direct application without further formulation optimization.

Importantly, the incorporation of black chokeberry pomace did not negatively affect the microbiological quality of vacuum-packed beef burgers during 14 days of refrigerated storage. Therefore, the use of shredded, non-dried chokeberry pomace can be considered a promising circular-economy strategy in meat product development. The valorization of this fruit-processing by-product in meat products may represent an approach that could contribute to more sustainable food systems through the utilization of underused resources. Furthermore, provided that the level of addition is carefully selected, black chokeberry pomace may serve as a valuable functional ingredient while offering potential opportunities for the incorporation of fruit-processing by-products into food production. Nevertheless, the observed effects on cooking-related parameters indicate that further research is needed to optimize water and fat retention during thermal processing. Future research should include both oxidative stability assessments and hedonic consumer testing to verify consumer acceptance and further evaluate the market potential of meat products enriched with chokeberry pomace under real-world consumption conditions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18157851/s1>: Figure S1: Hydraulic press used for pressing chokeberry fruits (a) and fresh chokeberry pomace leaving the hydraulic press (b) [source: own photos]. Figure S2: Fresh chokeberry pomace obtained using a hydraulic press (a) and shredded chokeberry pomace produced using a Thermomix device (b) [source: own photos]. Figure S3: Baked beef burgers differing in the amount of black chokeberry pomace added [source: own photo]. Figure S4: Consent form for participation in the organoleptic quality test of beef burgers signed by the evaluator. Table S1: Recipe of beef burgers.

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