

Enhancing pork meatball antioxidant potential and oxidative stability with seedless blackcurrant pomace ingredients and their effect on other quality characteristics

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ABSTRACT

This study investigates the use of ingredients produced from the seedless blackcurrant (*Ribes nigrum* L.) pomace (BCSk), a by-product of fruit processing, as antioxidants and quality enhancers of pork meatballs. The ingredients were obtained by supercritical CO₂ extraction and a combination of EtOH/water extraction of defatted BCSk. The quality parameters of pork meatballs with different BCSk extracts were determined at three time-points, 1, 7, and 14 days. In addition, the effect of 2% (w/w) solid BCSk ingredients on meatball quality was tested before extraction and after all extractions. The meatballs were packed under a modified atmosphere (70% N₂ and 30% CO₂) and kept at 4 ± 1 °C. All the ingredients used were found to significantly affect the colour parameters. Meatballs with dried BCSk powder showed the lowest cooking loss compared to the control sample and higher fibre content. The highest *in vitro* antioxidant activity values were measured for the samples with 2% of EtOH/water extract. The BCSk ingredients reduced lipid oxidation in meatballs. Our results demonstrated that BCSk ingredients can be used to enhance specific quality attributes of pork meatballs and represent promising antioxidant and fibre-rich ingredients for improving the functionality of meat products.

1. Introduction

Meat is a fundamental component of the human diet, providing high-quality proteins, essential amino acids, bioavailable iron, vitamins, and other important nutrients. However, high moisture and the presence of unsaturated fatty acids make it susceptible to spoilage due to microbial growth and lipid peroxidation. Moreover, harmful compounds as glycation end products, heterocyclic amines, polycyclic aromatic hydrocarbons, acrylamide, and nitrosamines may form during thermal processing of meat. Some of these processes may be controlled by using synthetic food additives; however, due to the negative consumer attitude, the research on their natural alternatives has been increasing during the last decades. The possibilities of using rich in natural polyphenolic antioxidants and antimicrobials plant extracts as alternative

meat preservatives, inhibitors of the formation of harmful compounds, and health promoters have been studied by many researchers, and these studies have been reviewed in several articles (Awad et al., 2022; Efenberger-Szmechtyk et al., 2020; Han et al., 2025; Munekata et al., 2020; Nikmaram et al., 2018; Shah et al., 2014; Yan et al., 2024).

Small fruit (commonly called berries) extracts, being rich in polyphenolic compounds, have also been tested as natural antioxidants in meat products (Lorenzo et al., 2018). Blackcurrants (*Ribes nigrum* L.), which are native to northern and central Europe, are recognized for their edible deep purple berries (further abbreviated as BC) accumulating high concentrations of anthocyanins and other bioactive compounds with potential health benefits (Cortez and Gonzalez de Mejia, 2019; Ejaz et al., 2023). For instance, BC exhibited the highest *in vitro* antioxidant, antimicrobial, and anti-inflammatory effects among the other berries

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studied by Borges et al. (2010). However, the use of whole berries in meat products, either as a powdered ingredient or as a source of extracts, economically and technologically, is not justified due to the high costs of raw materials and the presence of sugars and flavor compounds. Considering that berry processing side streams such as pomace, which is generated in large amounts during juice pressing and contains large fraction of bioactive compounds and dietary fiber (Venskutonis, 2020), their upcycling into the higher added value ingredients for foods seems to be a more promising strategy, which, in addition, is in line with the modern sustainability and circular economy issues. However, nowadays, still a large fraction of berry pomace is recycled as a low-value by-product or even discarded as waste, whereas Material Flow Cost Accounting analysis showed that the production of BC juice may benefit from the pomace upcycling to a marketable ingredient (May and Guenther, 2020).

Around 15–20% of BC is consumed as fresh fruits, while the rest is processed into the various longer shelf-life products, mainly juice and jams. Pressing juice generates large amounts of a by-product (pomace or press-cake), consisting of skins, pulp residues and seeds (Blejan et al., 2023). The content of skins and seeds in fresh BC was reported as 5.2 and 4.8% (Hilz et al., 2005), while the skin-to-seed ratio in the pomace, depending on harvesting year, was 4.3:5.7 and 3.8:6.2 (Sójka and Król, 2009). The seeds are rich in polyunsaturated fatty acids (Goffman & Galletti, 2001; Yang et al., 2011), while the skins with pulp residues contain more polyphenolic antioxidants, dietary fiber, and other health-promoting compounds (dos Santos Lima et al., 2023; Pieszka et al., 2015). The reports on the use of BC pomace in meat products are rather scarce. Water extract of BC pomace was used at 2.5–10% concentration in a linseed and sunflower oils-based emulsion gel for replacing pork backfat in Vienna sausages (Cîrstea et al., 2024). Considering significant compositional differences between the seeds and the skins it is evident that the ingredients produced from the separated anatomical parts of pomace would demonstrate in foods different, more specific effects. For instance, adding polyunsaturated fatty acid-rich ingredients from the seeds may enhance the susceptibility of meat to oxidation. To support this hypothesis, recently we reported the effects of various BC seed ingredients in the pork meatballs (Kerner et al., 2023).

This study aimed to evaluate the effect of seedless BC pomace (BCSk) ingredients on various pork meatball characteristics and oxidative stability during storage. For this purpose, BCSk ingredients, namely dried powder, defatted by supercritical CO₂ residue, combined ethanol and water extracts, and the residue after all extractions were prepared, characterized, and added to pork meatballs. Minced meat products were selected as being particularly sensitive to oxidation and microbial growth. To the best of our knowledge, the use of BC and other berry skin ingredients obtained after different extraction steps has not been tested in meat or any other food formulations, making it an innovative concept. It is expected that the results of this study may serve as a scientific background for the practical applications of BCSk ingredients in the meat products.

2. Materials and methods

2.1. Chemicals and reagents

Perchloric acid, 2-thiobarbituric acid (TBA), 1,1,3,3-tetraethoxypropane, butylated hydroxytoluene (BHT), sulfuric acid (H₂SO₄), boric acid (H₃BO₃), hydrogen chloride (HCl; 0.561 M), 2,2-diphenyl-1-picrylhydrazyl stable free radical (DPPH[•]), 2,2'-azino-bis(3-ethylbenzo-thiazoline-6-sulfonic acid (ABTS), 6-hydroxy-2,5,7,8-tetramethyl-chroman-2-carboxylic acid (Trolox), 2,2'-azobis(2-amidinopropane) dihydrochloride (AAPH) were purchased from Sigma-Aldrich Chemie (Steinheim, Germany). Sodium chloride (NaCl) (99.9%) was obtained from Rechem s.r.b. (Bratislava, Slovakia), sodium hydroxide (NaOH, 50%) from Ingle AS (Ingliste, Estonia), and Kjeltabs (FOSS Analytical A/S, Denmark) from Oridor Eesti OÜ (Tartu, Estonia). Ethanol (95% and

78%) was from the Estonian Spirit OÜ (Tallinn, Estonia), heat-stable α -amylase, amyloglucosidase, protease, analytical grade Celite and MES/TRIS buffer from Megazyme Ltd. (Wicklow, Ireland), acetone from Honeywell International Inc. (Charlotte, NC, USA).

2.2. Preparation and evaluation of blackcurrant (BCSk) ingredients

2.2.1. Extraction procedures

The seeds contain higher concentrations of oil and protein, whereas the skins with the pulp residues are rich in anthocyanins and other polyphenolic constituents (Pocevičienė et al., 2025). Therefore, separating these different anatomical parts before solvent extraction could increase the diversity of the recovered fractions, providing them with better specified properties and chemical composition in terms of their more precise application possibilities. The BC pomace was produced in 2022 by pressing freshly harvested berries. The press-cake was fractionated into the skins and seeds by the wet mechanical separation method and donated by the Cooperative Ribes LT (Biržai, Lithuania). The skin-to-seed ratio in the raw material was 5:2.

The dried skins (further indicated as R) were ground and defatted by extraction with supercritical CO₂ (scCO₂) using previously optimized parameters (Basegmez et al., 2017). After extraction, lipophilic extract and defatted residue (further indicated as AC) were obtained. In order to achieve exhaustive extraction of higher polarity compounds, the AC was consecutively extracted with ethanol and water. Firstly, six portions of AC (100 g each) were mixed with 300 mL of 96% ethanol in a 500 mL flask and extracted in a platform universal shaker PSU20 (Biosan, Riga, Latvia) for 2 h at 155 rpm. The solid residues were re-extracted with 200 mL of 96% ethanol. The extracts were filtered in a Buchner funnel Whatman filter paper No. 1 (Whatman International, Maidstone, U.K.), combined and evaporated in a rotary vacuum evaporator Rotavapor R-210 (Büchi Labortechnik, Flawil, Switzerland) at 40 °C. The yield of ethanol extract was $3.46 \pm 0.21\%$. The residues after ethanol extraction were dried at 40 °C, and 6 of its portions, 80 g each, were extracted with 400 mL of hot water in a shaker for 2 h. The residue was re-extracted 2 times with 200 and 150 mL of hot water. The extracts were decanted, combined, centrifuged in a refrigerated centrifuge Velocity 18R (Dynamica Scientific Ltd., Livingston, UK) at -18 °C for 20 min and freeze-dried in a Maxi Dry Lyo (Jonan Nordic A/S, Aellerød, Denmark) to obtain skin extract (further indicated as HOE). The yield of water extract was $3.85 \pm 0.19\%$. The dried residue after all extractions (further indicated as AA) was the final BC ingredient for the experiments.

2.2.2. Evaluation of BCSk ingredients

The BCSk ingredients were ground and analyzed according to the standard methods: moisture (LST EN ISO 665:2020), protein (LST EN ISO 8968-1:2014, LST EN 12135:2001, and LST ISO 937:2000), fat (LST EN ISO 659:2000 (ISO 659:2009)), ash (ISO 749:1977), and mineral (LST ISO 936:2000) content. All analyses were performed in four replicates.

The total phenolic content (TPC) was measured with Folin-Ciocalteu's reagent as originally described by Singleton et al. (1999) and adapted to the BC solids by using the quick, easy, new, cheap and reproducible (QUENCHER) method proposed by Gökmen et al. (2009). Briefly, 10 mg of sample or cellulose (blank) were mixed with 150 μ L of distilled H₂O, 750 μ L of Folin-Ciocalteu's reagent, and 600 μ L of Na₂CO₃ solution, vortexed for 15 s, shaken at 250 rpm for 2 hours in the dark, centrifuged (4500 rpm, 5 min) and the absorbance of optically clear supernatant was measured at 760 nm. Gallic acid solutions (150 μ L) at 0–80 μ g/mL concentrations were used for calibration.

ABTS^{•+} decolorization assay was performed according to Re et al. (1999), which is based on the reaction of a radical cation with an antioxidant resulting in a colour change. For solids, BCSk powder or cellulose (blank) was mixed with 25 μ L of MeOH and 1500 μ L of working ABTS^{•+} solution, vortexed for 15 s, shaken at 250 rpm for 2 hours in the

dark, centrifuged (4500 rpm, 5 min), and the absorbance of the optically clear supernatant was measured at 734 nm. Trolox solutions (25 µL) at 0–1500 µmol/L MeOH concentrations were used for calibration.

Oxygen radical absorbance capacity (ORAC) was determined as described by Prior et al. (2003) and Dávalos et al. (2004), using fluorescein as a fluorescent probe. BCSk solids or cellulose (blank) were mixed with 150 µL of phosphate buffer solution (PBS, 75 mmol/L, pH 7.4) and 900 µL of fluorescein solution (14 µmol/L in PBS), vortexed for 15 s, shaken at 250 rpm for 60 min in the dark, and then centrifuged at 4500 rpm for 5 min. An optically clear supernatant (175 µL) was transferred to a 96-well black opaque microplate and pre-incubated for 15 min at 37 °C. Subsequently, 25 µL of AAPH solution (240 mmol/L) was rapidly added as a peroxy radical generator using a multichannel pipette. Fluorescence was recorded every minute (1.1 min per cycle) for a total of 90–140 cycles. The subsequent experimental procedures and data analysis were performed as previously reported for extract analysis. Trolox solutions (150 µL) at concentrations of 0–500 µmol/L in PBS were used for calibration.

2.3. Preparation of pork meatballs and evaluation of their quality

2.3.1. Formulation and preparation

The preparation and packaging of pork meatballs was followed by the previously reported protocol (Kerner et al., 2023). Minced pork meat (moisture 66.90%, protein 17%, fat 15.37%, and ash 0.91%) was purchased from a local commercial abattoir. Briefly, three batches of pork meatballs (experimental replications) were produced. The control samples contained 89% minced pork meat, 10% tap water, and 1% salt, without the addition of BCSk ingredients. In the experimental samples, 2% of the minced pork meat was replaced with different BCSk ingredients, resulting in a total formulation of 100%. The concentration of BCSk ingredients was selected based on the previously performed preliminary evaluation of their effects on sensory quality. In total, approximately 2 kg of each type of meatball was prepared. The components were mixed manually according to the recipe, shaped in a self-made form weighing about 30 g (Ø 4.5 and depth 2 cm), followed by cooking in a pre-heated oven Inoxtrend E1 CUA-107E (Treviso, Italy) at 145 °C for 15 min. The cooked meatballs were cooled to room temperature, weighed, and packed under modified atmosphere conditions consisting of 70% N₂ and 30% CO₂ (Linde GAS AS, Tallinn, Estonia) with a Vision Pack S.r.l. VP01 (Packaging Factory Holding, Lallio, Bergamo, Italy). The packed meatballs were stored at 4 ± 1 °C. Three replicate samples were used for analysis, and for each sample, three technical replicate determinations were performed.

2.3.2. Chemical composition and cooking loss

The proximate chemical composition and cooking loss were measured on the preparation day. The meatball samples (at least 200 g) were ground and homogenized in a laboratory homogenizer Retsch GM200 (Retsch GmbH & Co, Haan, Germany) for the determination of moisture (EVS-ISO 1442:1999), protein (EVS-ISO 937:1978, Kjeldahl method), fat (EVS-ISO 2446:2001, Gerber method), and ash (ISO 936:1999). Dietary fibre content was measured using the Megazyme Dietary Fiber Assay Kit K-TDFR-100A (Megazyme, Wicklow, Ireland) by the AOAC 991.43 method.

For the cooking loss, meatballs were weighed prior to the heat treatment and again after cooling the meatballs to room temperature, by cooking in a pre-heated oven Inoxtrend E1 CUA-107E (Treviso, Italy) at 145 °C for 15 min. The cooking loss was obtained by the difference in weight of the meatballs and expressed in %.

2.3.3. pH and colour parameters

The pH was measured with a Seven 2Go™ pH-meter (Mettler-Toledo AG Analytical, Schwerzenbach, Switzerland). A pH meter was calibrated with pH 4 and pH 7 buffer solutions at room temperature. Briefly, 5 g of the sample was homogenized with 50 mL of 0.1 M KCl solution in Retsch

GM200 (ISO 2917:1999) laboratory homogenizer.

Colour parameters were determined on a X-Rite 964 spectrophotometer (X-Rite, Grand Rapids, MI, USA), equipped with an 8.0 mm aperture. After opening the package, the meatballs were cut into halves, allowed to bloom for 5 minutes and the colour characteristics were measured in three different places to calculate the average value. The results were expressed by the CIE (International Commission on Illumination) Lab system values (D65 and the observer angle of 10°) with *L** indicating lightness, *a** redness, and *b** yellowness. The total colour difference (ΔE_{Lab}) between the control and the test samples was calculated by the following formula (Equation (1)):

$$\Delta E_{Lab} = \sqrt{(L_0^* - L_1^*)^2 + (a_0^* - a_1^*)^2 + (b_0^* - b_1^*)^2} \quad (1)$$

where ΔE_{Lab} is the total colour difference between the control and test samples; L_0^* , a_0^* , b_0^* and L_1^* , a_1^* , b_1^* are the means of the colour parameters determined for the control and test samples, respectively.

The results are interpreted as follows: 0 < ΔE_{Lab} < 1 – the observer does not notice the difference; 1 < ΔE_{Lab} < 2 – only an experienced observer may notice the difference; 2 < ΔE_{Lab} < 3.5 – an inexperienced observer also notices the difference; when 3.5 < ΔE_{Lab} < 5 – a clear colour difference is noticeable; 5 < ΔE_{Lab} – an observer notices two different colours (Mokrzycki & Tatol, 2011).

2.3.4. DPPH• scavenging capacity

Meatballs were freeze-dried in a CHRIST Alpha 3-4 LSCbasic freeze-dryer (Martin Christ Gefriertrocknungsanlagen, Osterode am Harz, Germany) for 24 hours. All freeze-dried meatballs were pounded with the pestle in a mortar, and 3 g of each meatball sample were weighed into 50 mL tubes, which were filled with 70% EtOH, vortexed, and centrifuged at 5000 rpm for 10 min.

The DPPH• scavenging capacity assay was conducted according to Brand-Williams et al. (1995) with slight modifications. Briefly, 3 g of freeze-dried and ground meatballs were vortexed with 70% ethanol and centrifuged at 5000 rpm for 10 min. Subsequently, the meatball solutions (0.2 mL) were vortexed with 3.8 mL DPPH• solution, left in the dark for 30 min, and the absorbance was measured at 515 nm in a spectrophotometer Specord 250 plus (Analytik Jena, Germany). Trolox solutions (0.2 mL) at 0–1000 µmol/L EtOH concentrations were used for calibration. The assays were conducted in three replicates.

2.3.5. The main volatile metabolites

Two volatile metabolites indicating about oxidation (hexanal) and microbiological processes (butane-2,3-diol) in meat samples were analyzed by gas chromatography - time-of-flight mass spectrometry on a GC × GC-TOFMS LECO Pegasus 4D system, consisting of an Agilent 7890A GC, a Gerstel Multipurpose Sampler MPS (Gerstel GmbH, Mülheim an der Ruhr, Germany), coupled with a high-speed TOFMS detector (LECO, St. Joseph, MI, USA). The volatile compounds of fresh (days 1, 4, 7 and 11) and cooked meatballs (days 1, 7 and 14) were collected by the headspace solid phase microextraction (HS-SPME) method according to Pavlidis et al. (2019). Briefly, 2.5 g of the meat sample and 5 mL of 25% (w/w) NaCl solution were added to a 20 mL Gerstel glass vial and homogenized with a glass rod for 2 min. Then, the vial was closed with a magnetic cap with Silicone blue/PTFE white septa and vortexed at 1000 rpm for 15 min. HS-SPME was performed in a MPS with a Divinylbenzene/Carboxen/ Polydimethyl-siloxane fiber, 50/30 µm, 1 cm length, needle size 23 ga (Supelco, Bellefonte, PA, USA). The vial was equilibrated at 40 °C for 15 min and afterwards exposed to the sample HS for 30 min at 40 °C. The fiber was desorbed in the GC × GC-TOFMS injector for 180 s.

The column set consisted of a primary column BPX-5, 30 m, 0.25 mm i.d., 0.25 µm film thickness, connected to a secondary column, BPX-50, 1.2 m, 0.10 mm i.d., 0.1 µm film thickness (SGE Analytical Science, Australia). The primary oven was programmed as follows: 40 °C (1 min) ramped to 220 °C at 5 °C/min (1 min), finally ramped to 300 °C at 20 °C/

min (hold 1 min), with a modulator offset temperature of +15 °C. The transfer line temperature was 270 °C, the GC injector port was set at 150 °C, then at a rate of 720 °C ramped to 250 °C with a desorption time of 5 min. The carrier gas helium was set at 1 mL/min. The TOFMS acquisition rate was 10 spectra/s, and the mass range used for identification was from 30–450 m/z units. Detector's voltage was set at 1550 V and the ion source temperature of 250 °C. Data from the GC × GC-TOF/MS system were collected by ChromaTOF software v.4.22 (LECO) after a solvent peak delay of 250 s in a splitless mode for 60 s, a further valve was opened and purge flow was 20 mL/min; mass spectrum assignment was based on matching against Adams, Nist, MainLib, RepLib mass spectral libraries; signal-to-noise threshold was set as 50 with the minimum similarity accepted was 750. Two replicate analyses were performed on samples from each of three batches, i.e. the mean values were calculated from six injections (3 × 2).

The identification of volatile components was assigned by comparing their retention indices (RI) relative to C₇–C₃₀ standard *n*-alkanes, obtained on a nonpolar BPX-5 column with those provided in literature Adams (2007), and by comparing their mass spectra with the data provided by the Nist, MainLib, RepLib and Adams mass spectral libraries. Identification was assumed when a good match of mass spectrum and RI was achieved.

2.3.6. TBA reactive substances (TBARS)

The formation of the oxidation products was evaluated by measuring the TBA reactive substances (TBARS) following Pikul et al. (1989) with some modifications. Five grams of the sample were homogenized with 20 mL of 4% perchloric acid and 0.25 mL of butylated hydroxytoluene in an Ultra-Turax IKA T18 homogenizer (IKA, Staufen, Germany) and filtered. To minimize interference from anthocyanin pigments, the filtrate was treated with activated charcoal and filtered again before mixing equal volumes of the colourless filtrate and TBA reagent. The mixture was heated in a water bath at 80 °C for 1 h, cooled to room temperature, and the absorbance was measured at 538 nm against a reagent blank (the zero point of the calibration curve). TBARS were measured at three different time-points, namely 1, 7, and 14 days and expressed in malondialdehyde (MDA) mg/kg.

2.4. Statistical analysis

Statistical analyses were performed with the statistical package R 4.4.1. (R Core Team, 2024) and Statgraphics 18-X64. The effects of variant, storage time, and their interaction on the samples' pH, colour characteristics, and TBARS were analyzed using a linear mixed-effects model (LME) implemented with the lmer function in the lme4 package (Bates et al., 2015), with batch (three independent production replicates prepared over a three-month period using the same raw material) included as a random effect. For parameters showing significant interactions between sample type and storage period, pairwise comparisons were performed across all sample × storage period combinations. Superscripts in the corresponding tables indicate significant differences between these combinations, and standard errors reflect model-based estimates. The effects of variants and three batches on the sample moisture, protein, ash, and fibre content, as well as on the cooking loss were measured only on day 1 by LME. As DPPH[•] was analyzed on one batch with three repeated measurements, the lm function in the lme4 package (Bates et al., 2015) was used to calculate the statistical difference between samples' least square means.

The emmeans (Lenth, 2024) and multcomp (Hothorn et al., 2008) packages were used to compare the groups pairwise. Tukey's multiple comparison post hoc test was used to determine the groups' least square mean differences at the significance level of $\alpha = 0.05$. All model-assessed results are presented as least-square means ± standard error.

To determine significant differences between mean values of main volatile components (butane-2,3-diol and hexanal), one-way ANOVA was employed using the statistical software Statgraphics 18-X64.

Tukey's HSD (honestly significant difference) test was applied to identify significant differences between treatments at level of $p < 0.05$.

3. Results and discussion

3.1. Characterization of BCSk ingredients

3.1.1. Proximate chemical composition

First of all, it should be noted that extraction with scCO₂ effectively defatted BC skins. Since BC oil consists mainly of sensitive to oxidation polyunsaturated fatty acids, it may be assumed that the defatted ingredient will not harm the product stability. From the techno-economic point of view, scCO₂ extraction recovers a high-value lipophilic fraction, which due to its nutritional benefits, can find various other applications, e.g., in the production of functional foods, nutraceuticals, and cosmeceuticals. Finally, the green scCO₂ extraction method is preferable in the production of food-grade ingredients.

The differences in proximate chemical composition between solid BC skin ingredients (R, AC, and AA) of other constituents are not significant, although a slight increase in the percentage content of proteins, minerals, and dietary fiber may be observed after each extraction step, mainly after scCO₂ extraction (Table 1). Previously added to meatballs, solid BC seed ingredients contained remarkably higher amounts of proteins (Kerner et al., 2023). The slightly higher protein content in the extraction residues may be attributed to the removal of soluble in scCO₂ lipids, leading to a higher proportion of insoluble proteins and carbohydrates in the extraction residues. In general, berry processing by-products might be richer in protein than the whole fruit, due to their higher seed content, which is more protein-rich compared to the pulp and skin. Such by-products are also rich in dietary fiber. For instance, Alba et al. (2018) reported that in BC pomace, approximately 47% of the insoluble and 28% of the soluble fiber.

3.1.2. Antioxidant capacity characteristics

The *in vitro* antioxidant capacity indicators measured for BCSk ingredients used in this study are listed in Table 1. It is reasonable that the combined extract of defatted residues possessed several times higher values than solid BCSk products. Ethanol and water, and particularly their mixtures, are efficient solvents for extracting high polarity polyphenolic antioxidants such as flavonoids, phenolic acids, and their glycosides, while the major part of neutral constituents, such as polysaccharides, fat, and proteins, remain in the extraction residues. The ORAC and ABTS^{•+} scavenging values of the extract were almost equivalent to the antioxidant capacity of the synthetic antioxidant Trolox. For instance, the studies of blueberries and lingonberries have also shown that ethanol-water solvents recover higher amounts of phenolics and flavonoids compared to water-only extracts (Dini & Grumetto, 2022; Drózd et al., 2017). It should be noted that the antioxidant activity of the scCO₂ extraction residue AC was almost similar or even slightly higher compared to the initial dried material R, while after all extractions (AA) the antioxidant capacity values remarkably decreased. It can be attributed to the fact that scCO₂ does not dissolve polyphenolic antioxidants, while ethanol and water extracts these compounds quite efficiently. Moreover, the treatment of R at high pressures may have an effect on the availability of antioxidative active sites in the solid residue AC when the QUENCHER method is applied.

3.2. Antioxidant capacity of meatballs

It is known that polyphenols can neutralize free radicals through their scavenging activity. Compared to the control sample, meatballs with BCSk ingredients had significantly higher DPPH[•] scavenging values (Fig. 1). The highest values were measured in case of AC followed by HOE, which for the former ingredient can be explained by the increased bioavailability of certain antioxidants and the removal of oil and lipophilic compounds, whereas HOE is rich in the recovered from BCSk

Table 1

Proximate chemical composition and antioxidant properties of blackcurrant skin ingredients. Values are least square means $\pm$ standard error indicating within-group variability.

Ingredient	Moisture, %	Proteins, %	Lipids, %	Minerals, %	Carbohydrates, %	TPC, mg GAE/g	ABTS ^{•+} , mg TE /g	ORAC, mg TE /g
R	7.68 $\pm$ 0.31a	12.64 $\pm$ 0.33a	5.21 $\pm$ 0.58a	2.08 $\pm$ 0.00a	72.39*	38.24 $\pm$ 0.47b	95.4 $\pm$ 3.2b	62.91 $\pm$ 0.14b
AC	7.62 $\pm$ 0.09a	13.68 $\pm$ 0.43b	0.57 $\pm$ 0.07b	2.27 $\pm$ 0.03b	75.86*	41.17 $\pm$ 0.23c	98.4 $\pm$ 6.9b	75.22 $\pm$ 0.67c
HOE	-	-	-	-	-	125.6 $\pm$ 3.2d	658.2 $\pm$ 10.9c	701.7 $\pm$ 6.2d
AA	7.27 $\pm$ 0.07a	14.07 $\pm$ 0.24b	-	2.28 $\pm$ 0.00b	76.38*	9.36 $\pm$ 0.31a	22.6 $\pm$ 1.8a	18.14 $\pm$ 0.54a

a-d – different letters in columns indicate significant differences between means ($P < 0.05$) by Tukey's multiple comparison's post hoc test. R – raw blackcurrant pomace skins, AC – blackcurrant pomace skins after CO₂ extraction, HOE – combined extract of defatted residues consecutively isolated with EtOH and H₂O, AA – blackcurrant pomace skins after all extractions. *Calculated by retracting other measured components. TPC – total phenolic content; ABTS^{•+} – 2,2'-azino-bis(3-ethylbenzthiazoline-6-sulphonic acid); ORAC – oxygen radical absorbance capacity.

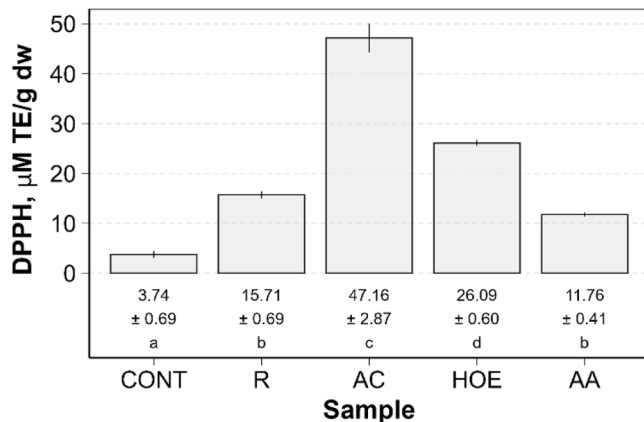


Fig. 1. Antioxidant capacity (DPPH*) of meatballs with and without BC skin ingredients (least square means $\pm$ standard error). a-d – least square means followed by different letters indicate significant differences between means ($P < 0.05$) by Tukey's multiple comparison's post hoc test. CONT – without plant-based ingredients, R – raw blackcurrant pomace skins, AC – blackcurrant pomace skins after CO₂ extraction, HOE – combined extract of defatted residues consecutively isolated with EtOH and H₂O, AA – blackcurrant pomace skins after all extractions.

polyphenolic antioxidants.

3.3. Proximate chemical composition, fibre content, and cooking losses of pork meatballs

It may be observed that the addition of 2% of BCSk ingredients to cooked pork meatballs did not have any notable effect on the proximate chemical composition and cooking loss (Table 2). Slightly higher protein content was in the samples with HOE, probably because of a larger cooking loss and lower moisture content, and AC, while the fat content of meatballs decreased compared to the control sample, especially in the case of AA containing the BCSk after all extractions and fiber-rich AC. The same tendency was also noticed by Sarv et al. (2023), when a small amount (1-2%) of rowanberry pomace ingredients were tested in meatballs, and a significant decrease in fat content was determined for the meatballs with the addition of fiber-rich and defatted with scCO₂ ingredients and the final extraction residue.

Cooking loss is an important technological factor in the thermal processing of meat products. Besides its effects on sensory quality characteristics such as juiciness, texture, and flavor, cooking loss is related to the overall product yield (Pietrasik et al., 2020). There were no significant differences in cooking loss between the control samples and the samples with BCSk powders, R, AC, and AA; however, a tendency of reduced cooking loss after adding these BCSk ingredients may be observed. For instance, the lowest cooking losses were observed in meatballs containing R and AA, with no statistically significant difference between these treatments. The highest cooking loss was

Table 2

Proximate chemical composition and cooking losses of pork meatballs with blackcurrant skin ingredients (least square means $\pm$ standard error indicating within-group variability).

Sample	Moisture, %	Protein, %	Fat, %	Ash, %	Fibre, %	Cooking loss, %
Control	57.01 $\pm$ 0.56a	20.75 $\pm$ 0.43ab	20.11 $\pm$ 0.76a	2.06 $\pm$ 0.02ab	0.00 $\pm$ 0.00d	27.96 $\pm$ 1.99ab
R	56.98 $\pm$ 1.11a	19.57 $\pm$ 0.41b	17.47 $\pm$ 1.08ac	1.91 $\pm$ 0.01a	1.06 $\pm$ 0.02a	24.77 $\pm$ 1.88a
AC	57.83 $\pm$ 0.21ab	21.32 $\pm$ 0.72ac	15.46 $\pm$ 0.58bc	1.95 $\pm$ 0.09ab	0.98 $\pm$ 0.03a	27.49 $\pm$ 2.62ab
HOE	56.26 $\pm$ 0.61a	22.55 $\pm$ 0.78c	16.99 $\pm$ 0.87bc	2.12 $\pm$ 0.04b	nd.	33.06 $\pm$ 3.16b
AA	59.39 $\pm$ 0.34b	20.47 $\pm$ 0.29ab	14.59 $\pm$ 0.45b	1.91 $\pm$ 0.02a	0.99 $\pm$ $\pm$ 0.02a	25.74 $\pm$ 2.56a

a-d – different letters in columns indicate significant differences between means ($P < 0.05$) by Tukey's multiple comparison's post hoc test. Control – without plant-based ingredients, R – raw blackcurrant pomace skins, AC – blackcurrant pomace skins after CO₂ extraction, HOE – combined extract of defatted residues consecutively isolated with EtOH and H₂O, AA – blackcurrant pomace skins after all extractions. nd – not determined.

determined for the product with HOE, which was even higher than for the control sample, 33.06% and 27.96%, respectively. It is well-known that berry pomace powder strongly absorbs water (de Alencar et al., 2022) and therefore even when added at low concentrations, it may reduce cooking loss. On the contrary, soluble extract HOE may have some adverse effect on cooking loss.

The content of fibre of the products with dried BCSk powder (R) and extraction residues (AC and AA) was similar, approximately 1%. Incorporating dietary fibre into the meat products offers numerous benefits from nutritional, functional, and technological perspectives, and therefore can lead to the development of healthier, more palatable meat products, meeting the growing consumer demand for nutritious and functional foods. Although the content of dietary fibre in the meatballs with BC powders was comparatively low, the benefits of BCSk powder incorporation into the widely consumed minced meat products may play a positive role in the improvement of product quality. For comparison, the incorporation of 2% of wine-making by-product (grape skin) powder into the beef burgers increased the content of dietary fibre by approx. 1%, which is in agreement with our results (de Alencar et al., 2022).

3.4. Evaluation of physicochemical parameters during storage

The changes in pH of pork meatballs during the refrigerated storage are presented in Fig. 2. pH is a significant quality parameter of meat products, as it affects sensory properties, tenderness, cooking loss, and

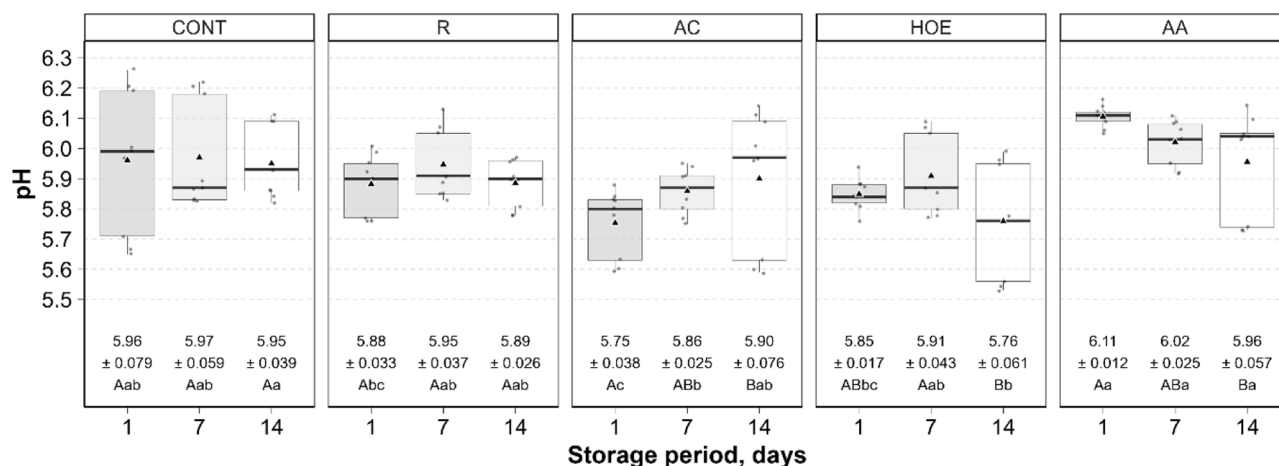


Fig. 2. Effect of BC skin ingredients and storage period (days) on the pH-value of cooked pork meatballs. Values are least square means $\pm$ standard error indicating within-group variability. The observed values are presented with grey dots and least square means with black triangle. CONT – without plant-based ingredients, R – raw blackcurrant pomace skins, AC – blackcurrant pomace skins after CO₂ extraction, HOE – combined extract of defatted residues consecutively isolated with EtOH and H₂O, AA – blackcurrant pomace skins after all extractions. Least square means followed by different uppercase letters differ significantly between storage periods within the same sample, and those followed by different lowercase letters differ significantly between samples within the same storage period, according to Tukey's post hoc test for multiple comparisons ($P < 0.05$).

colour (Barrón-Ayala et al., 2020; Das et al., 2020). In general, the fluctuations of pH were not remarkable; however, in some cases significant. All BCSk ingredients slightly decreased the pH of meatballs except for AA, which increased this characteristic. It may be explained by the fact that BCSk powders before their extraction with ethanol and water contained some amounts of organic acids such as malic, citric, and quinic (Tian et al., 2019), which were fully removed from AA by water extraction. On day 1, the lower pH values observed in AC and HOE can be attributed to the presence of residual organic acids in the BC-derived ingredients. Organic acids are not removed by non-polar scCO₂ extraction and thus remain in AC, while they are co-extracted together with phenolic compounds into the ethanol–water extract (HOE). In contrast, AA is expected to contain only negligible amounts of organic acids and phenolics, which may explain the absence of an initial acidifying effect in this group.

The changes in pH values were not significant after 7 days of storage of all meatball samples. The observed pH changes during storage were formulation-dependent; however, although some differences were statistically significant, their magnitude was relatively small and became apparent mainly after 14 days of storage. Therefore, the practical relevance of these variations should be interpreted with caution. During storage, significant differences were limited. However, after 14 days, the pH of the sample with AC slightly increased while that with AA decreased from 6.11 to 5.96 and reached the level of the control product. By day 14, HOE showed a lower pH compared to CONT and AA, which is consistent with presence of extracted organic acids. At the same time, the increase in pH observed in AC and the decrease in AA at the end of storage were relatively small, and final pH values did not differ significantly among most treatments except for HOE.

Given the complexity of meat systems, these late-stage pH shifts are likely the result of multiple concurrent processes. A decrease in pH may be associated with microbial growth and lactic acid production during the 14-day storage period, as well as continued biochemical reactions and oxidative processes (in AA, predominantly protein oxidation). Conversely, a slight pH increase may result from protein degradation, amino acid deamination, and the formation of basic nitrogenous compounds during storage. As several mechanisms may act simultaneously, it is not possible to attribute the observed pH dynamics to a single physicochemical factor. The observed pH dynamics underscore the importance of considering ingredient-storage interactions rather than main effects alone. The differential behavior of AC and AA highlights, how extraction strategy not only alters chemical composition but also

affects the temporal stability of physicochemical traits in meat matrices.

Previously reported effects of the BC seed ingredients (only dried powders and their residues after extractions), which were produced in a similar way, on the pH pork meatballs were somewhat different Kerner et al. (2023). The addition of 2% of ethanolic extract of the defatted with scCO₂ black chokeberry pomace powder remarkably reduced the pH of pork burgers (Tamkutė et al., 2021).

Colour plays an important role in consumers' acceptance and the quality of a product. The impact of blackcurrant skin ingredients on colour characteristics and their changes during storage was evaluated by CIE $L^*a^*b^*$ system. The appearance, characteristic colour, and the increased redness of the pork meatballs with the addition of 2% of BC skin ingredients is represented in Fig. 3.

The colour of meatballs is strongly affected by the added ingredients, mainly due to the high content of anthocyanin pigments in BC. It is well known that anthocyanins are the main BC pigments, and their content is higher in the skin fraction than in the juice (Kapasakalidis et al., 2006). Red-coloured, anthocyanin-rich cranberry pomace extracts imparted similar colour changes in pork meat products studied by Tamkutė et al. (2019).

The changes in L^* , a^* , and b^* values during the 14 days of chilled storage of meatballs are presented in Fig. 4, from where significant differences can be observed due to the intensive colour of the added ingredients. It is obvious that all used BCSk ingredients significantly decreased the L^* value, especially in the case of adding the AC. The same tendency (increase in redness and decrease in lightness) was determined by Jia et al. (2012), when BC extract was added to pork patties at 5, 10 and 20 g/kg and by de Alencar et al. (2022), when grape skin flour from wine processing was used in the formulation of beef burgers. Lightness did not change significantly in the control sample during the 14 days of storage, remaining within the range of 84.27 to 86.30. Similar tendencies were reported by Tamkutė et al. (2021) when chokeberry extract isolated with pressurized ethanol from defatted pomace was added to pork meat products.

As previously highlighted, the increase in meatballs' redness value can be attributed to the high anthocyanin pigment content in BCSk. The cyanidin and delphinidin derivatives are commonly found in BC fruits, constituting 97–98% of their total content (Šimerdová et al., 2021). A significant increase in redness (a^*) was observed in the product with HOE followed by AC and R. HOE was produced using polar EtOH and H₂O solvents, which effectively recover anthocyanidins and their glycosides. The effect of the residue after all extractions (AA) on the L^*

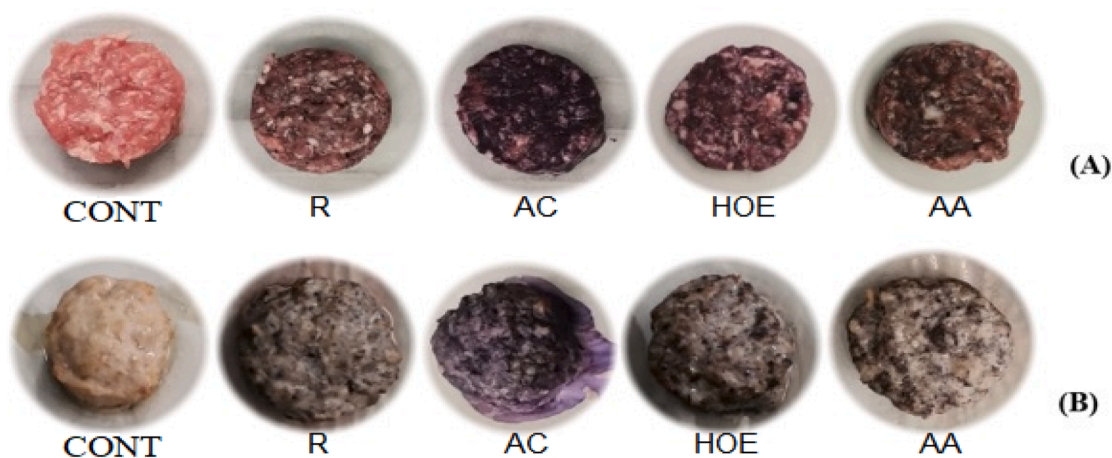


Fig. 3. The visual appearance of pork meatballs with the addition of BC skin ingredients – (A) raw and (B) cooked meatballs. CONT – without plant-based ingredients, R – raw blackcurrant pomace skins, AC – blackcurrant pomace skins after CO₂ extraction, HOE – combined extract of defatted residues consecutively isolated with EtOH and H₂O, AA – blackcurrant pomace skins after all extractions.

value was slightly lower compared with the unextracted with polar solvents R and AC. However, it should be noted that all BCSk ingredients were dark-coloured substances, because even after extraction, some residual amounts of pigments remain in the product.

The yellowness (b^*) coordinates were higher in control sample remaining quite stable during the storage period. In samples with BCSk ingredients, the values were similar between samples and during the storage period. Only in the case of AC, the b^* values for unknown reasons were slightly lower. Pereira et al. (2022) used grape pomace meal in beef burgers and also observed a reduction in b^* values. To conclude, in terms of the traditional colour of meat products, the addition of BCSk ingredients may have an undesirable effect on the visual appearance of meat products.

ΔE aims to indicate how close the colours are to the standard, i.e. control sample. All used BCSk ingredients affected the total colour difference (ΔE_{Lab}) between the control and other samples during the 14-day chilled storage period (Fig. 5). According to the results, a clear colour difference and two different colours are noticed by the observers ($\Delta E_{Lab} > 5$), which can be attributed to the presence of the dark purple colour of BCSk ingredients. As visual appearance is important to the consumer when making purchasing decisions, there might be a need to decrease the colour-changing effect for developing a consumer-ready product. On the other hand, considering consumers' attitude towards healthier diets the addition of plant-origin bioactive compounds may overweight colour-related shortcomings. The effect of the powdered BC seed ingredients on the total colour difference (ΔE_{Lab}) was also clearly observed, particularly in the case of adding 5% (Kerner et al., 2023).

3.5. Effect of BCSk ingredients on the oxidation, hexanal, and butane-2,3-diol levels of pork meatballs during the storage period

The reaction between thiobarbituric acid (TBA) and malondialdehyde (MDA) generates thiobarbituric acid reactive substances (TBARS). As a result, TBARS or TBA values are commonly used as indirect indicators to assess the extent of lipid oxidation. Additionally, MDA values can serve as markers of lipid oxidation, as MDA is an intermediate product in this process (Wu et al., 2016). Therefore, antioxidants are used in meat products to delay oxidation. Lately, plant extracts have been added to meat products to delay or inhibit lipid oxidation and increase the shelf-life. The measured TBARS values of pork meatballs during the 14 days of storage are represented in Fig. 6. It should be noted that the method is based on visible light absorption; therefore, the addition of highly-coloured and different BC ingredients may affect the initial TBARS values independently of the concentration of MDA. Most

likely due to these matrix-related effects the initial values (1 day) of meatballs with R, AC, and AA were significantly lower compared with the values measured for the samples without BC ingredients and with skin extract (HOE). However, although HOE is the richest ingredient in anthocyanins, its initial TBARS values were not reduced to the same extent. This suggests that the observed differences cannot be attributed solely to pigment-related optical interference, but rather to a combination of factors, including differences in antioxidant composition, extract polarity, and interactions with meat matrix components. Considering this assumption, the effects of BCSk ingredients are evaluated depending on the changes in TBARS during storage. From this perspective, the TBARS value of the control sample increased 2-fold after 14 days of storage, reaching 0.489 mg/kg, whereas the value of the sample with strong antioxidant HOE during the same period of time decreased from 0.298 to 0.198 mg/kg. In contrast to the control, which showed a significant increase in TBARS values during storage, the BCSk-treated samples remained stable, with no significant changes in TBARS values over the storage period. Lipid oxidation in the control sample increased rapidly, particularly after 7 days of storage.

At day 7, no significant differences in TBARS values were observed among the samples. By day 14, a significant decrease in TBARS values compared to the control was observed only in the HOE sample, whereas the remaining BCSk treatments did not differ significantly from the control. A similar tendency was observed by Jia et al. (2012), who added BC extract into pork patties at 5, 10, and 20 g/kg, and the TBARS assay values decreased during 9-day storage period. Fourati et al. (2020) studied pomegranate (*Punica granatum*) peel extracts and found that 1% of the aqueous peel extract reduced lipid oxidation in minced beef stored for 21 days at 4 °C.

In interpreting the TBARS results of the present study, it should be noted that a sample-specific blank (without TBA reagent) was not included in the assay. Although the filtrates were treated with activated charcoal prior to analysis to reduce interference from anthocyanin pigments, residual interference cannot be entirely excluded. The findings from these authors indicate that plant-based ingredients inhibit lipid oxidation in meat products by disrupting radical chain reactions. Consequently, it may be assumed that the effects of BCSk additives on TBARS values of meat are an interplay of several factors such as: added with BCSk antioxidants; physico-chemical effects of BCSk biopolymers and their interactions with other substances, including those involved in the generation of malondialdehyde; possible effects of added BCSk substances on Fe²⁺/Fe³⁺ in pork heme pigment; interference of coloured pigments in the spectrophotometric determination of TBARS. Finally, heat treatment during cooking may also play an important role in these

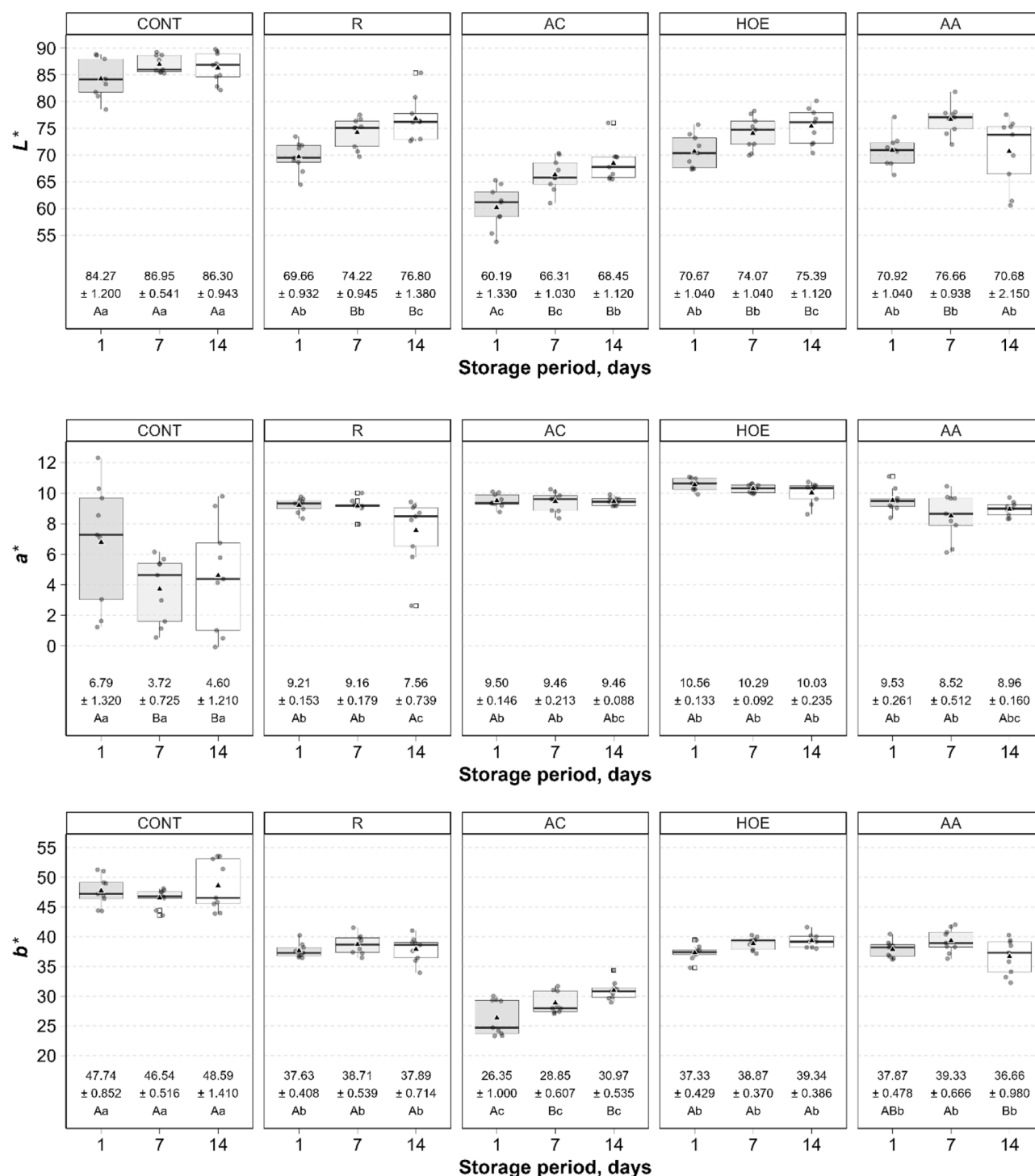


Fig. 4. The changes in the colour parameters (L^* - lightness, a^* - redness and b^* - yellowness) of pork meatballs with BC skin ingredients during the 14-days of storage period. Values are least square means $\pm$ standard error indicating within-group variability. The observed values are presented with grey dots, outliers with square and least square means with black triangle. CONT – without plant-based ingredients, R – raw blackcurrant pomace skins, AC – blackcurrant pomace skins after CO_2 extraction, HOE – combined extract of defatted residues consecutively isolated with EtOH and H_2O , AA – blackcurrant pomace skins after all extractions. Least square means followed by different uppercase letters differ significantly between storage periods within the same sample, and those followed by different lowercase letters differ significantly between samples within the same storage period, according to Tukey's post hoc test for multiple comparisons ($P < 0.05$).

processes in a very complex meat system, particularly in case of using BCSk ingredients. Wood et al. (2004) stated that MDA values up to 2.00 mg/kg product are not detectable by consumers. None of the samples tested in this research during the storage period reached this threshold.

Although the present study focused on antioxidant potential, oxidative stability, and quality characteristics, previous studies have

also demonstrated the antibacterial activity of blackcurrant berries and pomace extracts against several foodborne pathogens, as well as their potential application in meat products (Anton et al., 2019; Meremäe et al., 2024). Therefore, future studies should include microbiological analyses to provide a more comprehensive evaluation of the functional potential of blackcurrant pomace ingredients in meat products.

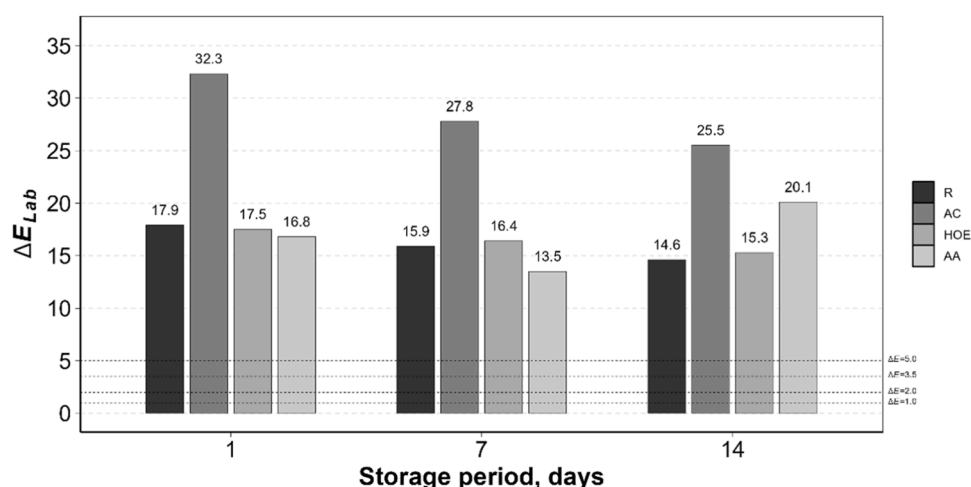


Fig. 5. The total colour difference (ΔE_{Lab}) between control and test samples during the 14-days storage period: $0 < \Delta E_{Lab} < 1$ —the observer does not notice a difference, $1 < \Delta E_{Lab} < 2$ —only an experienced observer may notice the difference, $2 < \Delta E_{Lab} < 3.5$ —an unexperienced observer also notices the difference, $3.5 < \Delta E_{Lab} < 5$ —a clear difference in colour is noticed, and $5 < \Delta E_{Lab}$ —an observer notices two different colours. R – raw blackcurrant pomace skins, AC – blackcurrant pomace skins after CO_2 extraction, HOE – combined extract of defatted residues consecutively isolated with EtOH and H_2O , AA – blackcurrant pomace skins after all extractions.

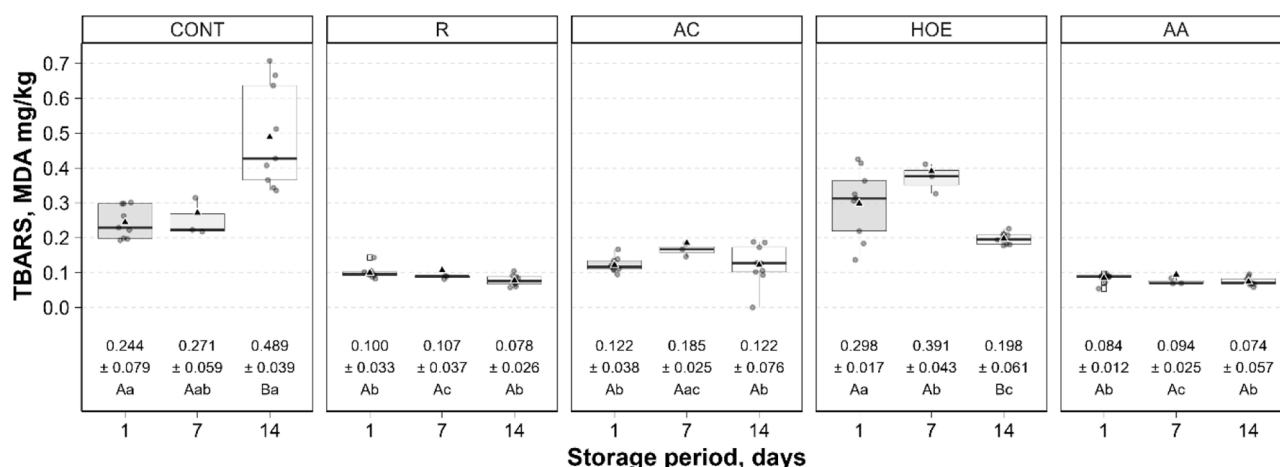


Fig. 6. Changes in the TBARS assay values of cooked pork meatballs enriched with 2% of blackcurrant skin ingredients stored in modified atmosphere during the storage period. Values are the least square means $\pm$ standard error indicating within-group variability. The observed values are presented with grey dots; the outliers are given with a square and least square means with black triangle. CONT – without plant-based ingredients; R – with 2% of raw blackcurrant pomace skins; AC – with 2% of blackcurrant pomace skins after CO_2 extraction; HOE – with 2% of combined extract of defatted residues consecutively isolated with EtOH and H_2O ; AA – with 2% of blackcurrant pomace skins after all extractions. Least square means followed by different uppercase letters differ significantly between storage periods within the same sample, and those followed by different lowercase letters differ significantly between samples within the same storage period, according to Tukey's post hoc test for multiple comparisons ($P < 0.05$).

Volatile lipid oxidation products, also known as secondary oxidation products, significantly contribute to the deterioration of flavor and taste in meat at high concentrations (Kaban, 2009). Among these, hexanal, as a secondary product of lipid oxidation, was identified as the major volatile aldehyde formed during lipid peroxidation. Headspace techniques were employed to measure the volatile components. Fig. 7B presents the data showing the variation in the amount of hexanal in cooked meatballs containing BCSk ingredients. These analyses were performed using headspace solid-phase microextraction gas chromatography with time-of-flight mass spectrometry (HS-SPME-GC-TOFMS). The hexanal content is expressed in arbitrary units (au), representing the total ion current of the relevant peaks, as the meatball samples were sufficiently solid to preclude the uniform distribution of an internal standard throughout the sample volume. Despite this limitation, the hexanal peak area was proportional to its concentration in the product, providing reliable comparative data. A significant increase in hexanal

content was observed in the control sample (without BCSk ingredients) over time. The lower abundance of hexanal in meatballs with BCSk may be explained by the inhibition of oxidative processes during cooking; whereas during storage the effect of BCSk was less evident. After 14 days of storage, all samples containing BCSk ingredients exhibited elevated hexanal levels compared to their initial measurements. However, these levels remained consistently lower than those of the control sample. Notably, meatballs enriched with antioxidant-rich polyphenols from AC and HOE demonstrated the lowest hexanal levels, highlighting their effectiveness in mitigating lipid oxidation. On the other hand, slightly higher amounts of hexanal were observed in the samples with the initial BC powder (R) than in the samples with the defatted powder (AC). This finding may support the hypothesis that elimination of polyunsaturated fat from BCSk may have a positive effect on the stability of pork meatballs. Whereas, the content of hexanal in the case of using the BCSk powder after all extractions (AA) was similar to the product with R. This

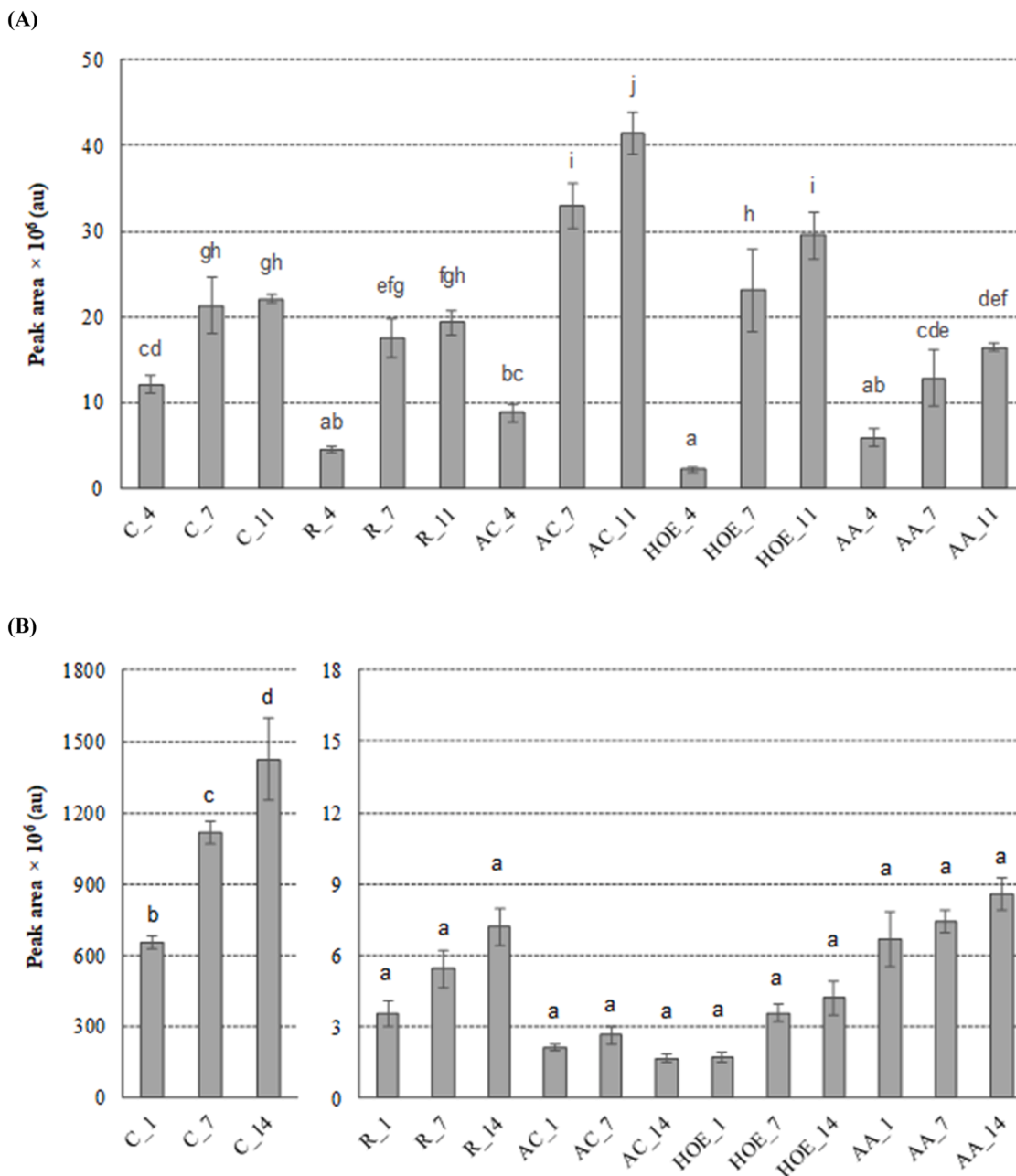


Fig. 7. Variation in the absolute amounts (in arbitrary units, $\text{au} \times 10^6$) of Butane-2,3-diol in the headspace of fresh meatballs (A) and hexanal in cooked meatballs (B) during the storage at $+4^\circ\text{C}$ (days 1, 4, 7 and 11 fresh meatballs and days 1, 7, 14 for cooked meatballs). C – without plant-based ingredients; R – with 2% of raw blackcurrant pomace skins; AC – with 2% of blackcurrant pomace skins after CO_2 extraction; HOE – with 2% of combined extract of defatted residues consecutively isolated with EtOH and H_2O ; AA – with 2% of blackcurrant pomace skins after all extractions. a–j – different letters within the columns indicate significance difference between meatballs samples during storage (one-way ANOVA, $P < 0.05$).

finding may be explained by the elimination of polyphenolic antioxidants from AC via ethanol and water extractions. Similar results were obtained when using raw and defatted hempseed ingredients extracted by scCO_2 (Kerner et al., 2021). Data on the hexanal level of cooked pork meatballs with BCSk ingredients during storage at $+4^\circ\text{C}$ correlate with DPPH $^\bullet$ assay values in the sample with AC.

The level of Butane-2,3-diol was measured in the fresh meat samples during storage. Stanborough et al. (2017) reported that *Brochothrix thermosphacta*, a problematic meat spoilage bacterium, is capable of producing several organoleptically unpleasant compounds, including butanediol and acetoin, which may impart cheesy, sour, and malty odors that characterize its growth on meat. Acetoin can be converted to butane-2,3-diol in the presence of 2,3-butanediol dehydrogenase

(Johansson et al., 2011). BCSk additives significantly reduced butane-2,3-diol content in the 4-day stored meat samples, HOE being the most effective ingredient followed by R and AA. However, during further storage, the differences compared with the control samples were not significant, except for the product with AC and AA demonstrating the largest and the lowest butane-2,3-diol peak, respectively. Our previous studies demonstrated that ethanolic extracts of raspberry (Kryževičutė et al., 2017), cranberry (Tamkutė et al., 2019), and black chokeberry (Tamkutė et al., 2021) effectively inhibited *B. thermosphacta* in pork meat.

4. Conclusions

The present study provides evidence of the potential of using BC skin ingredients (R – raw blackcurrant pomace skins, AC – blackcurrant pomace skins after CO₂ extraction, HOE – combined extract of defatted residues consecutively isolated with EtOH and H₂O, AA – blackcurrant pomace skins after all extractions at the concentration of 2%) in meat products to enhance specific quality attributes and to be considered as promising antioxidants and fibre-rich materials increasing the foods' functionality. Used BC skin ingredients had a significant effect on the product's colour, reducing the lightness and increasing redness compared to control sample. The effects on technological quality parameters were formulation-dependent. The effects of BCSk ingredients on cooking loss were not significant; however, HOE demonstrated some tendency of increasing cooking loss compared to the other samples, particularly with R and AA, when cooking loss was significantly lower. The differences in cooking loss between control and HOE containing samples were not significant. Probably, soluble HOE increased the content of free water in the products before cooking; on the contrary, solid BCSk ingredients increased their water binding capacity. BC skin ingredients effectively reduced lipid oxidation in meatballs compared to the control sample. A high increase in the hexanal content was detected in the control sample. Meatballs enriched with antioxidant-rich polyphenols from AC and HOE exhibited the lowest hexanal levels.

CRedit authorship contribution statement

Kristi Kerner: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Renata Baranauskienė:** Methodology, Formal analysis. **Rita Kazernavičiūtė:** Methodology, Formal analysis. **Alo Tānavots:** Writing – review & editing, Visualization. **Viive Sarv:** Writing – review & editing, Methodology, Formal analysis. **Ivi Jõudu:** Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Petras Rimantas Venskutonis:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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