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# Production of restructured beef jerky using blood plasma solutions activated by non-thermal atmospheric plasma*

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**The effect of blood plasma powder (2.5, 5, and 7.5% w/w in water) activated using non-thermal atmospheric plasma (T1, T2, and T3, respectively) was investigated as a nitrite source in the production of restructured beef jerky. A group without a nitrite source (NC) and a group cured with 100 ppm of sodium nitrite (PC) were used as negative control and positive control groups, respectively. The nitrite content of the plasma-activated solutions was adjusted to match that of the positive control by calculating the required plasma treatment time, based on previous studies. The obtained results showed that addition of treated solutions with nonthermal plasma for a 70 min, at a level of 20% in relation to the meat, can have beneficial effects on nitrosylhemochrome content, redness, and TBARS values of restructured jerky. These effects were statistically comparable ($p \geq 0.05$) to sodium nitrite-cured samples. Furthermore, compared to the PC group, the T1, T2, and T3 treatments exhibited significantly lower water activity and higher protein content ($p < 0.05$). The T2 and T3 treatments also showed increased lightness and shear force values ($p < 0.05$) compared to the control groups (NC and PC). It should be noted that the T3 group had the highest ($p < 0.05$)**

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**residual nitrite content among all the samples. However, a sensory analysis is necessary to assess consumer acceptance with regard to differences in the odor profile of the treatments, according to the Principal Components Analysis (PCA).**

**KEY WORDS: beef jerky / restructured meat products / blood plasma / non-thermal plasma / nitrite**

Jerky is a ready-to-eat product which is made by preserving meat, usually beef, also ostrich meat using a hot air drying [Hrbańczuk *et al.* 1998, Choi *et al*. 2008, US Department of Agriculture, 2014, Zdanowska-Sąsiadek *et al*. 2018, Inguglia *et al*. 2020]. The traditional method for preparation of the jerky involves curing thinly sliced meat and subsequently drying or smoking it to eliminate most of the moisture [Han *et al*. 2023, Nummer *et al*. 2004, Scheinberg *et al*. 2014]. Apart from its unique flavor and texture [Choi *et al*. 2008], beef jerky is valued for high protein content, convenience, and long shelf life [Nummer *et al.* 2004, Pilasombut *et al.* 2019]. Moreover, jerky offers a versatile consumption option, allowing for its direct consumption as a stand-alone snack or inclusion in a diverse range of culinary dishes.

The restructuring of meat is an increasingly important process that allows small cuts of meat to be used in high-value products [Gupta and Sharma 2023]. An example of meat restructuring can be found in the production of restructured (ground) jerky [Kim *et al.* 2021, Luckose *et al*. 2017]. This process involves combining minced or small pieces of meat with a curing solution and optionally incorporating binding agents [Handayani *et al.* 2023]. Subsequently, the resulting mixture undergoes the drying procedure. Binders might improve the texture of ground jerky by providing a cohesive and firm structure and help hold the meat particles together during the drying process, preventing the jerky from crumbling or disintegrating. While the utilization of blood plasma as a binder is not a conventional approach in food processing, it offers measurable benefits due to its potential source of low-cost proteins [Silva and Silvestre 2003]. Proteins possess the ability to form a three-dimensional gel structure and establish water bindings, thereby improving the texture of restructured meat products and contributing to their nutritional value [Gupta and Sharma 2018]. To date, a wide range of plant proteins, such as chickpea, lentil, tapioca, and soy proteins, have been employed in meat systems due to their beneficial functional properties [Modi *et al.* 2004, Serdaroglu *et al.* 2005, Yeung et al. 2021ab, 2022, Gupta and Sharma 2023, Handayani *et al*. 2023]. Importantly, plasma proteins characterize by good solubility over the whole pH range and low viscosity [Feiner 2006]. Moreover, blood plasma contains a diverse range of antimicrobial compounds capable of inhibiting the growth of spoilage and foodborne bacteria, molds and yeasts [Harmsen *et al.* 1995, Levy 2000]. These properties of blood plasma could potentially enhance the safety and extend the shelf life of jerky. Lastly, it's worth noting that the presence of residual blood in meat is considered a natural component and does not raise any associated allergic concerns when consumed [Parés *et al.* 2011].

To ensure microbiological safety, both whole-muscle and restructured jerky should be heated to an internal temperature of 71°C before drying [US Department of Agriculture, 2014]. However, Harrison *et al*. [1998] demonstrated that using a

curing mix in ground beef jerky led to a greater reduction in bacteria counts compared to curing free jerky. Consequently, like many other meat products, jerky undergoes a curing process to limit the risk of microbial spoilage. In addition, curing is an effective method of inhibiting oxidation during storage [Karwowska *et al*. 2020], as well as imparting a distinctive flavor profile and improving the color of meat products [Gómez *et al.* 2020]. To achieve the desired curing effects, a variety of methods can be employed, including dry curing, wet curing including brining, or the injection of a curing solution into the meat. in recent years, alternative and innovative curing methods have been developed to overcome the limitations of traditional methods that use sodium or potassium nitrite/nitrate. One of such methods involves adding extracts or powders of plant ingredients that naturally contain pre-converted nitrites, such as celery, parsley, beetroot, cabbage, and mushrooms [Jin *et al.* 2018, Siekmann *et al.* 2021, Sucu and Turp 2018]. Another solution is curing with nitrite from non-thermal atmospheric plasma (NTAP), which can generate a complex mixture of reactive species, including ions, electrons, excited molecules, radicals, and UV radiation [Meng *et al.* 2022, Rudy *et al.* 2020]. Direct plasma treatment of meat can generate nitrite ions, but this can result in a decrease in pH that leads to the decomposition of nitrite ions [Jung *et al*. 2017] . To prevent this, plasma water containing chemical buffers can be added to the batter [Jung *et al*. 2015, Yong *et al.* 2018]. Recent studies suggest that using plant and animal protein solutions instead of water containing synthetic chemical buffers for plasma nitrite generation offers a more sustainable and environmentally-friendly alternative for producing nitrite compounds in meat processing. There are many studies which have been conducted on the use of soybean, pea and lentil solutions, as well as milk and egg whites for dry and wet curing of various types of meat products [Marcinkowska-Lesiak *et al*. 2022abc, 2023].

Konieczny *et al.* [2007] emphasized that the essential sensory characteristics of beef jerky that are considered to be the most important are its texture, color and flavor. Based on the above information, the authors hypothesized that blood plasma may not only improve the quality of restructured jerky, but also, due to its high protein content and high pH, it may also prove to be a promising material for the production of nitrites through plasma treatment. This, in turn, may have a positive influence on the color and aroma of the jerky. Hence, the current work analyzed the feasibility and effectiveness of using blood plasma subjected to non-thermal atmospheric plasma treatment as a pioneering alternative curing strategy for the production of dried products. This innovative approach aims to obtain the highest quality jerky without the addition of sodium or potassium nitrites, phosphates, or chemical buffers.

## Material and methods

### Materials and reagents

Beef (m. *biceps femoris*) was obtained from a local supplier (Zakłady Mięsne Łuków S.A., Łuków, Poland). Non-meat ingredients, including sodium chloride

(purchased from Ciech, Janikowo, Poland) and dried blood plasma (purchased from MAR-ROL, Koźmin Wlk., Poland), were sourced from the local market. Sodium nitrite and other analytical grade chemicals and reagents were purchased from Sigma-Aldrich (St. Louis, MO, USA).

**Preparation of plasma treated blood plasma**

200 g each of 2.5, 5 and 7.5% (w/w) solutions of blood plasma in water were prepared in glass beakers. Then, the solutions were each positioned 15 cm below the plasma nozzle and treated with non-thermal air plasma at a flow rate of 2 m3/h using a plasma system with a high voltage generator (300 W) operating at a frequency of 20 kHz (Diener electronic GmbH & Co. KG, Ebhausen, Germany). Magnetic stirring (1200 rpm) was also used as part of the procedure. After plasma treatment, the solutions were adjusted to a final weight of 200 grams with water. According to Kim *et al*. [2021], the addition of 100 ppm of ingoing sodium nitrite allows for the inclusion of about 67 ppm of nitrite ions into the meat batter. Based on our previous published data [Marcinkowska-Lesiak *et al*. 2023], the process needs to be run for 140 minutes to yield approximately 67 mg/100 g of nitrite in a protein solution with a final pH>6. Considering the above, the whole procedure was carried out for 70 minutes to obtain about 67 mg/200g of nitrite ions. The solutions were prepared on the same day for each batch.

**Restructured beef jerky formulation, processing and storage**

Restructured beef jerky was manufactured at a laboratory scale, involving the

**Scheme 1.** Experimental restructured jerky recipes

| INGREDIENTS (g) | TREATMENT | | | | |
|---|---|---|---|---|---|
| | NC | PC | T1 | T2 | T3 |
| Beef | 1000 | 1000 | 1000 | 1000 | 1000 |
| Cold water | 200 | 200 | 5 | 10 | 15 |
| 2.5% (w/w) aqueous solution of dried blood plasma treated for 70 min with air plasma | - | - | 200 | - | - |
| 5% (w/w) aqueous solution of dried blood plasma treated for 70 min with air plasma | - | - | - | 200 | - |
| 7.5% (w/w) aqueous solution of dried blood plasma treated for 70 min with air plasma | - | - | - | - | 200 |
| Salt | 15 | 15 | 15 | 15 | 15 |
| Sodium nitrite | - | 0.1 | - | - | - |

NC – negative control (beef jerky without sources of nitrite); PC – positive control (beef jerky with 100 ppm of sodium nitrite); T1 – group with 2.5% aqueous solution of dried blood plasma treated with air plasma; T2 – group with 5% aqueous solution of dried blood plasma treated with air plasma; T3 – group with 7.5% aqueous solution of dried blood plasma treated with air plasma.

production of five treatments (Scheme 1).

Three separate batches of beef jerky were prepared using 5 kg of Musculus biceps femoris meat from carcasses less than 30 months old per batch. Each treatment was made using 1000 g of meat according to the process shown in Figure 1. All analyses

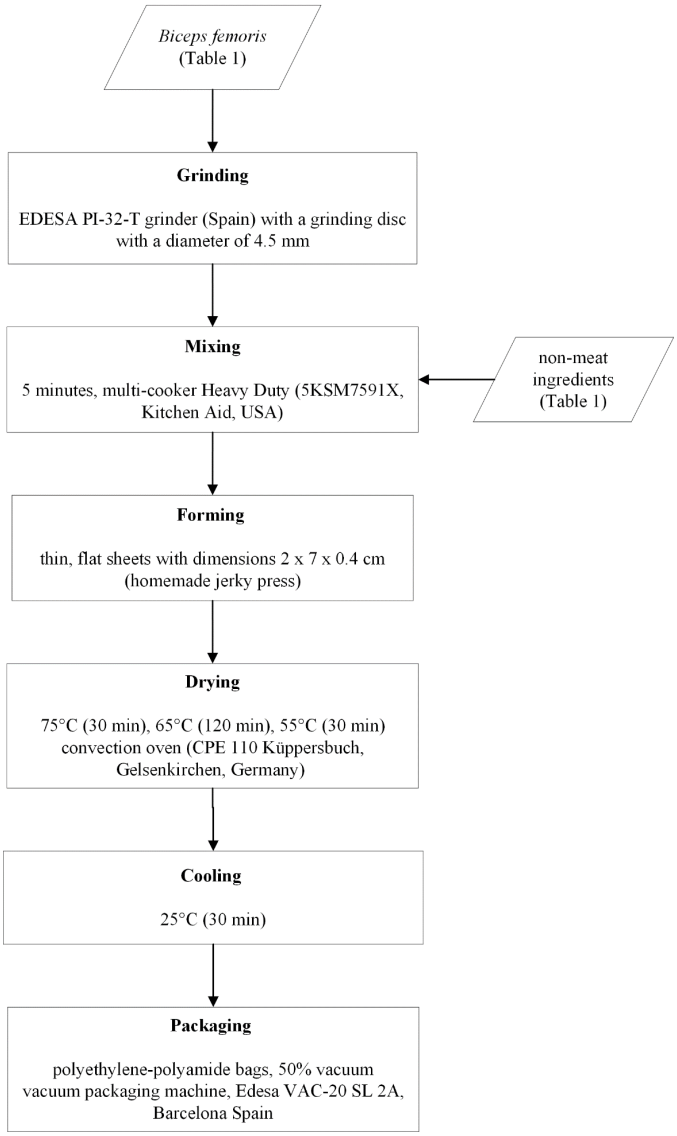


Fig. 1. Diagram of restructured beef jerky production.

were conducted on the day after production.

**Analytical methods**

**Water activity.** Measurements of the water activity of meat batters and jerky were carried out using the AquaLab apparatus (4TEV, Dew Point, Water Activity Meter). Measurements were made in three repetitions.

**Proximate composition**. To determine the moisture, protein, and fat content of both meat batters and dried beef, NIR Flex N-500 spectrometer was used (Büchi Labortechnik AG, Flawil, Switzerland). Homogenized samples (Ultra Turrax homogenizer T18 basic, IKA Werke, Staufen, Germany) weighting approximately 100 g were placed on a Petri dish to a thickness of approx. 0.5 cm. All measurements were performed using a NIRFlex Solids module (spectral range of 12.500-400 $cm^{-1}$) in three replications for each treatment.

**Yield**. The efficiency of the analyzed treatments was calculated on the basis of the

$$\text{Yield (\%)} = \left(\frac{W_x}{W_0}\right) \text{x } 100\% \quad (1)$$

difference in weight of each batch before and after heat treatment using the following equation:

where: W0 – weight of batch before heat treatment (g); Wx – weight of batch after heat treatment (g).

**pH measurement**. The pH of the meat batters was analyzed using a Testo 205 pH-meter (Testo Inc., Lenzkirch, Germany) equipped with a glass electrode. For the pH analysis of the blood plasma solutions and jerky, FiveEasyTM F20 meter was used (Mettler Toledo LLC, United States). To prepare the meat suspensions, 5 g of jerky samples were homogenized using an Ultra Turrax homogenizer (T18 basic, IKA Werke, Staufen, Germany) with 20 mL of distilled water. Both devices were calibrated using standardized buffers with pH values of 4.01 and 7.00 at room temperature, and all measurements were conducted in triplicate.

**Nitrite concentration**. The nitrite content in restructured jerky was measured following slightly modified method of Lee *et al.* [2018]. Homogenized samples (Ultra Turrax homogenizer T18 basic, IKA Werke, Staufen, Germany), each weighting 10 g, were mixed with hot water (150 mL, 80°C), NaOH (0.5 M, 10 mL), and zinc sulphate (12%, 10 mL), and heated at 80°C for 20 min in a shaking water bath. After cooling, 2 mL of 10% ammonium acetate (pH adjusted with ammonia water to 9.1) was added, followed by filtration using Whatman no. 1 paper. 20 mL of filtrates were mixed with 1 mL sulfanilamide in acid solution (30 mM), 1 mL N-(1-naphthyl)ethylenediamine dihydrochloride (5 mM), and 3 ml of deionized water and the absorbances were measured at 540 nm after 20 min using multimode microplate reader (SparkTM 10M Tecan Group, Männedorf, Switzerland). The residual nitrite content was calculated using the calibration curve prepared from sodium nitrite standard solutions, with all measurements performed in triplicate.

**Heme iron content.** The method described by Cheng and Ockerman [2003] was

used with some modifications to measure the heme iron content in all treatments. Samples (5 g) after homogenization in an Ultra Turrax homogenizer (model T18 basic, IKA Werke, Staufen, Germany) were mixed with 20 ml of acetone, 1 ml of distilled water and 0.5 ml of concentrated hydrochloric acid. The resulting mixtures were then kept in the dark for an hour before being filtered (Whatman No. 1 paper). The following equation was used to determine the content of heme iron in jerky:

$$\text{Heme iron (ppm)} = A640 \times 680 \times 0.0882 \quad (2)$$

**Nitrosylhemochrome content**. The nitrosylhemochrome content in jerky was determined by Lee *et al.* [2018] method. 10 g of samples were homogenized with 3 mL of deionized water and 40 mL of acetone. The resulting solutions were kept in the dark for 15 min and, after being filtered through Whatman No. 1 paper, the absorbance at 540 nm was measured using SparkTM 10M multimode microplate reader (Tecan Group, Männedorf, Switzerland). Nitrosylhemochrome concentration was calculated by multiplying the absorbance by 290. In turn, total pigment concentration was determined by homogenizing 10 g of samples with 2 mL of deionized water, 1 mL of HCl, and 40 mL of acetone. The resulting solutions were kept in the dark at 4°C for 1 h and the absorbance at 640 nm was measured after filtering through Whatman No. 1 paper. Total pigment concentration was calculated by multiplying the absorbance by 680. Nitrosylhemochrome content was expressed as a percentage by dividing the nitrosylhemochrome concentration by the total pigment concentration. The experiment was repeated three times.

**Color measurement**. The Minolta chromameter (CR-400, Konica Minolta Inc., Tokyo, Japan) with a standardized light source (D65 illuminant) and an observer angle of 2° was used to measure the instrumental color of the meat batters and jerky. Reflectance was measured with a spot diameter of 8 mm, and the equipment was calibrated using the white standard calibration plate (L* = 98.45, a* = −0.10, b* = −0.13) prior to analysis. The L* (lightness), a* (redness), and b* (yellowness) values were determined for all samples. Three measurements from the surface of each sausage batter were taken immediately prior to the stuffing process in each batch. In addition, three measurements from random locations on the surface of three jerky samples from each treatment were taken in each batch. Based on the a* and b* values,

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

the C* (chroma, relative saturation) values were also calculated according to the following formula:

**TBARS values**. The lipid oxidation of jerky was assessed by measuring the 2-thiobarbituric acid reactive substances value (TBARS), following the modified method described by Pikul *et al*. [1989]. First, 5g of the sample was homogenized for 2 min (12 rpm×1000) with 50 mL of 20% w/v trichloroacetic acid (acidified with 1.6% phosphoric acid) and 2.5 mL of an antioxidant solution (0.5% propyl gallate and 0.5% EDTA in a solution of water and ethanol in equal proportions) using an

Ultra Turrax homogenizer (T18 basic, IKA Werke, Staufen, Germany). The resulting solutions were filtered through Whatman no. 1 paper, diluted to 100 mL with a solution containing water and ethanol in a 1:1 ratio, and mixed thoroughly. Then, 5 mL of the filtrate from each treatment and 5 mL of 0.02 M 2-thiobarbituric acid were placed in phalcones, vortexed, heated for 30 min in a water bath (80°C), and then centrifuged for 10 min (1800 rpm, MPW-56, Med. Instruments, Warsaw, Poland) after cooling. Finally, the absorbance of the samples was measured at 532 nm using a microplate reader (SparkTM 10M, Tecan Group, Männedorf, Switzerland). The TBARS values of the samples were calculated using a standard curve generated with 1,1,3,3-tetramethoxypropane, and expressed as mg malonaldehyde equivalent/kg sample. TBARS values were measured in triplicate for each treatment in each batch.

**Texture**. Texture of samples (6 × 1.5 × 0.2 cm) was measured using the Universal Testing Machine (Instron 5965, Norwood, MA, USA). Three samples from each group were tested in each batch for this purpose, and the test speed was set at 2 mm/s. Shear force was expressed in Newtons (N) and shear energy in Joules (J).

**Aroma profile**. The aroma profile of the jerky was determined using an electronic nose (Heracles II, Alpha M.O.S., Toulouse, France). The analysis of volatile compounds was conducted by placing 2 g of each sample in a 20 mL headspace vial, which was then sealed with a teflon-faced silicon rubber, following the methodology described by Wojtasik-Kalinowska *et al.* [2016] and Górska-Horczyczak *et al.* [2017]. Duplicate measurements were performed for each treatment, and specific volatile compounds were identified using AroChemBase (Alpha MOS Co., Toulouse, France).

#### Statistical analysis

Analysis of variance was performed for all variables using a general linear model (Statistica 13.3 program, StatSoft Inc., Tulsa, OK) with treatment as a fixed effect and batch (replication) as a random effect. The Tukey's multiple-range test with a significance level of $p<0.05$ was used to determine differences between treatments. Mean values with their standard errors (SE) are given for all results. Additionally, principal component analysis (Alpha Soft, version 8.0) was utilized to analyze the aroma profile data.

## Results and discussion

#### Water activity, moisture, protein and fat content

High water activity (aw) in jerky can promote microbial growth, increasing the risk of foodborne illnesses. To ensure the safety and quality of jerky, it is crucial to maintain water activity below 0.85 [Zhao *et al.* 2011], with a targeted range typically falling around 0.7 to prevent mold growth [Han *et al*. 2023, Nummer *et al.* 2004]. This range effectively inhibits microbial growth, extends the product's shelf life, and preserves the desired texture of the jerky [Juneja *et al*. 2016]. In comparison to whole muscle jerky, restructured jerky has a softer texture but higher water activity, which

makes it more susceptible to microbial growth and lipid oxidation [Lemma *et al*. 2022]. According to Table 1, the water activity values of the meat batters right before the process were similar ($p \geq 0.05$). Also desired aw values after drying were achieved in all treatments (Tab. 1). Nevertheless, samples with the addition of aqueous solutions of dried blood plasma treated with air plasma (T1, T2, T3) were characterized by significantly lower ($p<0.05$) water activity values, ranging from 0.688 to 0.713, compared to the control groups (NC, PC), which exhibited water activity values in the range of 0.742 to 0.745. According to literature the water activity of jerky and thus their shelf-life are influenced by various factors, including the drying conditions, as well as the raw materials [Albright *et al*. 2003, Choi *et al*. 2008, Han *et al*. 2023].

The moisture content is mainly related to the free migration of water [Shi *et al.* 2021]. Higher moisture content leads to higher water activity [Han *et al*. 2021], as observed in our results (Tab. 1). The groups with higher water activity values (NC, PC) also had significantly higher water content compared to the other groups (T1, T2, and T3). Similarly, proteins can affect water activity by binding and retaining water molecules. Therefore, a higher protein content in product may contribute to a lower water activity by binding a portion of the available water. However, it is important to note that jerky contains mainly proteins in a denatured form, which have limited ability to rehydrate and resolubilize [Morr 1989]. In addition, Qian *et al.* [2022] reported that plasma-activated water was found to reduce WHC (water holding capacity) of chicken meat by causing the loss of soluble proteins, consequently leading to an increased separation between muscle fibers. Consistent with these findings, the

**Table 1**. Effect of blood plasma subjected to non-thermal atmospheric plasma treatment on water activity, moisture, protein and fat content of meat batter and restructured beef jerky (mean ± SE)

| Group | $a_w$ (-) | Water (%) | Protein (%) | Fat (%) |
|---|---|---|---|---|
| | | *meat batter* | | |
| NC | 0.990±0.001 | 77.80±0.16 | 18.58±0.04$^{a}$ | 1.02±0.04 |
| PC | 0.992±0.001 | 77.64±0.10 | 18.44±0.05$^{a}$ | 1.03±0.03 |
| T1 | 0.989±0.001 | 77.70±0.11 | 19.09±0.06$^{b}$ | 0.91±0.04 |
| T2 | 0.988±0.001 | 77.52±0.22 | 19.50±0.03$^{c}$ | 0.94±0.04 |
| T3 | 0.988±0.001 | 77.42±0.06 | 19.69±0.05$^{d}$ | 0.89±0.04 |
| | | *final product* | | |
| NC | 0.745±0.006$^{c}$ | 28.57±0.12$^{a}$ | 64.03±0.15$^{a}$ | 2.19±0.05 |
| PC | 0.742±0.003$^{c}$ | 28.72±0.12$^{a}$ | 64.56±0.17$^{a}$ | 2.28±0.07 |
| T1 | 0.713±0.002$^{b}$ | 27.79±0.04$^{b}$ | 66.81±0.22$^{b}$ | 1.91±0.16 |
| T2 | 0.702±0.003$^{ab}$ | 26.83±0.06$^{c}$ | 68.03±0.12$^{c}$ | 1.96±0.14 |
| T3 | 0.688±0.003$^{a}$ | 26.27±0.04$^{d}$ | 68.92±0.16$^{d}$ | 1.91±0.14 |

NC – negative control (beef jerky without sources of nitrite); PC – positive control (beef jerky with 100 ppm of sodium nitrite); T1 – group with 2.5% aqueous solution of dried blood plasma treated with air plasma; T2 – group with 5% aqueous solution of dried blood plasma treated with air plasma; T3 – group with 7.5% aqueous solution of dried blood plasma treated with air plasma.

$^{ad}$Within columns means bearing different superscripts differ significantly at $p<0.05$.

groups treated with plasma-activated solutions (T1, T2, T3) in our study exhibited significantly lower water activity compared to the control groups. Ultimately, fats are hydrophobic and repel water, which can potentially lead to a lower water activity. However, in our study, there were no significant differences in fat content, both before and after the process ($p \geq 0.05$). Considering the above, the use of blood plasma as a protein source, even after air plasma treatment, can help control water activity in jerky, thereby enhancing its safety, quality, and preservation.

**Yield and pH**. The high water migration and evaporation that occur due to protein thermal denaturation [Zhang *et al*. 2022] can lead to low yield values of jerky. Table 2 presents the impact of the treatment on the percentage yield of restructured jerky. The results indicate that the analyzed groups did not differ significantly ($p \geq 0.05$). The process efficiency of both the control groups (NC, PC) and those with aqueous solutions of dried blood plasma treated by air plasma (T1, T2, T3) ranged from 29.98±0.58% to 31.98±0.81%.

Maintaining appropriate pH levels in meat processing is essential because it directly affects the texture, flavor and shelf life of restructured jerky, with pH fluctuations affecting product quality and characteristics. According to Yang *et al.* [2009] the pH values of jerky samples obtained from beef *semimembranosus* were about 5.76. However, it is important to note that the pH range can vary depending on the specific recipe and processing conditions. As shown in Table 2, the treatment had

**Table 2**. Effect of blood plasma subjected to non-thermal atmospheric plasma treatment on yield of restructured beef jerky an pH of meat batter and final product (mean ±SE)

| Group | Yield (%) | pH meat batter (-) | pH final product (-) |
|---|---|---|---|
| NC | 29.98±0.58 | 5.58±0.01$^{a}$ | 5.79±0.00$^{a}$ |
| PC | 30.63±0.18 | 5.58±0.00$^{a}$ | 5.79±0.00$^{a}$ |
| T1 | 30.51±0.98 | 5.59±0.01$^{ab}$ | 5.80±0.01$^{ab}$ |
| T2 | 30.05±0.52 | 5.63±0.01$^{b}$ | 5.81±0.00$^{b}$ |
| T3 | 31.98±0.81 | 5.68±0.00$^{c}$ | 5.84±0.00$^{c}$ |

NC – negative control (beef jerky without sources of nitrite); PC – positive control (beef jerky with 100 ppm of sodium nitrite); T1 – group with 2.5% aqueous solution of dried blood plasma treated with air plasma; T2 – group with 5% aqueous solution of dried blood plasma treated with air plasma; T3 – group with 7.5% aqueous solution of dried blood plasma treated with air plasma.
$^{ac}$Within columns means bearing different superscripts differ significantly at $p<0.05$.

a significant effect ($p<0.05$) on the pH values of both the meat batters and the final products.

The observed effect on the pH of the meat batters and finished products can be attributed to the buffering capacity of the blood plasma proteins, which played a role in maintaining the pH of the dried blood plasma solutions above 6 after cold plasma treatment [Cheng *et al.* 2021]. Increasing the amount of blood plasma in the solution treated with air plasma resulted in higher pH values for both the meat batters and the

final products. The group that contained 200 g of 7.5% aqueous solution of dried blood plasma treated with air plasma (T3) exhibited the highest pH values ($p<0.05$) compared to the other groups. However, no significant differences ($p\geq0.05$) in pH values were observed between the NC and PC groups. These findings are consistent with previous research that demonstrated higher pH values for pork sausages containing plasma-treated soy solution or plasma-treated milk powder compared to sausages with $NaNO_2$ or without nitrites [Marcinkowska-Lesiak *et al*. 2022ab]. To ensure food safety and achieve the desired texture and flavor, it is important to maintain the pH level within the appropriate range. In this study, all groups achieved the desired range despite differences in pH values.

**Residual nitrite, heme iron and nitrosylhemochrome content.** The residual nitrite content in meat products, a critical factor for preservation and flavor, is influenced by various factors such as initial nitrite concentration, curing conditions, pH levels, and additional ingredients [Nader *et al*. 2022]. Table 3 shows that curing significantly affected residual nitrite content in jerky. Samples without sources of nitrite (NC group) were characterized, as expected, by significantly lower nitrite content compared to PC, T1, T2 and T3 groups ($p<0.05$). Moreover, there were significant differences between cured samples ($p<0.05$). Gibson *et al.* [1984] mentioned that in meat slurries characterized by a high pH, the rate of nitrite loss was slower. This indicates that a higher pH in the meat slurries can help preserve the residual nitrite content, potentially resulting in higher levels of nitrite remaining in the product. This finding is consistent with our study, which showed that the T3 group, with the highest

**Table 3**. Effect of blood plasma subjected to non-thermal atmospheric plasma treatment on residual nitrite, heme iron and nitrosylhemochrome content (mean ±SE) of restructured beef jerky

| Group | Residual nitrite content (ppm) | Heme iron content (ppm) | Nitrosylhemochrome content (%) |
|---|---|---|---|
| NC | $0.46\pm0.04^{a}$ | $47.19\pm0.14^{d}$ | $6.12\pm0.30^{a}$ |
| PC | $43.84\pm0.68^{b}$ | $45.43\pm0.28^{c}$ | $39.03\pm0.37^{b}$ |
| T1 | $43.27\pm1.04^{b}$ | $45.08\pm0.22^{c}$ | $39.12\pm0.34^{b}$ |
| T2 | $44.37\pm0.56^{b}$ | $43.24\pm0.19^{b}$ | $40.07\pm0.17^{b}$ |
| T3 | $49.48\pm0.46^{c}$ | $39.27\pm0.22^{a}$ | $43.25\pm0.24^{c}$ |

NC – negative control (beef jerky without sources of nitrite); PC – positive control (beef jerky with 100 ppm of sodium nitrite); T1 – group with 2.5% aqueous solution of dried blood plasma treated with air plasma; T2 – group with 5% aqueous solution of dried blood plasma treated with air plasma; T3 – group with 7.5% aqueous solution of dried blood plasma treated with air plasma.
[ad]Within columns means bearing different superscripts differ significantly at $p<0.05$.

pH value of meat batter as well final product, also were characterized by the highest residual nitrite content (Tab. 3, $p<0.05$).

Throughout the drying process, the heme iron content decreases as a result of the oxidation of oxymyoglobin to metmyoglobin [Shi *et al*. 2021]. In addition, cured meat

products exhibit a complex relationship among residual nitrite content, heme iron, and nitrosylhemochrome. When nitrites react with heme iron, a part of it can be transformed into nitrosylhemochrome after through heat treatment [de La Pomélie *et al.* 2018]. According to the above, in our study the treatment without source of nitrite (NC) were characterized by the highest heme iron content and the lowest nitrosylhemochrome content (Tab. 3, $p<0.05$) compared to other groups. Additionally, the T3 samples, characterized by the highest content of residual nitrites, contained significantly more nitrosylhemochrome and less heme iron compared to the other cured groups (PC, T1, and T2), suggesting that higher levels of nitrite during curing may result in the formation of more nitrosylhemochrome and a lower heme iron content in the final product. The obtained result could also be influenced by the concentration of blood plasma in the meat stuffing, which contains various components, including proteins that have the ability to bind heme iron or modify its chemical state. This may explain why the T2 group, although having comparable levels of nitrosylhemochrome with the PC and T1, had a lower heme iron content than these groups.

**Color parameters.** The color parameters (L*, a*, b*) of both meat batters and finished products were influenced by the curing method (Tab. 4, $p<0.05$). The curing process resulted in increased lightness (L* values) and decreased redness (a* values) of the meat batters compared to the group without nitrite ($p<0.05$). Furthermore, meat batters cured with blood plasma treated with non-thermal atmospheric plasma ($p<0.05$) exhibited higher b* values in comparison to samples cured with sodium nitrite and uncured samples. In contrary, according to Hadinoto *et al.* [2023] reduction in oxymyoglobin content caused decrease of yellowness of beef samples spraying

**Table 4**. Effect of blood plasma subjected to non-thermal atmospheric plasma treatment on color parameters of meat batter and restructured beef jerky (mean ±SE)

| Group | L* (-) | a* (%) | b* (%) | C* (%) |
|---|---|---|---|---|
| | | *meat batter* | | |
| NC | 36.76±0.30$^{a}$ | 22.08±0.31$^{b}$ | 8.49±0.18$^{b}$ | 23.66±0.35$^{d}$ |
| PC | 39.10±0.48$^{b}$ | 10.20±0.11$^{a}$ | 6.79±0.12$^{a}$ | 12.26±0.13$^{a}$ |
| T1 | 41.04±0.31$^{c}$ | 10.54±0.14$^{a}$ | 9.06±0.18$^{b}$ | 13.90±0.22$^{b}$ |
| T2 | 41.97±0.27$^{cd}$ | 10.56±0.11$^{a}$ | 9.78±0.17$^{c}$ | 14.39±0.18$^{b}$ |
| T3 | 43.07±0.25$^{d}$ | 10.76±0.07$^{a}$ | 10.97±0.16$^{d}$ | 15.38±0.12$^{c}$ |
| | | *final product* | | |
| NC | 24.63±0.35$^{a}$ | 7.88±0.12$^{a}$ | 2.10±0.11$^{a}$ | 8.17±0.14$^{a}$ |
| PC | 25.49±0.28$^{ab}$ | 16.14±0.17$^{b}$ | 4.05±0.10$^{b}$ | 16.64±0.18$^{b}$ |
| T1 | 26.45±0.27$^{bc}$ | 15.79±0.28$^{b}$ | 3.76±0.10$^{b}$ | 16.23±0.29$^{b}$ |
| T2 | 27.49±0.19$^{c}$ | 15.83±0.33$^{b}$ | 4.16±0.14$^{b}$ | 16.39±0.33$^{b}$ |
| T3 | 29.02±0.36$^{d}$ | 17.06±0.18$^{c}$ | 4.66±0.10$^{c}$ | 17.69±0.18$^{c}$ |

NC – negative control (beef jerky without sources of nitrite); PC – positive control (beef jerky with 100 ppm of sodium nitrite); T1 - group with 2.5% aqueous solution of dried blood plasma treated with air plasma; T2 - group with 5% aqueous solution of dried blood plasma treated with air plasma; T3 - group with 7.5% aqueous solution of dried blood plasma treated with air plasma.

$^{ad}$Within columns means bearing different superscripts differ significantly at $p<0.05$.

with plasma activated water. The observed differences in b values can be attributed to the presence of proteins in non-thermal plasma treated blood plasma solutions.

Regarding the final product, the incorporation of non-thermal plasma-treated dried blood plasma aqueous solutions resulted in enhancement in the lightness of jerky when compared to the NC group, with statistical significance ($p<0.05$). Additionally, both the T2 and T3 groups exhibited significantly higher lightness values than the PC group ($p<0.05$). Notably, the T2 group was found to be darker than the T3 group ($p<0.05$). These findings are of particular interest, as literature [Chen *et al*. 2019] indicates a generally positive correlation between water content and the lightness of dry meat products. Despite the lower water content observed in the T1, T2, and T3 groups compared to the control groups, the increasing concentration of blood plasma in the final product led to an increase in the lightness of the jerky. This suggests that the proteins present in the blood plasma may have influenced the lightness of the final product, independent of the water content. Additionally, Cheng *et al*. [2021] demonstrated that metmyoglobin solutions became lighter after plasma treatment exceeding 4 minutes. This effect is likely attributed to the accumulation of hydrogen peroxide ($H_2O_2$), which interacts with the sixth coordination bond of the central iron in MetMb, resulting in the observed lightening of the solutions.

Heating contributes to a browning reaction in the presence of high concentrations of metmyoglobin [Killinger *et al.* 2000]. As a consequence, during the drying process of uncured jerky (group NC) there was a noticeable reduction in redness (Tab. 1). As expected, cured samples (PC, T1, T2, and T3 groups) exhibited higher values ($p<0.05$) of the a* parameter compared to the NC group after drying. Additionally, the T3 group, characterized by the highest content of nitrosylhemochrome (Tab. 3), were the most red compared to other cured groups (Tab. 4, $p<0.05$) what could it mean that nitrosylhemochrome, a stable compound formed after heat treatment, plays a key role in creating the color of cured meats, with higher levels resulting in a more pronounced reddish color [Pegg & Shahidi 2000]. This result was consistent with that of Inguglia *et al.* [2020], who investigated the impact of plasma-activated water on the redness of wet-cured whole muscle jerky. Similar to the a* parameter, the b* parameter, displayed a consistent trend among the samples from the PC, T1, T2, and T3 groups, with significantly higher values ($p<0.05$) compared to the NC group. Furthermore, when comparing the cured jerky, the T3 group also exhibited the most intense yellow coloration in comparison to the other groups. In the case of wet curing using plasma-activated water (PAW), there was no significant effect observed on the b values of the jerky [Inguglia *et al.* 2020].

The C* parameter, representing the chroma or color strength, also showed significant differences ($p<0.05$) between the cured groups and the NC group, both in the meat batters and final products (Tab. 4). The meat batters from the PC, T1, T2, and T3 groups demonstrated lower values of the C* parameter ($p<0.05$) than the NC group, indicating they less vivid color. Our results are consistent with the study conducted by Hadinoto *et al*. [2023] which analyzed the impact of mist spraying and

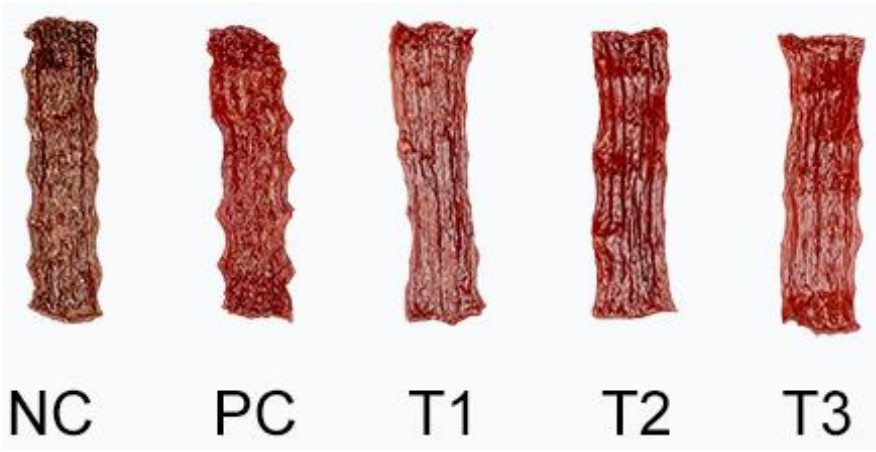


Fig. 2. Representative images of restructured jerky - top view, from left: NC – negative control (beef jerky without sources of nitrite); PC – positive control (beef jerky with 100 ppm of sodium nitrite); T1 – group with 2.5% aqueous solution of dried blood plasma treated with air plasma; T2 – group with 5% aqueous solution of dried blood plasma treated with air plasma; T3 – group with 7.5% aqueous solution of dried blood plasma treated with air plasma.

immersion of beef samples with plasma-activated water containing nitrite. Conversely, the restructured jerky samples cured with different sources of nitrite exhibited higher values of chroma than the NC group, with the highest values obtained for T3 group. These results highlight the impact of the curing method on the color characteristics of meat products, emphasizing the importance of their optimalization to achieve the desired color attributes of jerky (Fig. 2).

**TBARS values**. During the drying process of jerky, the TBARS values can increase as a result of lipid oxidation. As the moisture content decreases and the jerky undergoes drying, the exposure of fats to oxygen can promote oxidation, leading to the production of oxidative compounds such as malondialdehyde (MDA), which is measured through TBARS analysis. TBARS (Thiobarbituric Acid Reactive Substances) is a common method for assessing the extent of lipid oxidation in food products. Typical TBARS values for beef jerky after drying can vary depending on various factors including the processing conditions, storage conditions, and the composition of the jerky. However, acceptable TBARS values for meat products should not exceed 2 mg of MDA per kg of sample [Ripoll *et al.* 2011]. The results presented in Table 5 demonstrate that the curing process, regardless of the source of nitrite, led to a significant ($p<0.05$) reduction in oxidation compared to the NC group from the first day of storage ($p<0.05$). This reduction in oxidation can be attributed to the antioxidant effect of nitrites. The obtained results demonstrate that aqua solutions of dried plasma treated with nonthermal plasma effectively preserved the lipid oxidation of jerky. However, it is important to note that all measured values of oxidation, indicated by TBARS values, remained relatively low, ranging from 0.42

to 0.51 mg MDA/kg, and fell within the acceptable range. This may be attributed to the low fat content of the product, as shown in Table 1. Similarly, in a study by [Han *et al*. 2023], TBARS values of beef jerky marinated with 100 ppm of sodium nitrite and subjected to hydrostatic pressure combined with moisture regulators were found to be below 0.5 mg MDA/kg. Furthermore, no statistically significant differences ($p \geq 0.05$) were observed among the cured samples (PC, T1, T2, T3). These findings are consistent with prior studies [Marcinkowska-Lesiak *et al*. 2022ab, 2023] suggesting that alternative sources of nitrite obtained through non-thermal plasma have a similar potential to sodium nitrite in preserving the oxidative stability of cured meat products.

**Texture.** Shear force and shear energy are important parameters used to assess the texture and tenderness of jerky. These measurements can provide valuable insights into the impact of various factors such as processing techniques, ingredients, and storage conditions on the final quality of the meat product [Han *et al*. 2007]. Shear force, in this context, refers to the force required to cut or shear through the jerky, essentially measuring its resistance to being cut or torn apart. Heating leads to the denaturation, coagulation, and contraction of myofibrillar proteins, resulting in increased density

**Table 5**. Effect of blood plasma subjected to non-thermal atmospheric plasma treatment on TBARS content, shear force and shear energy (mean±SE) of restructured beef jerky

| Group | TBARS (mg MDA/kg) | Shear Force (N) | Shear Energy (J) |
|---|---|---|---|
| NC | 0.51±0.01$^{b}$ | 215.79±7.00$^{a}$ | 0.21±0.02$^{a}$ |
| PC | 0.42±0.01$^{a}$ | 190.15±9.74$^{a}$ | 0.20±0.02$^{a}$ |
| T1 | 0.44±0.00$^{a}$ | 237.79±12.76$^{a}$ | 0.23±0.02$^{a}$ |
| T2 | 0.43±0.01$^{a}$ | 300.23±17.14$^{b}$ | 0.23±0.01$^{a}$ |
| T3 | 0.45±0.01$^{a}$ | 422.53±14.81$^{c}$ | 0.35±0.02$^{b}$ |

NC – negative control (beef jerky without sources of nitrite); PC – positive control (beef jerky with 100 ppm of sodium nitrite); T1 – group with 2.5% aqueous solution of dried blood plasma treated with air plasma; T2 – group with 5% aqueous solution of dried blood plasma treated with air plasma; T3 – group with 7.5% aqueous solution of dried blood plasma treated with air plasma.
$^{ac}$Within columns means bearing different superscripts differ significantly at $p<0.05$.

per unit area and enhanced resistance to shear force [Shi *et al*. 2021]. According to Table 5, also the treatment had a significant effect ($p<0.05$) on the shear force values of the jerky. The NC, PC and T1 groups showed similar values of this parameter. However, the addition of 200 g of 5 and 7.5% aqueous solutions of air plasma treated dried blood plasma led to a significant ($p<0.05$) increase in shear force compared to the other groups. Group T3 were characterized by the highest average shear force values among all samples, which can be attributed to the lower moisture content in the final product. Oxidation is believed to have a potential impact on the formation of cross-links, which can restrict the swelling of proteins after exposure to cold plasma treatment, primarily through the generation of reactive oxygen and nitrogen species [Bao & Ertbjerg 2019]. However, the addition of aqueous solutions of dried blood

plasma treated with air plasma to meat batters may have a beneficial effect on the texture of restructured jerky. Its addition in T2 and T3 group facilitated the binding of meat particles, resulting in the creation of a cohesive structure in jerky. This cohesive structure was probably responsible for the observed increase in shear force in these groups, which can be attributed to the formation of a gel-like structure. Also in the case of liver pâtés, the authors did not observe any deterioration in the functional properties of egg whites subjected to non-thermal plasma treatment compared to the control groups [Marcinkowska-Lesiak *et al*. 2023]. In terms of shear energy, which measures the work required to deform or break meat products during shearing, the average values of the T3 group also were significantly different from the other groups (Table 5, $p<0.05$). These findings are consistent with existing literature that highlights the influence of moisture content on the textural properties of meat products [Herrero *et al*. 2007, Lorenzo *et al*. 2014]. However, it is important to note that according to Konieczny *et al.* [2007], a texture that is excessively hard due to low moisture content may not be preferred by consumers. While the higher shear force values observed in Group T3 may be attributed to the lower moisture content, it is crucial to strike a balance between achieving desirable texture and avoiding excessive hardness.

**Aroma profile**. In this study, principal component analysis (PCA) was used to determine the major sources of variability in the aroma of the analyzed jerky samples. Figure 3 illustrates the distribution of scent profiles among the different treatments (NC, PC, T1, T2, T3) on a two-dimensional plane based on the selected components: PC1 and PC2. The horizontal axis explains 4.38% of the data variance, while the

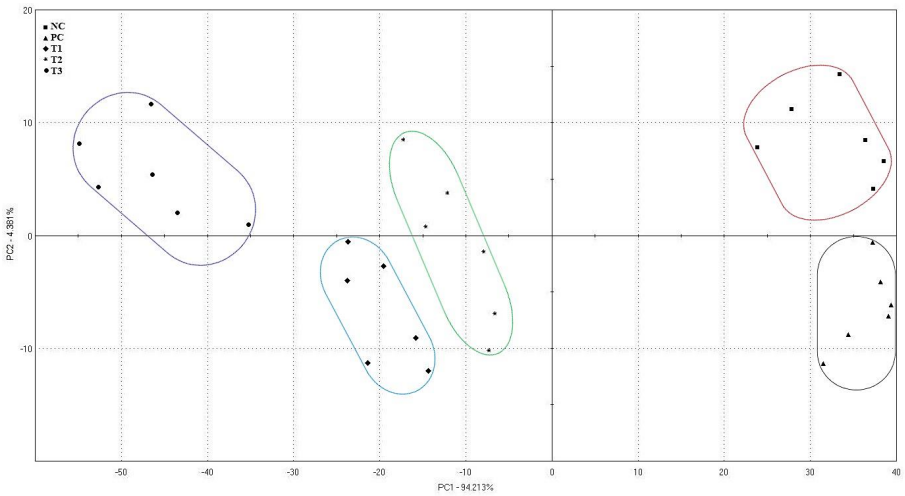


Fig. 3. PCA analysis of restructured beef jerky: NC – negative control (beef jerky without sources of nitrite); PC – positive control (beef jerky with 100 ppm of sodium nitrite); T1 – group with 2.5% aqueous solution of dried blood plasma treated with air plasma; T2 – group with 5% aqueous solution of dried blood plasma treated with air plasma; T3 – group with 7.5% aqueous solution of dried blood plasma treated with air plasma.

vertical axis accounts for 94.21%, indicating that the differences among the samples were more significant along the vertical axis than the horizontal axis. The use of sodium nitrite did not result in significant changes in the aroma profile of jerky when compared to the NC group. The use of air plasma-treated aqueous solutions of dried blood plasma resulted in significant differences in the aroma profiles of the samples as revealed by the principal component analysis (PCA). The PCA analysis showed that the aroma profiles of T1, T2 and T3 groups differed significantly not only from the negative control (NC) group but also from the positive control (PC) group.

During the heating process, jerky undergoes an intricate transformation that results

**Table 6**. Volatile compounds' characteristic of restructured beef jerky cured with alternative nitrite sources

| Compounds | DB5 | Sensory descriptors | NC | PC | T1 | T2 | T3 |
|---|---|---|---|---|---|---|---|
| *ALCOHOLS* | | | | | | | |
| Ethanol | 460 | alcoholic | + | + | + | + | + |
| 1-Propanol | 520 | alcoholic | + | + | + | + | + |
| n-Butanol | 651 | n-butanol; fermented | + | + | | + | + |
| Pentan-2-ol | 692 | alcoholic | + | + | + | + | + |
| 2-Penten-1-ol | 760 | grassy; green | + | + | + | + | + |
| propylenglycol | 730 | alcoholic; caramelized | + | + | + | + | + |
| 2-Hexen-1-ol | 867 | caramelized | + | + | + | + | + |
| *ALDEHYDES* | | | | | | | |
| 2-Methylpropanal | 515 | aldehydic | + | + | + | + | + |
| 3-Methylbutanal | 640 | aldehydic; almond | + | | + | + | + |
| 2-Methylbutanal | 663 | almond | + | + | + | + | + |
| Furfural | 841 | almond | + | + | + | + | + |
| *KETONES* | | | | | | | |
| Butane-2,3-dione | 558 | butter; carmelized | + | + | | | |
| *CARBOXYLIC ACIDS* | | | | | | | |
| Butanoic acid | 812 | butter | | + | + | + | |
| 3-Methylbutanoic acid | 879 | acidic | + | + | + | + | + |
| Propanoic acid hexylester | 1104 | - | | | + | | |
| *PYRAZINES* | | | | | | | |
| Pyrazine | 725 | bitter | + | + | + | + | + |
| 2,3-Dimethylpyrazine | 949 | baked | + | + | + | + | + |
| Trimethylpyrazine | 1001 | baked | + | + | + | + | + |
| 2-Ethyl-6-methylpyrazine | 1014 | roast | + | + | + | + | + |
| *THIOPHENE* | | | | | | | |
| Thiophene | 676 | alliaceous | | | + | + | + |
| *PYRIDINE* | | | | | | | |
| Pyridine | 752 | cold meat fat | + | + | + | + | + |
| *TERPENES* | | | | | | | |
| 1R-(+)-alpha-pinene | 925 | aromatic | + | + | + | + | + |
| 1S-()-a-pinene | 964 | camphor | + | + | + | + | + |
| beta-Pinene | 985 | dry | + | + | + | + | + |
| L-limonene | 1048 | citrus | + | + | + | + | + |
| gamma-terpinene | 1076 | etheral | + | + | + | + | + |
| *OTHERS* | | | | | | | |
| Dimethyl disulfide | 743 | cabbage | + | + | + | + | + |
| (E)-2-Penten-1-ol | 760 | grassy; green | + | + | + | + | + |
| 1-Methyl-4-isopropenyl-1-cyclohexane | 1035 | - | | | + | + | + |
| Acetophenone | 1065 | almond | | | + | + | + |
| 2-Methoxy-3-(1-methylpropyl) | 1170 | - | + | | | | |
| Pyridine, 2-pentyl-pyrazine | 1197 | - | + | | | | |
| Decanal | 1231 | aldehydic; burnt | + | | | | |

DB5 – Order of elution in DB-5 non-polar column; NC – negative control (beef jerky without sources of nitrite); PC – positive control (beef jerky with 100 ppm of sodium nitrite); T1 – group with 2.5% aqueous solution of dried blood plasma treated with air plasma; T2 – group with 5% aqueous solution of dried blood plasma treated with air plasma; T3 – group with 7.5% aqueous solution of dried blood plasma treated with air plasma.

in the formation of over 1000 volatile compounds, which primarily originate from lipid oxidation and Maillard reactions, with notable contributions from pyrazines, imidazoles, thiophenes, and furans [Luo *et al.* 2020, Pegg & Shahidi 2004]. These volatile compounds can impart specific aromas and flavors to the jerky, adding to its overall sensory profile. In the analyzed treatments, a total of 33 volatile compounds were identified. Among them, 28 were detected in the NC group, 25 in the PC group, 26 in the T1 group, 28 in the T2 group, and 27 in the T3 group (Tab. 6). These compounds including alcohols (7 compounds), terpenes (5 compounds), aldehydes (4 compounds), and pyrazines (4 compounds). Moreover, the groups cured with alternative nitrite sources (T1, T2, T3) exhibited the presence of thiophene, which imparts roasted, meaty aroma [Flores 2018], 1-methyl-4-isopropenyl-1-cyclohexane, known for its floral and spicy notes, and acetophenone, which offers a alliaceous aroma associated with members of the Allium genus, like garlic or onion. These compounds likely contributed to the distinct flavors observed in groups T1, T2, and T3. However, the butane-2,3-dione, recognized for its buttery and caramelized notes, was absent in these groups. These differences in the aroma profile might have influenced the variations observed between the control groups (NC, PC) and the groups treated with aqueous solutions of dried blood plasma exposed to air plasma (T1, T2, T3) as shown in Figure 3. It is worth noting that aldehydes, such as hexanal, nonanal, heptanal, and decanal, are typically considered as products of lipid oxidation [Luo *et al*. 2019]. However, none of these aldehydes were detected in the analyzed samples, which is consistent with the low TBARS (thiobarbituric acid reactive substances) values reported in Table 5.

Based on the obtained results, it seems that using solutions of dried blood plasma treated by non-thermal plasma, particularly the group T2 containing a 5% aqueous solution of dried blood plasma, is the most favorable choice for the production of restructured beef jerky. This treatment resulted in similar pH, residual nitrite content, redness, and TBARS values compared to jerky cured with sodium nitrite. At the same time, it resulted in lower water activity values, higher protein content, higher lightness, and shear force values compared to the control groups, indicating potential improvements in safety, nutritional value, color attributes, and texture of the restructured jerky. However, a high level of dried blood plasma in the solution treated by non-thermal plasma may increase the pH of the final product, resulting in an increased residual nitrite content in the jerky (T3 group). Additionally, a sensory analysis of the jerky produced using this alternative curing method should be carried out due to significant differences in aroma profiles of the T1, T2, and T3 groups compared to the group cured with sodium nitrite. Nevertheless, the obtained results suggest that using the appropriate concentration of dried blood plasma in a solution treated by non-thermal plasma could be a promising alternative to traditional methods for producing restructured beef jerky.

**Declaration of competing interest**

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

**REFERENCES**


1. ALBRIGHT S.N., KENDALL P.A., AVENS J.S., SOFOS J.N., 2003 – Pretreatment effect on inactivation of Escherichia coli O157:H7 inoculated beef jerky. ***Lwt*** 36(4), 381-389.
2. BAO Y., ERTBJERG P., 2019 – Effects of protein oxidation on the texture and water-holding of meat: a review. ***Critical Reviews in Food Science and Nutrition*** 59(22), 3564-3578.
3. CHEN J., HU Y., WEN R., LIU Q., CHEN Q., KONG B., 2019 – Effect of NaCl substitutes on the physical, microbial and sensory characteristics of Harbin dry sausage. ***Meat Science*** 156, 205-213.
4. CHENG JEN HUA, OCKERMAN H.W., 2003 – Effect of phosphate with tumbling on lipid oxidation of precooked roast beef. ***Meat Science*** 65(4), 1353-1359.
5. CHENG JUN HU, CHEN Y.Q., SUN D.W., 2021 – Effects of plasma activated solution on the colour and structure of metmyoglobin and oxymyoglobin. ***Food Chemistry*** 353 (September 2020).
6. CHOI J.-H., JEONG J.-Y., HAN D.-J., CHOI Y.-S., KIM H.-Y., LEE M.-A., LEE E.-S., PAIK H.-D., KIM C.-J., 2008 – Effects of pork/beef levels and various casings on quality properties of semi-dried jerky. ***Meat Science***, 80(2), 278-286.
7. DE LA POMÉLIE D., SANTÉ-LHOUTELLIER V., GATELLIER P., 2018 – Mechanisms and kinetics of heme iron nitrosylation in an in vitro gastro-intestinal model. F***ood Chemistry*** 239, 86-93.
8. FEINER G., 2006 – Meat Products Handbook: Practical Science and Technology.
9. FLORES M., 2018 – Understanding the implications of current health trends on the aroma of wet and dry cured meat products. ***Meat Science*** 144, 53-61.
10. GIBSON A.M., ROBERTS T.A., ROBINSON A., 1984 – Factors controlling the growth of Clostridium botulinum types A and B in pasteurized cured meats VI. Nitrite monitoring during storage of pasteurized pork slurries. ***International Journal of Food Science & Technology*** 19(1), 29-44.
11. GÓMEZ I., JANARDHANAN R., IBAÑEZ F.C., BERIAIN M.J., 2020 – The effects of processing and preservation technologies on meat quality: Sensory and nutritional aspects. ***Foods*** 9(10), 1-30.
12. GÓRSKA-HORCZYCZAK E., WOJTASIK-KALINOWSKA I., GUZEK D., SUN D.W., WIERZBICKA A., 2017 – Differentiation of chill-stored and frozen pork necks using electronic nose with ultra-fast gas chromatography. ***Journal of Food Process Engineering*** 40(5), e12540.
13. GUPTA S., SHARMA B.D., 2018 – Quality characteristics of functional restructured spent hen meat slices developed by utilizing different binders and extenders. ***Food Science and Technology Research*** 24(2), 241-247.
14. GUPTA S., SHARMA B.D., 2023 – Effect of texturized soy protein on quality of restructured meat slices from spent hen. ***Agricultural Research*** 12, 319-324.
15. HADINOTO K., YANG H., ZHANG T., CULLEN P.J., PRESCOTT S., TRUJILLO F.J., 2023 – The antimicrobial effects of mist spraying and immersion on beef samples with plasma-activated water. ***Meat Science*** 200, 109165.
16. HAN D.J., JEONG J.Y., CHOI J.H., CHOI Y.S., KIM H.Y., LEE M.A., LEE E.S., PAIK H.D., KIM C.J., 2007 – Effects of drying conditions on quality properties of pork jerky. ***Korean Journal for Food Science of Animal Resources***, 27(1), 29-34.
17. HAN G., CHEN Q., XIA X., LIU Q., KONG B., WANG H., 2021 – High hydrostatic pressure combined with moisture regulators improves the tenderness and quality of beef jerky. ***Meat Science*** 181, 108617.
18. HAN G., FAN Y., CHEN Q., XIA X., LIU Q., LI M., KONG B., 2023 – Quality and flavor changes in beef jerky caused by high hydrostatic pressure combined with moisture regulator treatments during storage. ***Food Science of Animal Products*** 1(1), 9240001.

19. HANDAYANI B.R., WERDININGSIH W., RAHAYU T.I., FAJRI A.Z., 2023 – Properties of ready to eat ground beef jerky with the addition of tapioca flour. AIP Conference Proceedings, 2586(August 2018).
20. HARMSEN M.C., SWART P.J., BÉTHUNE M.-P. DE, PAUWELS R., CLERCQ E. DE THE T.B., MEIJER D.K.F., 1995 – Antiviral effects of plasma and milk proteins: lactoferrin shows potent activity against both human immunodeficiency virus and human cytomegalovirus replication in vitro. ***The Journal of Infectious Diseases*** 172(2), 380-388.
21. HARRISON J.A., HARRISON M.A., ROSE R.A., 1998 – Survival of Escherichia coli O157:H7 in ground beef jerky assessed on two plating media. ***Journal of Food Protection***, 61(1), 11-13.
22. HERRERO A.M., ORDÓÑEZ J.A., DE AVILA R., HERRANZ B., DE LA HOZ L., CAMBERO M.I., 2007 – Breaking strength of dry fermented sausages and their correlation with texture profile analysis (TPA) and physico-chemical characteristics. ***Meat Science***, 77(3), 331-338.
23. HORBAŃCZUK J.O., SALES J., CELEDA T., KONECKA A., ZIĘBA G., KAWKA P., 1998 – Cholesterol content and fatty acid composition of ostrich meat as influenced by subspecies. ***Meat Science*** 50, 3, 385-388.
24. INGUGLIA E.S., OLIVEIRA M., BURGESS C.M., KERRY J.P., TIWARI B.K., 2020 – Plasma-activated water as an alternative nitrite source for the curing of beef jerky: Influence on quality and inactivation of Listeria innocua. ***Innovative Food Science and Emerging Technologies***, 59 (December 2019), 102276.
25. JIN S.K., CHOI J.S., YANG H.S., PARK T.S., YIM D.G., 2018 – Natural curing agents as nitrite alternatives and their effects on the physicochemical, microbiological properties and sensory evaluation of sausages during storage. ***Meat Science***, 146, 34-40.
26. JUNEJA V.K., VALENZUELA-MELENDRES M., HEPERKAN D., BAUTISTA D., ANDERSON D., HWANG C.-A., PEÑA-RAMOS A., CAMOU J.P., TORRENTERA-OLIVERA N., 2016 – Development of a predictive model for Salmonella spp. reduction in meat jerky product with temperature, potassium sorbate, pH, and water activity as controlling factors. ***International Journal of Food Microbiology***, 236, 1-8.
27. JUNG S., KIM H.J., PARK S., YONG H.I., CHOE J.H., JEON H.J., CHOE W., JO C., 2015 – Color developing capacity of plasma-treated water as a source of nitrite for meat curing. ***Korean Journal for Food Science of Animal Resources*** 35(5), 703-706.
28. JUNG S., LEE J., LIM Y., CHOE W., YONG H.I., JO C., 2017 – Direct infusion of nitrite into meat batter by atmospheric pressure plasma treatment. ***Innovative Food Science and Emerging Technologies*** 39, 113-118.
29. KARWOWSKA M., KONONIUK A., WÓJCIAK K.M., 2020 – Impact of sodium nitrite reduction on lipid oxidation and antioxidant properties of cooked meat products. ***Antioxidants*** 9(1), 9.
30. KILLINGER K.M., HUNT M.C., CAMPBELL R.E., KROPF D.H., 2000 – Factors affecting premature browning during cooking of store-purchased ground beef. ***Journal of Food Science*** 65(4), 585-588.
31. KIM J. W., LEE H.J., SHIN D.J., BAEK K.H., YONG H.I., JUNG S., Jo C., 2021 – Enrichment of nitrite in onion powder using atmospheric pressure plasma and egg whites for meat curing. ***Lwt*** 135 (July 2020), 110050.
32. KIM S.M., KIM T.K., KIM H.W., JUNG S., YONG H.I., CHOI Y.S., 2021 – Quality characteristics of semi-dried restructured jerky processed using super-heated steam. ***Foods*** 10(4), 1-13.
33. KONIECZNY P., STANGIERSKI J., KIJOWSKI J., 2007 – Physical and chemical characteristics and acceptability of home style beef jerky. ***Meat Science*** 76(2), 253-257.
34. Lee J., Jo K., Lim Y., Jeon H.J., Choe J. H., Jo C., Jung S., 2018 – The use of atmospheric pressure plasma as a curing process for canned ground ham. ***Food Chemistry*** 240, 430–436.

35. LEMMA B.B., LEE J.H., KANNAN G., KOUAKOU B., 2022 – Natural preservative properties of raisins in restructured goat meat (chevon) jerky. ***International Journal of Food Properties***, 25(1), 1736-1752.
36. Levy O., 2000 – Antimicrobial proteins and peptides of blood: Templates for novel antimicrobial agents. ***Blood*** 96(8), 2664-2672.
37. LORENZO J.M., GÓMEZ M., FONSECA S., 2014 – Effect of commercial starter cultures on physicochemical characteristics, microbial counts and free fatty acid composition of dry-cured foal sausage. ***Food Control*** 46, 382-389.
38. LUCKOSE F., PANDEY M.C., HARILAL P.T., 2017 – Effect of sodium chloride reduction on drying kinetics of restructured chicken jerky. ***Food Bioscience*** 19, 156-162.
39. LUO J., YAN W., NASIRU M.M., ZHUANG H., ZHOU G., ZHANG J., 2019 – Evaluation of physicochemical properties and volatile compounds of Chinese dried pork loin curing with plasma-treated water brine. ***Scientific Reports*** 9(1), 1-11.
40. LUO Y., ZHAO L., XU J., SU L., JIN Z., SU R., JIN Y., 2020 – Effect of fermentation and postcooking procedure on quality parameters and volatile compounds of beef jerky. ***Food Science and Nutrition*** 8(5), 2316-2326.
41. MARCINKOWSKA-LESIAK M., ALIREZALU K., STELMASIAK A., WOJTASIK-KALINOWSKA I., ONOPIUK A., SZPICER A., POLTORAK A., 2023 – Physicochemical characteristics of pork liver pâtés containing nonthermal air plasma-treated egg white as an alternative source of nitrite. ***Applied Sciences*** (Switzerland), 13(7), 4464.
42. MARCINKOWSKA-LESIAK M., WOJTASIK-KALINOWSKA I., ONOPIUK A., STELMASIAK A., WIERZBICKA A., POLTORAK A., 2022a – Application of atmospheric pressure cold plasma activated plant protein preparations solutions as an alternative curing method for pork sausages. ***Meat Science*** 187 (February), 108751.
43. MARCINKOWSKA-LESIAK M., WOJTASIK-KALINOWSKA I., ONOPIUK A., STELMASIAK A., WIERZBICKA A., POLTORAK A., 2022b – Green technology for pork loin wet curing–unconventional use of cow and soy milk treated with non-thermal atmospheric plasma. ***Foods*** 11(16), 2523.
44. MARCINKOWSKA-LESIAK M., WOJTASIK-KALINOWSKA I., ONOPIUK A., STELMASIAK A., WIERZBICKA A., PÓŁTORAK A., 2022 – Plasma-activated milk powder as a sodium nitrite alternative in pork sausages. ***Meat Science*** 192(June), 108880.
45. MENG D., YANG X., LIU H., ZHANG D., HOU C., WANG Z., 2022 – Effect of cold-plasma-treated phosphate solution to substitute partial nitrite on the color, texture, and flavor of smoked sausage. ***Bioengineering*** 9(12), 794.
46. MODI V. K., MAHENDRAKAR N.S., NARASIMHA RAO D., SACHINDRA N.M., 2004 – Quality of buffalo meat burger containing legume flours as binders. ***Meat Science***, 66(1), 143-149.
47. MORR C.V., 1989 – Beneficial and adverse effects of water-protein interactions in selected dairy products. ***Journal of Dairy Science*** 72(2), 575-580.
48. NADER M., HOSSEININEZHAD B., BERIZI E., MAZLOOMI S.M., HOSSEINZADEH S., ZARE M., DERAKHSHAN Z., CONTI G.O., FERRANTE M., 2022 – The residual nitrate and nitrite levels in meat products in Iran: A systematic review, meta-analysis and health risk assessment. ***Environmental Research*** 207, 112180.
49. NUMMER B.A., HARRISON J.A., HARRISON M.A., KENDALL P., SOFOS J.N., ANDRESS E.L., 2004 – Effects of preparation methods on the microbiological safety of home-dried meat jerky. ***Journal of Food Protectio***n 67(10), 2337-2341.
50. PARÉS D., SAGUER E., CARRETERO C., 2011 – Blood by-products as ingredients in processed meat. In Processed Meats: Improving safety, nutrition and quality. Woodhead Publishing Limited.

https://doi.org/10.1533/9780857092946.2.218.

51. PEGG R. B., SHAHIDI F., 2000 – The N-Nitrosamine Problem and Nitrite Alternatives. Nitrite Curing of Meat.
52. PEGG R.B., SHAHIDI F., 2004 – Heat effects on meat. Flavour development. Encyclopedia of ***Meat Sciences*** 1, 570-578.
53. PIKUL J., LESZCZYNSKI D.E., KUMMEROW F.A., 1989 – Evaluation of three modified tba methods for measuring lipid oxidation in chicken meat. ***Journal of Agricultural and Food Chemistry*** 37(5), 1309-1313.
54. PILASOMBUT K., SORAPUKDEE S., CHETAWAN T., NGAMYEESOON N., 2019 – Effect of glycerol on improving quality of ready to eat Nham jerky, an innovation of Thai fermented meat product. ***International Journal of Agricultural Technology***, 15(2), 333-346.
55. QIAN J., YAN L., YING K., LUO J., ZHUANG H., YAN W., ZHANG J., ZHAO Y., 2022 – Plasma-activated water: A novel frozen meat thawing media for reducing microbial contamination on chicken and improving the characteristics of protein. ***Food Chemistry*** 375, 131661.
56. RIPOLL G., ALCALDE M.J., HORCADA A., PANEA B., 2011 – Suckling kid breed and slaughter weight discrimination using muscle colour and visible reflectance. ***Meat Science***, 87(2), 151-156.
57. RUDY M., KUCHARYK S., DUMA-KOCAN P., STANISLAWCZYK R., GIL M., 2020 – Unconventional methods of preserving meat products and their impact on health and the environment. ***Sustainability*** (Switzerland), 12(15), 5948.
58. SCHEINBERG J.A., SVOBODA A.L., CUTTER C.N., 2014 – High-pressure processing and boiling water treatments for reducing Listeria monocytogenes, Escherichia coli O157:H7, Salmonella spp., and Staphylococcus aureus during beef jerky processing. ***Food Control*** 39, 105-110.
59. SERDAROGLU M., YILDIZ TURP G., ABRODÍMOV K., 2005 – Quality of. low-fat meatballs containing Legume flours as extenders. ***Meat Science*** 70, 99-105.
60. SHI S., ZHAO M., LI Y., KONG B., LIU Q., SUN F., YU W., XIA X., 2021 – Effect of hot air gradient drying on quality and appearance of beef jerky. ***Lwt*** 150 (February), 111974.
61. SIEKMANN L., PLÖTZ M., KRISCHEK C., 2021 – Alternative curing methods. Current clinical ***Microbiology Reports*** 8(2), 40-48.
62. SILVA V.D.M., SILVESTRE M.P.C., 2003 – Functional properties of bovine blood plasma intended for use as a functional ingredient in human food. ***LWT - Food Science and Technology*** 36(7), 709-718.
63. SUCU C., TURP G.Y., 2018 – The investigation of the use of beetroot powder in Turkish fermented beef sausage (sucuk) as nitrite alternative. ***Meat Science*** 140 (February), 158-166.
64. US DEPARTMENT OF AGRICULTURE, F.S.I.S., 2014 – FSIS Compliance guideline for meat and poultry jerky produced by small and very small establishments. 1–54. https://www.fsis.usda.gov/guidelines/2014-0010
65. WOJTASIK-KALINOWSKA I., GUZEK D., GÓRSKA-HORCZYCZAK E., GŁABSKA D., BRODOWSKA M., SUN D.W., WIERZBICKA A., 2016 – Volatile compounds and fatty acids profile in Longissimus dorsi muscle from pigs fed with feed containing bioactive components. ***LWT - Food Science and Technology*** 67, 112-117.
66. YANG H.S., HWANG Y.H., JOO S.T., PARK G.B., 2009 – The physicochemical and microbiological characteristics of pork jerky in comparison to beef jerky. ***Meat Science***, 82(3), 289-294.
67. YEUNG A.W.K., CHOUDHARY N., TEWARI D., EL-DEMERDASH A., TOMCZYK M., DAS N., PIRGOZLIEV V., LUCARINI M., DURAZZO A., SOUTO E.B., SANTINI A., DEVKOTA H.P., UDDIN M.S., ECHEVERRÍA J., WANG D., GAN R-Y., BRNČIĆ M., KALFIN R.E., DE R., CENANOVIC M., SAI C.S., KAPOOR B., KIRILOV K., TZVETKOV N.T., BELAKOVA

B., UHRIN P., JÓŹWIK A., HORBANCZUK O.K., STRZAŁKOWSKA N., KOSZARSKA M., CHARUTA A., HORBAŃCZUK J.O., ATANASOV A.G., 2022 – Lycopene: total-scale literature landscape analysis of a valuable nutraceutical with numerous potential applications in the promotion of human and animal health . ***Animal Science Papers and Reports*** 40, 2, 119-134.

68. YEUNG A.W.K., CHOUDHARY N., TEWARI D., EL-DEMERDASH A., HORBANCZUK O.K., DAS N., PIRGOZLIEV V., LUCARINI M., DURAZZO A., SOUTO E.B., SANTINI A., DEVKOTA H.P., UDDIN M.S., ECHEVERRIA J., WANG, D., GAN, R.Y., BRNCIC M., KALFIN R.E., TZVETKOV N.T., JOZWIK A., SOLKA M., STRZALKOWSKA N., HORBANCZUK J.O., ATANASOV A.G., 2021a – Quercetin: total-scale literature landscape analysis of a valuable nutraceutical with numerous potential applications in the promotion of human and animal health – a review. ***Animal Science Papers and Reports*** 39, 199-212.
69. YEUNG A.W.K., TZVETKOV N.T., EL-DEMERDASH A., HORBANCZUK O.K., DAS N., PIRGOZLIEV V., LUCARINI M., DURAZZO A., SOUTO E.B., SANTINI A., DEVKOTA H.P., UDDIN M., ECHEVERRÍA J., WANG D., GAN R.Y., BRNČIĆ M., KALFIN R., TANCHEVA L.P., TEWARI D., BERINDAN-NEAGOE I., SAMPINO S., STRZAŁKOWSKA N., MARCHEWKA J., JOZWIK A., HORBANCZUK J. O., ATANASOV A.G., 2021b – Apple polyphenols in human and animal health. ***Animal Science Papers and Repor***ts 39, 105-118.
70. YONG H.I., PARK J., KIM H.J., JUNG S., PARK S., LEE H. J., CHOE W., JO C., 2018 – An innovative curing process with plasma-treated water for production of loin ham and for its quality and safety. ***Plasma Processes and Polymers*** 15(2), 1-9.
71. ZDANOWSKA-SĄSIADEK Ż., MARCHEWKA J., HORBAŃCZUK J.O., WIERZBICKA A., LIPIŃSKA P., JÓŹWIK A., ATANASOV A.G., HUMINIECKI Ł., SIEROŃ A., SIEROŃ K., STRZAŁKOWSKA N., STELMASIAK A., DE SMET S., VAN HECKE T., HOFFMAN L.C., 2018 – Nutrients composition in fit snacks made from ostrich, beef and chicken dried meat. ***Molecules*** 23, 1267.
72. ZHANG W.K., ZHANG C., QI B., MUJUMDAR A.S., XIE L., WANG H., NI J.B., XIAO H.W., 2022 – Hot-air impingement roast drying of beef jerky: Effect of relative humidity on quality attributes. ***Drying Technology*** 41(2), 277-289.
73. ZHAO L., JIN Y., MA C., SONG H., LI H., WANG Z., XIAO S., 2011 – Physico-chemical characteristics and free fatty acid composition of dry fermented mutton sausages as affected by the use of various combinations of starter cultures and spices. ***Meat Science*** 88(4), 761-766.