

Article

Quality Evaluation of Ostrich Semi-Fine Sausages with Reduced Sodium Nitrite Levels in the Context of Regulatory Changes

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Abstract

The aim of this study was to analyze the impact of reducing sodium nitrite (NaNO_2) content on the quality of selected meat products in the context of changing legal regulations governing its use. The research material consisted of ostrich semi-fine sausage prepared in four variants: V1 (150 mg/kg NaNO_2), V2 (120 mg/kg NaNO_2), V3 (60 mg/kg NaNO_2), and V4 (0 mg/kg NaNO_2). The scope of this study included evaluation of production yield, pH value, basic composition, residual nitrite content, color, texture, volatile compound profile, semi-consumer evaluation, and statistical analysis. A significant effect of NaNO_2 level, storage time, and their interaction was observed on most physicochemical parameters. No statistically significant differences were found in water, protein, fat, or salt content. Variant V2 demonstrated good color stability and high sensory acceptability, while V3 showed a noticeable decrease in color intensity and a less favorable aroma profile. The results indicate that reducing NaNO_2 content affects product quality, and its total elimination may require the use of alternative preservation methods.

Keywords: ostrich sausage; sodium nitrite; chemical composition; color; pH; texture; residual nitric level; sensory evaluation



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1. Introduction

Currently, consumers focus on healthy eating and prefer lean and tasty meat with good culinary, nutritional, and technological properties [1]. Ostrich meat is a nutritionally beneficial raw material to produce meat products. It is characterized by a low intramuscular fat content and a favorable fatty acid ratio [2,3], which largely depends on the type of feeding. Furthermore, ostrich meat is characterized by high nutritional properties, such as low sodium content and high iron, phosphorus, and manganese content compared to meats from other species, as well as exceptional flavor [3,4]. The main products made from ostrich meat include fresh meat, sausages and pates [4–7], and the production of meat products involves the use of preservatives.

Preservatives are chemical compounds added to food in small amounts (usually in the 0.1–0.2% range), whose primary purpose is to prevent unfavorable microbiological changes, such as the growth of bacteria, molds, or yeasts, thereby extending the shelf life of food products [8,9]. Effective preservatives should exhibit antimicrobial activity even

at low concentrations, be resistant to high temperatures, oxidation, and acidic environments, and not adversely affect the product's organoleptic properties. Furthermore, they should be highly water-soluble and non-toxic in recommended amounts. The most used preservatives include benzoic acid (E210), sodium benzoate (E211), p-hydroxybenzoic acid ethyl ester (E214), nisin (E234), and propionic acid (E280). In accordance with applicable regulations, the use of nitrites is also permitted in meat processing and cheesemaking. These are the salts of nitric acid and nitrous acid with sodium or potassium, respectively: sodium nitrate (NaNO_3), potassium nitrate (KNO_3), sodium nitrite (NaNO_2), and potassium nitrite (KNO_2). Each of these compounds has been assigned an "E" number in accordance with the European Food Safety Agency (EFSA) classification: E249— KNO_2 , E250— NaNO_2 , E251— NaNO_3 , and E252— KNO_3 .

Nitrates do not exhibit direct antimicrobial activity, but after microbiological conversion in organisms or food to nitrites, they become active against anaerobic bacteria, including *Clostridium botulinum*—the microorganism responsible for the production of botulinum toxin [10,11], as well as Gram-negative bacteria of the *Salmonella* genus, and, to a lesser extent, *Staphylococcus aureus* and *Listeria monocytogenes* [12,13]. Their use stabilizes meat color through the formation of nitrosomyoglobin and inhibits bacteria through the formation of nitrolic acids and the binding of nitrogen oxides to hemoproteins, resulting in the blocking of enzymatic systems, including dehydrogenases. It is worth noting, however, that nitrites do not inhibit the growth of yeasts and molds, and their presence in food can lead to the formation of nitrosamines—potentially carcinogenic compounds of meat [14–16].

The use of curing mixtures containing nitrates or nitrites to preserve meat is one of the oldest methods of meat preservation, known as curing. Curing aims to extend the shelf life of products and impart the characteristic flavor, aroma, and color typical of cured meat [17,18]. The effectiveness of the process depends on the quality of the raw material and the technological conditions. The characteristic pink color of cured meat results from the formation of nitrosylmyochromogen—a stable pigment formed by the reaction of nitric oxide with myoglobin during heat treatment. In addition, the binding of nitric oxide to heme iron limits oxidative reactions by reducing the availability of reactive oxygen species, thereby contributing to greater oxidative stability of the product. Moreover, nitrites influence the aromatic profile and taste of meat products through interactions with other meat components, such as amino acids [12,14,16,19].

Despite their preservative properties, nitrites can react with secondary and tertiary amines, leading to the formation of N-nitrosamines—compounds with documented carcinogenic properties. The concentration of these compounds is closely correlated with the amount of nitrites used in the curing process [20]. Excessive presence of these compounds may not only have toxicological effects but also contribute to the formation of nitroso compounds in the gastrointestinal tract and negatively impact the nutritional value of products by reducing the absorption of β -carotene, B vitamins, and proteins. Furthermore, NaNO_2 provides an additional source of sodium in the diet.

The International Agency for Research on Cancer [21] confirmed the link between preformed nitrosamines and the risk of colon cancer and pointed to a link between dietary nitrites and stomach cancer. Of particular note is a study conducted by scientists from Queen's University Belfast, which showed that the consumption of nitrate-preserved meat increases the risk of developing colon cancer. A study on mice with adenomatous polyposis showed that an 8-week diet containing 15% nitrite-preserved hot dogs increased the number of tumors by 53% compared to the control group, and markers of lipid peroxidation in urine and serum were 59% and 108% higher, respectively [22].

For this reason, nitrites should be used in the food industry in quantities necessary to achieve the intended technological purpose, but no greater than necessary. Legislation in this area aims to strike a balance between the risk of nitrosamine formation in meat products associated with the presence of nitrites and the benefits resulting from their impact on food safety (inactivation of bacteria, particularly *Clostridium botulinum*, which poses a significant health risk to consumers). In 2023, Commission Regulation (EU 2023/2108) [23] was issued, which updated the method of expressing maximum nitrite and nitrate levels—not as sodium salts, but as nitrite and nitrate ions, in line with the ADI values. The FAO/WHO Joint Expert Committee on Food Additives (JECFA) established an ADI of 0–0.07 mg/kg/bw, expressed as nitrite ion [24]. Conversion factors were also introduced by EU Regulations: 0.67 for NaNO₂ to nitrite ion and 0.73 for NaNO₂ to nitrate ion. The maximum permissible levels of nitrite ions are: 80 mg/kg in unprocessed and heat-treated meat products (with a residual level of up to 45 mg/kg), 55 mg/kg in sterilized products ($F^\circ > 3.00$) with a residual level of 25 mg/kg, and up to 105 mg/kg in traditional meat products (with a residual level of up to 50 mg/kg). The regulations also require monitoring of the residual level of nitrite in the finished product throughout its shelf life. Exceeding this limit requires analysis of the causes and taking corrective action by the manufacturer.

In this context, the appropriate formulation and processing of meat products is therefore crucial. The use of nitrites in legally permitted amounts, the use of fresh meat, and low cooking temperatures reduce the amount of nitrosamines in the final product. Furthermore, the use of natural antioxidants, such as vitamins C and E, can neutralize reactive nitrogen compounds, inhibiting the formation of nitrosamines. Similarly, storage at low temperatures can reduce the risk of reactions between nitrites and amines derived from meat proteins, which contributes to a safer curing process [14–16]. Taking into account the increasing regulatory restrictions and consumer concerns regarding nitrite use, it is essential to evaluate the technological, sensory, and safety implications of reducing NaNO₂ levels in meat formulations.

Compared with beef and pork, the technological properties of ostrich meat has been studied much less extensively, despite its growing use in meat processing [25]. Nevertheless, the high pH of ostrich meat increases its susceptibility to microbial spoilage during storage [26]. Recent studies on ostrich meat also indicate that this species contains higher levels of myoglobin (and thus iron) as well as a greater proportion of unsaturated fatty acids compared with, for example, beef or chicken, which contributes to its lower oxidative stability [27]. In such meats, nitrite plays a crucial role by limiting microbial growth, reducing oxidation, and stabilizing pigment reactions, thereby decreasing metmyoglobin formation and supporting the development of the characteristic cured color. At the same time, nitrite contributes to flavor formation and stability in ostrich meat. According to the literature, its effect on the aroma profile results from two concurrent mechanisms: a strong antioxidant action that decreases the formation of lipid-derived aldehydes responsible for rancid off-flavors, and nitrite-dependent reactions that generate characteristic cured-meat aroma compounds (e.g., Strecker aldehydes) [28]. Previous studies have noted a lack of supporting data regarding the characteristics of ostrich meat relevant to its incorporation into processed ostrich meat products [29]. Given these factors, evaluating the effect of nitrite addition on the quality attributes and storage stability of ostrich meat products becomes essential. Therefore, the aim of this study was to evaluate the effect of NaNO₂ (E250) content on the quality of ostrich semi-fine sausages stored for 14 days under refrigerated conditions.

2. Material and Methods

2.1. Material

The raw materials used in this study included ostrich meat originating from the *musculus gluteus medius*, sourced from “Strusia Kraina & MOBAX” Sp. j. (Bobrowniki, Poland). The meat was obtained from animals slaughtered under standard commercial conditions and delivered to the laboratory under refrigerated conditions (≤ 4 °C) approximately 24 h post-mortem. Pork jowl was obtained from the “Koniarek” meat processing plant (Kozia Góra, Poland). All ingredients were stored and handled in accordance with food safety and quality standards prior to their use in experimental procedures.

The four sausage variants ostrich sausages were produced in three independent batches in a randomized order (the detailed composition of each formulation is presented in Table 1).

Table 1. Formulation of analyzed ostrich meat sausages.

Ingredients (%)	Variant 1	Variant 2	Variant 3	Variant 4
Ostrich meat	70	70	70	70
Pork yowl	30	30	30	30
Salt	2.5	2.5	2.5	2.5
NaNO ₂	0.015	0.012	0.006	-
Sodium polyphosphate	0.25	0.25	0.25	0.25
Fresh garlic	0.15	0.15	0.15	0.15
Ground white pepper	0.07	0.07	0.07	0.07
Nutmeg	0.03	0.03	0.03	0.03
Ice water	10	10	10	10

For each treatment, 700 g of the meat mixture was portioned into cubes and comminuted using a grinder (EDES PI-32-T, Madrid, Spain) equipped with a 4.5 mm plate for both meat and fat. Subsequently, the meat and non-meat ingredients were homogenized using a planetary mixer (Multi-Function All-in-One Cooker, Heavy Duty 5KSM7591X, KitchenAid, St. Joseph, MI, USA). The resulting batters were then filled into natural pork casings (30–32 mm in diameter) employing the same KitchenAid mixer fitted with a sausage stuffer attachment (KitchenAid, St. Joseph, MI, USA). After setting (1 h at 8–10 °C), the sausages were cooked in a convection oven (CPE 110, Küppersbusch, Gelsenkirchen, Germany) until an internal temperature of 72 °C was reached (process temperature 93 °C), followed by rapid cooling in an ice bath and cold air to 4–6 °C.

Samples were packed in PA/PE bags and stored under refrigerated conditions (4 ± 1 °C) at approximately 90% vacuum. Analyses were conducted on days 1, 7, and 14 of storage. Three sausages were prepared per replication for each sampling day.

2.2. Analysis

2.2.1. Production Efficiency Assessment

A weight-based method was used to calculate production efficiency. All variants were weighed before heat treatment, and the procedure was repeated after steaming and cooling. Production efficiency was calculated for three independent production batches prepared under identical processing conditions as the ratio of mass after heat treatment to mass before heat treatment, expressed as a percentage [30].

2.2.2. Basic Chemical Composition

The water, protein, fat, and salt content of all product variants was determined using a NIRFlex N-500 spectrometer (Büchi Labortechnik AG, Flawil, Switzerland). Samples for analysis were prepared by homogenizing 100 g of product using a B-400 homogenizer

(Büchi Labortechnik AG) and then applying the sample to a Petri dish in a 0.5 cm thick layer, evenly covering its surface. Measurements were performed in reflectance mode using the NIRFlex Solids module, within the spectral range of 12,500–400 cm^{-1} . Three independent replicates were performed for each variant.

2.2.3. pH Measurement

The pH of the finished products was measured according to method described by Marcinkowska et al. [31], using a Testo 205 pH meter equipped with an integrated penetration electrode. Three measurements were performed for each variant at three storage time points: days 1, 7, and 14.

2.2.4. Color Parameters Measurement

Color measurement was performed using a Konica Minolta CR-400 colorimeter, previously calibrated against a white standard ($L^* = 98.45$; $a^* = -20.10$; $b^* = -20.13$). Analysis was performed in six replicates for each product variant, at three points: 1, 7, and 14 days of storage.

Based on the obtained a^* and b^* coordinates, chroma (C^*) was calculated according to Formula (1) [32]:

$$C^{*2} = \sqrt{(a^*)^2 + (b^*)^2} \quad (1)$$

To assess color variability, the hue angle (H°) was also determined, calculated according to the following Formula (2):

$$H^\circ = \arctan \frac{b^*}{a^*} \quad (2)$$

2.2.5. Instrumental Texture Analysis

The mechanical properties of the products were evaluated using Texture Profile Analysis (TPA) with an Instron 5965 Universal Testing Machine (Instron, Norwood, MA, USA), in accordance with the methodology described by Marcinkowska et al. [31]. For this purpose, 25 mm thick sausage slices were cut to cylinder-shapes, 25.4 mm in diameter and then they underwent two cycles of 50% compression. The following texture parameters were determined as part of the analysis: hardness (N), springiness (-), cohesiveness (-), adhesiveness (J/cm^2). Six cores from each treatment were tested per batch.

2.2.6. Determination of Residual Nitrite Levels

Residual nitrite content in the analyzed variants was determined according to the modified AOAC method no. 973.31 according to Lee et al. [10]. For this purpose, 10 g of homogenized meat product was thoroughly mixed with 150 mL of water at 80 °C. Then, 10 mL of 0.5 M NaOH was added and thoroughly mixed again. The same process was repeated with 12% zinc sulfate. The resulting mixture was heated in a stirred water bath at 80 °C for 20 min and then cooled in water for 10 min. The next step was to add 2 mL of 10% ammonium acetate (pH 9.1), mix thoroughly, and filter through filter paper (Whatman no. 4). To 20 mL of filtrate, 1 mL of a 30 mM solution of sulfanilamide in acidic solution ($\text{HCl}:\text{H}_2\text{O}$, 1:1, v/v) and 1 mL of 5 mM N-(1-naphthyl)ethylenediamine dihydrochloride were added, and the volume was adjusted to 25 mL with deionized water. After 20 min, the absorbance was read at 540 nm using a Spark 10M multimodal microplate reader (Spark™ 10M, Tecan Group, Männedorf, Switzerland). The concentration of nitrite ions in the samples was calculated based on a previously prepared calibration curve, generated from the absorbance readings of standard NaNO_2 solutions. Triplicate measurements were performed for each sample.

2.2.7. Volatile Compound Profile

The volatile compound profiles of the four analyzed ostrich sausage variants were identified using a Heracles II electronic nose (Alpha M.O.S., Toulouse, France). Approximately 2 g of each sausage sample was placed in 20-mL headspace vial sealed with a Teflon-coated silicone rubber stopper and then processed according to the methodologies described by Wojtasik-Kalinowska et al. [33] and Górska-Horczyzak et al. [34]. Identification of volatile compounds was performed using the AroChemBase database (Alpha MOS Co., Toulouse, France). The volatile compound profile analysis was performed in triplicate for each variant.

2.2.8. Semi-Consumer Evaluation

To evaluate the sensory acceptability of sausages 24 h after production, a semi-consumer test was conducted, focusing on organoleptic characteristics influencing consumer purchasing decisions. This study was conducted on a group of 30 sensory-neutral participants. A five-point hedonic scale was used, with the following ratings: 1—definitely not acceptable, 2—somewhat unacceptable, 3—neither acceptable nor unacceptable, 4—somewhat acceptable, and 5—definitely acceptable. Four sensory attributes were assessed: color, texture, aroma, and overall impression. Each participant received samples of all variants under identical serving conditions, with randomly assigned code numbers to eliminate order bias. Samples were stored under refrigeration until served.

2.3. Statistical Analysis

The obtained physicochemical data were statistically analyzed using Statistica 13.3 (StatSoft Inc., Tulsa, OK, USA). For production efficiency (PEF), basic chemical composition, and sensory evaluation results, a one-way analysis of variance (ANOVA) was performed, taking into account only the effect of the NaNO₂ addition level. For pH, color parameters, texture characteristics, and residual nitrite content, a two-way ANOVA was applied, considering two independent factors: NaNO₂ addition level (group—G) and storage time (day—D), as well as their interaction (G × D). When statistically significant differences were found ($p < 0.05$), Tukey's post hoc test was used to identify significant differences between means. For aroma profile data, principal component analysis (PCA) was performed using Alpha Soft Version 8.0 (Alpha MOS, Toulouse, France). The results for physicochemical parameters are expressed as mean ± standard deviation (SD), and for sensory analysis as mean ± standard error (SE).

3. Results and Discussion

3.1. Physicochemical Parameters

3.1.1. Production Efficiency, Basic Composition and pH

The average production efficiency was $93.03 \pm 1.26\%$ ranging from 90.74% to 94.78% and indicating little variation between the formulation groups ($p \geq 0.05$). The obtained data suggest that the presence or absence of NaNO₂ (E250) at the levels used did not significantly impact the efficiency of the technological process for producing cooked ostrich sausages. This observation is consistent with the findings of Marcinkowska-Lesiak et al. [31], who reported no significant differences in cooking loss between nitrite-free sausages (NC) and those cured conventionally with NaNO₂ (PC).

There were no statistically significant differences ($p \geq 0.05$) in water, protein, fat, or salt content between groups with different levels of NaNO₂ addition, nor in relation to storage time or their interactions. Average content of water, protein, fat and salt in studied was 64.59 ± 0.36 , 16.69 ± 0.29 , 13.6 ± 0.35 and 1.6 ± 0.15 , respectively. These results indicate that variations in NaNO₂ concentration in the formulation, as well as storage time, did

not affect the basic chemical composition of the ostrich sausages. This is consistent with the fact that NaNO_2 primarily acts as a color stabilizer, antioxidant, and antimicrobial agent, rather than influencing the moisture or macronutrient balance of the product [31]. The obtained values are comparable to those reported by Hoffman and Mellet [35], who found similar protein (13.35%) and fat (14.85%) contents in ostrich sausages, confirming the reproducibility of ostrich meat composition. Furthermore, Fernández-López et al. [36] documented that ostrich sausages are characterized by a high protein content, which is also confirmed by the obtained results and highlights the beneficial nutritional profile of ostrich meat.

One-way ANOVA indicated that the NaNO_2 level did not significantly affect production efficiency (PEF) or basic chemical composition. However, two-way ANOVA revealed significant effects of NaNO_2 level (TS), storage time (ST), and their interaction (TS $\times$ ST) on most of the remaining physicochemical parameters, including pH, color (except the L^* values), texture, and residual nitrite content.

Analysis of the pH values of ground ostrich sausages stored for 14 days under refrigeration conditions revealed significant changes related to both storage time and NaNO_2 concentration (Table 2).

Table 2. Effect of NaNO_2 level on the pH value and of ostrich sausages during 14 days of refrigerated storage.

Item	Time of Storage, Day		Group				Influence		Interaction TS $\times$ G
			V1 ¹	V2	V3	V4	Time of Storage (TS)	Group (G)	
pH	1	Mean	6.30 ^{aA 2}	6.30 ^{aBA}	6.32 ^{aBA}	6.32 ^{aA}	** 3	**	***
		$\pm$ SD	0.01	0.01	0.01	0.01			
	7	Mean	6.30 ^{aA}	6.31 ^{aA}	6.32 ^{aA}	6.34 ^{bB}			
		$\pm$ SD	0.01	0.01	0.01	0.01			
	14	Mean	6.29 ^{aA}	6.34 ^{bB}	6.42 ^{bD}	6.37 ^{cC}			
		$\pm$ SD	0.01	0.01	0.01	0.01			

¹ V1—meat products with 150 ppm NaNO_2 added; V2—meat products with 120 ppm NaNO_2 added; V3—meat products with 60 ppm NaNO_2 added; V4—meat products without NaNO_2 added. ² Lowercase letters (a–c) in a column denote significant statistical differences ($p < 0.05$) between storage days within the same group; uppercase letters (A–C) in a row denote significant statistical differences ($p < 0.05$) between groups with different NaNO_2 levels on the same storage day. ³ NS—no significant statistical differences; ($p \geq 0.05$)—significance at the level of $p < 0.05$; **—significance at the level of $p < 0.01$; ***—significance at the level of $p < 0.001$.

Significant effect on pH of both sausage type and storage time ($p < 0.01$) was found, as well as an interaction between these factors ($p < 0.001$), suggesting that changes in pH over time were dependent on the level of NaNO_2 added. The content of nitrite ions varied significantly, presenting higher springiness than the control, depending on their addition to sausage ($p < 0.001$), whereas storage time did not influence the independent factor (NS). On day 1, mean pH values in all groups (V1–V4) were similar and ranged within a narrow range from 6.30 to 6.32, with no significant statistical differences between groups ($p \geq 0.05$). However, significant variation in pH was observed both within and between groups with increasing storage time. On day 7 of storage, the pH in variant V4 (without NaNO_2) was significantly higher than in the other samples ($p < 0.05$), which may suggest faster microflora development or intensified biochemical changes in the preservative-free sample. These differences intensified after 14 days of storage—the pH in group V3 (60 ppm) reached 6.42, and in V4—6.37, which was significantly higher than in groups V1 and V2 (6.29–6.34). Statistically significant differences between storage days within individual groups confirm that pH levels were dependent on storage time. At the same time, significant differences between groups on the same day indicate that the degree of NaNO_2 addition affected the stability of the product's pH. The higher pH observed in sausages with reduced nitrite levels may indicate lower effectiveness in suppressing microbial activity or enzymatic protein degradation, both of which are important for the microbiological stability and

sensory quality of the product [37]. Similar effects were reported by Karwowska et al. [38], who observed that cooked pork products without nitrite (PP0) exhibited significantly higher pH values than nitrite-containing variants (PP50–PP150), indicating greater susceptibility to microbial spoilage. Their results also confirmed that the acidity of samples with NaNO₂ remained stable throughout storage, whereas its reduction led to a significant pH increase, indicating reduced microbiological stability in nitrite-free formulations.

3.1.2. Color Parameters

The L* parameter values (Table 3) did not show significant statistical differences ($p \geq 0.05$) between storage days or treatment groups, indicating a stable product lightness regardless of NaNO₂ addition.

Table 3. Effect of NaNO₂ level on color parameters of ostrich sausages during 14 days of refrigerated storage.

Item	Time of Storage, Day		Group				Influence		Interaction
			V1 ¹	V2	V3	V4	Time of Storage (TS)	Group (G)	
L*	1	Mean	52.72	53.76	55.86	56.25	NS ³	NS	NS
		±SD	1.86	2.47	2.38	1.95			
	7	Mean	52.42	54.63	53.92	54.88			
		±SD	0.72	2.11	1.72	0.86			
	14	Mean	54.71	54.38	54.47	55.06			
		±SD	1.27	2.03	3.66	1.72			
a*	1	Mean	21.21 ^{2aB}	19.89 ^{aB}	20.66 ^{bB}	12.56 ^{aA}	*	***	***
		±SD	0.30	1.66	0.88	0.63			
	7	Mean	18.59 ^{aB}	16.89 ^{aB}	14.07 ^{aB}	8.50 ^{aA}			
		±SD	2.68	1.85	1.48	4.46			
	14	Mean	7.46 ^{aB}	6.73 ^{aB}	6.05 ^{aB}	7.09 ^{aB}			
		±SD	0.18	0.90	1.10	0.54			
b*	1	Mean	7.46 ^b	6.73 ^a	6.05 ^a	7.09 ^a	*	NS	NS
		±SD	0.18	0.90	1.10	0.54			
	7	Mean	7.04 ^a	7.29 ^{ab}	7.24 ^{ab}	7.59 ^a			
		±SD	0.41	0.82	0.20	0.23			
	14	Mean	7.23 ^{ab}	8.02 ^b	8.38 ^b	9.35 ^b			
		±SD	0.68	1.0	1.71	2.56			
C*	1	Mean	23.30 ^{aB}	22.50 ^{aB}	21.12 ^{bB}	13.72 ^{aA}	NS	***	***
		±SD	0.31	1.2	1.67	0.57			
	7	Mean	22.35 ^{aB}	21.19 ^{aB}	21.90 ^{bB}	14.68 ^{aA}			
		±SD	0.39	1.84	0.85	0.66			
	14	Mean	19.9 ^{aB}	18.74 ^{aB}	16.47 ^{aAB}	13.25 ^{aA}			
		±SD	2.33	1.29	0.79	1.70			
H°	1	Mean	0.33 ^{aA}	0.30 ^{aA}	0.29 ^{aA}	0.54 ^{aA}	*	***	***
		±SD	0.01	0.03	0.04	0.02			
	7	Mean	0.32 ^{aA}	0.35 ^{aA}	0.34 ^{aA}	0.54 ^{aA}			
		±SD	0.02	0.01	0.02	0.01			
	14	Mean	0.38 ^{aA}	0.45 ^{aA}	0.54 ^{aAB}	0.86 ^{aB}			
		±SD	0.08	0.09	0.13	0.36			

¹ V1—meat products with 150 ppm NaNO₂ added; V2—meat products with 120 ppm NaNO₂ added; V3—meat products with 60 ppm NaNO₂ added; V4—meat products without NaNO₂ added. ² Lowercase letters (a–b) in a column denote significant statistical differences ($p < 0.05$) between storage days within the same group; uppercase letters (A–B) in a row denote significant statistical differences ($p < 0.05$) between groups with different NaNO₂ levels on the same storage day. ³ NS—no significant statistical differences; ($p \geq 0.05$) *—significance at the level of $p < 0.05$; **—significance at the level of $p < 0.01$; ***—significance at the level of $p < 0.001$.

The L* values ranged from 52.42 to 56.25, indicating a moderately light color typical of steamed products, which is consistent with the characteristics reported for cooked ostrich sausages [36]. These findings are also in line with the results of Marcinkowska-Lesiak et al. [39], who observed that the lightness (L*) of cooked pork sausages remained relatively stable during refrigerated storage, with no significant differences between conventionally cured and nitrite-free samples. The authors concluded that NaNO₂ has a limited effect on surface brightness, as its primary role concerns the stabilization of red pigments rather than overall lightness. Similarly, Cavalheiro et al. [40]

reported that in fermented sausages containing ostrich meat, L^* values remained stable across formulations, suggesting that changes in meat composition or curing conditions had minimal influence on product lightness. This stability in lightness may be related to the natural color characteristics of ostrich meat and the gentle steaming process, which prevents surface darkening.

The a^* parameter (redness) was characterized by statistically significant differences between groups, particularly evident on day 14 (Table 3, $p < 0.05$). The highest a^* values were recorded on all days in group V1 (150 ppm NaNO_2) across all analyzing days, while the lowest were recorded in the control group V4 (without nitrite). The decrease in a^* values in all groups over 14 days of storage confirms the natural degradation of meat pigments, although the presence of nitrite significantly slowed this process. These findings are consistent with earlier studies indicating that nitrite forms nitrosyl complexes which preserve the typical pink-red color of cured products. Similar results were reported by Wójciak et al. [41], who demonstrated that nitrite levels above 100 mg/kg effectively stabilized the cured color of roasted beef during storage, while lower concentrations led to accelerated pigment oxidation and loss of redness. The mechanism is linked to the formation of stable nitrosyl-heme complexes, as also described by Marco et al. [42], who noted that nitrite contributes both to red color stabilization and delayed oxidative rancidity through its antioxidant effect on heme pigments. This stabilizing effect has been widely confirmed for cured products, where nitric oxide binds to myoglobin forming nitrosomyoglobin and, after thermal processing, nitrosylhemochrome pigment, which maintains the characteristic pink-red hue of cured meat even during prolonged storage [43].

The b^* parameter (yellowness) did not show significant differences between variants, but the overall trend indicates a slight increase in yellow shade with storage time—particularly visible in groups V3 and V4 (from 6.05 to 8.38 and from 7.09 to 9.35). This may indicate progressive oxidative changes and a loss of red color in favor of yellow-brown shades, typical of aging meat products. The gradual increase in b^* values in nitrite-free samples corresponds to pigment oxidation and metmyoglobin accumulation, as described by Marazzeq et al. [44], who observed similar tendencies when nitrite was replaced by natural antioxidants (olive leaf extract). Their findings confirmed that the absence of nitrite accelerates the oxidation of ferrous myoglobin to ferric forms, resulting in a perceptible yellow-brown discoloration.

The C^* (chroma) values, representing color saturation, were significantly higher in the groups containing NaNO_2 , especially during the initial days of storage (e.g., V1: 23.30; V4: 13.72). A decrease in C^* values after 14 days was observed in all variants, with the smallest decrease occurring in the control group (V4), which was already characterized by low initial color saturation. Those results demonstrate that NaNO_2 effectively enhances both the intensity and stability of color. Deniz and Serdaroğlu [43] similarly reported that nitrite addition increased cured pigment concentration and overall chroma values in turkey rolls, particularly when cooked at lower endpoint temperatures, confirming nitrite's central role in pigment stabilization. Furthermore, the correlation between residual nitrite levels and color stability observed in this study aligns with modeling data from King et al. [45], who showed that residual nitrite concentrations directly influence chemical stability in cured meat matrices through continuous nitric oxide release and secondary pigment formation.

The H° (hue angle) parameter increased with storage time, indicating a gradual shift in color towards more yellow-gray tones. The highest H° value after 14 days was observed in group V4 (0.86), indicating a color shift toward a more yellow-gray hue. Variants V1 and V2 maintained lower H° values, corresponding to a more reddish-pink color characteristic of fresh cured products. This confirms the protective role of nitrite in

maintaining characteristic cured color and limiting oxidative discoloration. Comparable effects were noted by Marco et al. [42], who demonstrated that nitrite addition delayed lipid oxidation and prevented color deterioration in long-ripened fermented sausages.

In summary, our results demonstrated that decreasing the nitrite concentration from 150 to 120 mg/kg did not adversely affect color parameters (L^* , a^* , b^* , C^* , H°) during 14 days of refrigerated storage (Table 3). Both groups (V1—150 ppm and V2—120 ppm NaNO_2) maintained high a^* and C^* values and low H° values, indicating stable redness and color saturation. In contrast, samples containing 60 mg/kg NaNO_2 (V3) showed significantly lower a^* values ($p < 0.05$) and a more pronounced increase in the H° parameter, confirming faster pigment oxidation and a shift toward yellow-brown hues. These results show that reducing the NaNO_2 level to 120 mg/kg, in accordance with current legislation, maintains the desirable cured color comparable to that obtained with higher concentrations. This finding agrees with the results of Wójciak et al. [41], who found that lowering the NaNO_2 content to 100 mg/kg does not negatively affect the color quality or microbiological safety of cured beef products.

3.1.3. Texture Parameters

Table 4 presents the results regarding the effect of NaNO_2 level and refrigerated storage time on the textural properties of ostrich meat sausages.

Table 4. Effect of NaNO_2 level on texture parameters of ostrich sausages during 14 days of refrigerated storage.

Item	Time of Storage, Day		Group				Influence		Interaction
			V1 ¹	V2	V3	V4	Time of Storage (TS)	Group (G)	
Hardness (N)	1	Mean	17.39 ^{2aA}	22.44 ^{aA}	19.92 ^{aA}	19.50 ^{aA}	NS ³	***	***
		±SD	1.50	1.67	2.67	5.05			
	7	Mean	13.947 ^{aA}	28.59 ^{aB}	25.6 ^{aB}	34.25 ^{abC}			
		±SD	1.37	2.74	4.92	7.56			
	14	Mean	16.96 ^{aA}	31.95 ^{aB}	34.55 ^{aB}	41.57 ^{bB}			
		±SD	0.64	9.50	12.46	5.46			
Adhesiveness (J/cm ²)	1	Mean	−0.04 ^{bA}	−0.05 ^{aA}	−0.04 ^{aA}	−0.03 ^{aA}	NS	***	***
		±SD	0.00	0.01	0.00	0.01			
	7	Mean	−0.06 ^{abA}	−0.06 ^{aA}	−0.05 ^{aA}	−0.02 ^{aB}			
		±SD	0.01	0.00	0.01	0.00			
	14	Mean	−0.07 ^{aA}	−0.07 ^{aA}	−0.06 ^{aA}	−0.02 ^{aB}			
		±SD	0.01	0.02	0.01	0.00			
Springiness (−)	1	Mean	0.54 ^{aB}	0.47 ^{aB}	0.49 ^{aB}	0.22 ^{aA}	NS	***	***
		±SD	0.05	0.07	0.03	0.00			
	7	Mean	0.48 ^{aB}	0.51 ^{aB}	0.51 ^{aB}	0.27 ^{abA}			
		±SD	0.04	0.02	0.05	0.04			
	14	Mean	0.47 ^{aAB}	0.50 ^{aB}	0.49 ^{aAB}	0.38 ^{bA}			
		±SD	0.04	0.00	0.03	0.04			
Cohesiveness (−)	1	Mean	0.60 ^{aB}	0.62 ^{aB}	0.58 ^{aB}	0.45 ^{aA}	NS	***	***
		±SD	0.04	0.08	0.04	0.03			
	7	Mean	0.59 ^{aB}	0.60 ^{aB}	0.59 ^{aB}	0.41 ^{aA}			
		±SD	0.08	0.02	0.01	0.02			
	14	Mean	0.55 ^{aB}	0.57 ^{aB}	0.56 ^{aB}	0.36 ^{aA}			
		±SD	0.02	0.01	0.02	0.03			

¹ V1—meat products with 150 ppm NaNO_2 added; V2—meat products with 120 ppm NaNO_2 added; V3—meat products with 60 ppm NaNO_2 added; V4—meat products without NaNO_2 added. ² Lowercase letters (a–b) in a column denote significant statistical differences ($p < 0.05$) between storage days within the same group; uppercase letters (A–B) in a row denote significant statistical differences ($p < 0.05$) between groups with different NaNO_2 levels on the same storage day. ³ NS—no significant statistical differences; ($p \geq 0.05$)—significance at the level of $p < 0.05$; **—significance at the level of $p < 0.01$; ***—significance at the level of $p < 0.001$.

The results showed significant differences between groups and days of storage. Initially (day 1), the hardness of all products was in the range of 17.39–22.44 N and did not

differ statistically significantly ($p \geq 0.05$). However, after 14 days, a significant increase in this parameter was observed, particularly in groups V3 and V4 (34.55 and 41.57 N), with the significantly highest value for the variant without nitrite (V4). The hardness increased significantly in groups with low or no nitrite, suggesting that NaNO_2 limited gel tightening and water loss during storage. This effect can be explained by the smaller pH decrease and greater water-holding capacity (WHC) of nitrite-treated samples, which prevented excessive dehydration and cross-linking of myofibrillar proteins. Comparable findings were reported by Dong et al. [46], who observed that increasing NaNO_2 levels in pork sausages significantly reduced hardness and adhesiveness while increasing cohesiveness and springiness during chilled storage. According to the review by Dissanayake et al. [47], nitrite supports the maintenance of protein functionality and water-holding capacity in processed meat products. The authors explained that these effects are primarily linked to the nitrosation of sulfhydryl groups and the inhibition of oxidative denaturation, which together stabilize the myofibrillar protein matrix during processing and storage.

Adhesiveness showed no statistically significant differences ($p \geq 0.05$) among groups in the 1st day after production, although a consistent trend toward higher (more negative) values was observed in nitrite-containing sausages during storage. Beginning from 7th day V4 group was characterized by the lowest values of analyzed parameter, which was even lower after 14 days (-0.02 J/cm^2). This indicates that products with NaNO_2 retained a more hydrated and less compact surface, likely due to reduced protein aggregation. A similar relationship was reported by Dong et al. [46], who found that sausages manufactured with lower levels of NaNO_2 exhibited decreased adhesiveness during cold storage, suggesting reduced surface moisture and weaker water-binding capacity compared with samples containing higher nitrite concentrations.

The springiness parameter, reflecting the sample's ability to recover its shape after deformation, was strongly affected by nitrite addition. On day 1, nitrite-treated sausages (V1–V3) exhibited significantly higher springiness than the control (V4), suggesting that NaNO_2 might enhanced the elasticity of the protein matrix through statistically significant changes in TPA parameters h improved solubilization and thermal gelation of myofibrillar proteins. During storage, elasticity remained relatively stable in nitrite-containing groups, whereas in control group (V4) it increased slightly due to surface drying and structural stiffening. Similar behavior was observed by Dong et al. [46], who associated higher nitrite levels with improved springiness and cohesiveness due to a more uniform gel network formation.

Likewise, cohesiveness, reflecting the internal structural integrity of the product, was significantly higher in nitrite-treated sausages compared with the control ($p < 0.001$). Throughout the entire storage period, the V4 group was characterized by the lowest cohesiveness values. In contrast, no statistically significant changes in cohesiveness were observed within the V1–V3 groups during the two-week cold storage, indicating that nitrite addition could stabilize the internal structure of the sausages over time. These findings are consistent with Dong et al. [46], who reported higher cohesiveness in nitrite-containing cooked sausages.

Overall, the results demonstrate that NaNO_2 exerted a stabilizing and protective effect on the texture of ostrich meat sausages by maintaining a softer, more elastic, and cohesive structure. These outcomes are consistent with the observations of Dong et al. [46] and with the mechanisms described by Dissanayake et al. [47], who identified nitrite as an agent that enhances textural stability through its influence on myofibrillar protein interactions and its ability to control oxidative reactions. It should also be noted that no statistically significant changes in hardness or adhesiveness related to NaNO_2 addition were observed immediately after production, which is consistent with the results of our previous studies [30,31,39].

However, in ostrich sausages, significant differences in springiness and cohesiveness were detected on day 1 between nitrite-treated variants (V1–V3) and the control (V4), which may be influenced by the specific physicochemical properties of ostrich meat. These findings indicate that the effect of nitrite is not uniform across all TPA parameters at the initial stage of storage, and its stabilizing impact becomes more apparent in the subsequent days, as reflected by progressively greater differences in texture development between nitrite-treated and control sausages.

3.1.4. Residual Nitrite Level

The residual nitrite content in ostrich sausages showed significant differences both between the formulation variants and depending on storage time ($p < 0.001$ for the group factor, $p \geq 0.05$ for the storage time factor, $p < 0.001$ for the $G \times ST$ interaction). On the day of production (d1), the highest nitrite content was recorded in variant V1 (150 ppm NaNO_2), where the residual level was 41.17 ± 0.88 mg/kg. In subsequent variants, this content decreased in accordance with the decreasing dose of curing salt: V2 (120 ppm)— 36.29 ± 0.59 mg/kg, V3 (60 ppm)— 16.90 ± 0.30 mg/kg. In the control group V4 (without NaNO_2) this level was trace and amounted to only 0.22 ± 0.03 mg/kg (Table 5).

Table 5. Effect of the applied level of NaNO_2 on the residual nitrite content (mean $\pm$ standard deviation) in ostrich sausages during 14 days of storage under refrigerated conditions.

Item	Time of Storage, Day		Group				Influence		Interaction
			V1 ¹	V2	V3	V4	Time of Storage (TS)	Group (G)	
Nitrate ions (mg/kg)	1	Mean	41.17 ^{cD2}	36.29 ^{cC}	16.90 ^{cB}	0.22 ^{aA}	** ³	**	***
		$\pm$ SD	0.88	0.59	0.30	0.03			
	7	Mean	39.80 ^{bD}	35.11 ^{bC}	15.19 ^{bB}	0.13 ^{aA}			
		$\pm$ SD	0.17	0.30	0.09	0.04			
	14	Mean	35.28 ^{aD}	31.84 ^{aC}	13.13 ^{aB}	0.15 ^{aA}			
		$\pm$ SD	0.23	0.37	0.28	0.01			

¹ V1—meat products with 150 ppm NaNO_2 added; V2—meat products with 120 ppm NaNO_2 added; V3—meat products with 60 ppm NaNO_2 added; V4—meat products without NaNO_2 added. ² Lowercase letters (a–c) in a column denote significant statistical differences ($p < 0.05$) between storage days within the same group; uppercase letters (A–D) in a row denote significant statistical differences ($p < 0.05$) between groups with different NaNO_2 levels on the same storage day. ³ NS—no significant statistical differences; ($p \geq 0.05$)—significance at the level of $p < 0.05$; **—significance at the level of $p < 0.01$; ***—significance at the level of $p < 0.001$.

With extended storage, a systematic decrease in the residual nitrite ion (NO_2^-) content was observed in all variants containing this additive. After 14 days of storage, these values were: 35.28 ± 0.23 mg/kg in group V1 (150 ppm), 31.84 ± 0.37 mg/kg in V2 (120 ppm), and 13.13 ± 0.28 mg/kg in V3 (60 ppm), confirming the natural process of nitrite decomposition under refrigeration conditions. This decline results primarily from reactions of nitrite with myoglobin, lipids, and other reactive constituents of the meat matrix [48]. Similar trends have been widely reported in literature—for example, Deng et al. [49] demonstrated that residual nitrite concentrations in bacon decreased markedly with increasing dry-frying temperature and higher initial nitrite doses, which were positively correlated with N-nitrosamine formation and color changes during processing.

Statistically significant differences between the variants on each day of storage clearly indicate a relationship between the residual nitrite level and the initial dose of NaNO_2 . At the same time, the observed changes during storage, also statistically significant, confirm the dynamic nature of NO_2^- ion decomposition, which has both technological (myoglobin color fixation) and toxicological (risk of nitrosamine formation) implications [50]. The mechanism of nitrosation and its relation to carcinogenic N-nitroso compounds (NOCs) has been extensively reviewed by Zhang et al. [18], who emphasized that the balance

between antimicrobial safety and minimization of nitrosamine formation remains a critical technological challenge in meat processing.

As expected, variant V4 (produced without the addition of NaNO_2) was characterized by a very low and stable content of residual nitrite ions (<0.2 mg/kg) throughout the storage period. The presence of trace amounts may result from naturally occurring changes under the influence of microflora, the presence of nitrogen compounds in spices, plant materials, or process water. This observation aligns with recent findings for “nitrite-free” organic meat products, where comparable residual nitrate and nitrite concentrations were detected despite the absence of added curing salts. These levels originated mainly from natural sources such as herbs, spices, water, and from microbial nitrate reduction via nitrate reductase activity [51].

The results obtained are in agreement with earlier reports on cured meat products. For example, Sheng et al. [52] found mean residual nitrite concentrations of 13.7 ± 0.6 mg/kg across various processed meats in the United States, with depletion patterns depending on formulation and storage time. In contrast, Zhang et al. [53] reported that in China, a substantial proportion (23%) of meat samples exceeded national limits due to improper nitrite use. The values determined in the current study (13.13–41.17 mg/kg) thus align closely with typical residual levels reported internationally, indicating controlled and safe nitrite application. The observed reduction in nitrite content over time reflects both physicochemical and microbiological processes, including reactions with heme pigments and lipids, as well as microbial denitrification. Dong et al. [46] also observed that NaNO_2 influences not only chemical stability but also the textural properties of sausages during cold storage, underscoring its multifunctional role in cured meats. However, as shown by Ramezani et al. [54], nitrosamine formation tends to increase with prolonged storage, particularly in products with higher initial nitrite levels and lower ascorbic acid content, emphasizing the importance of antioxidant protection.

Regardless of the NaNO_2 level used, all tested ostrich sausages were within the permissible limits set by European Union legislation. According to Commission Regulation (EU) 2023/2108 [22], the maximum allowable residual nitrite ion concentration for heat-treated meat products is 45 mg/kg. Variants V1–V3 remained below this threshold, while V4 exhibited only trace levels. These findings confirm the compliance of the formulations with current EU food law and their safety for consumers. Moreover, long-term global monitoring studies, such as that conducted by Ledezma-Zamora et al. [55], emphasize the importance of maintaining residual nitrite at the lowest technologically feasible level to ensure both product safety and public health protection.

3.2. Volatile Compound Profile

Principal component analysis (PCA) revealed a clear effect of NaNO_2 content and storage time on the volatile compound profile of ostrich sausages (Figure 1).

Variants with NaNO_2 (V1—150 ppm, V2—120 ppm and V3—60 ppm) clustered closely together in the upper part of the graph, indicating a similar profile of characteristics and greater stability throughout 7 days of storage. After 14 days, slight shifts in sample distribution were observed within these variants, suggesting minor modifications in the aroma profile over time, but without significant qualitative changes. Samples without added nitrite (V4) were clearly separated from all nitrite-containing variants, reflecting a different and less stable volatile composition, likely associated with the absence of characteristic cured-meat aroma notes. The distribution of samples in the PCA space revealed that NaNO_2 contributes to maintaining a stable and distinctive volatile profile during storage.

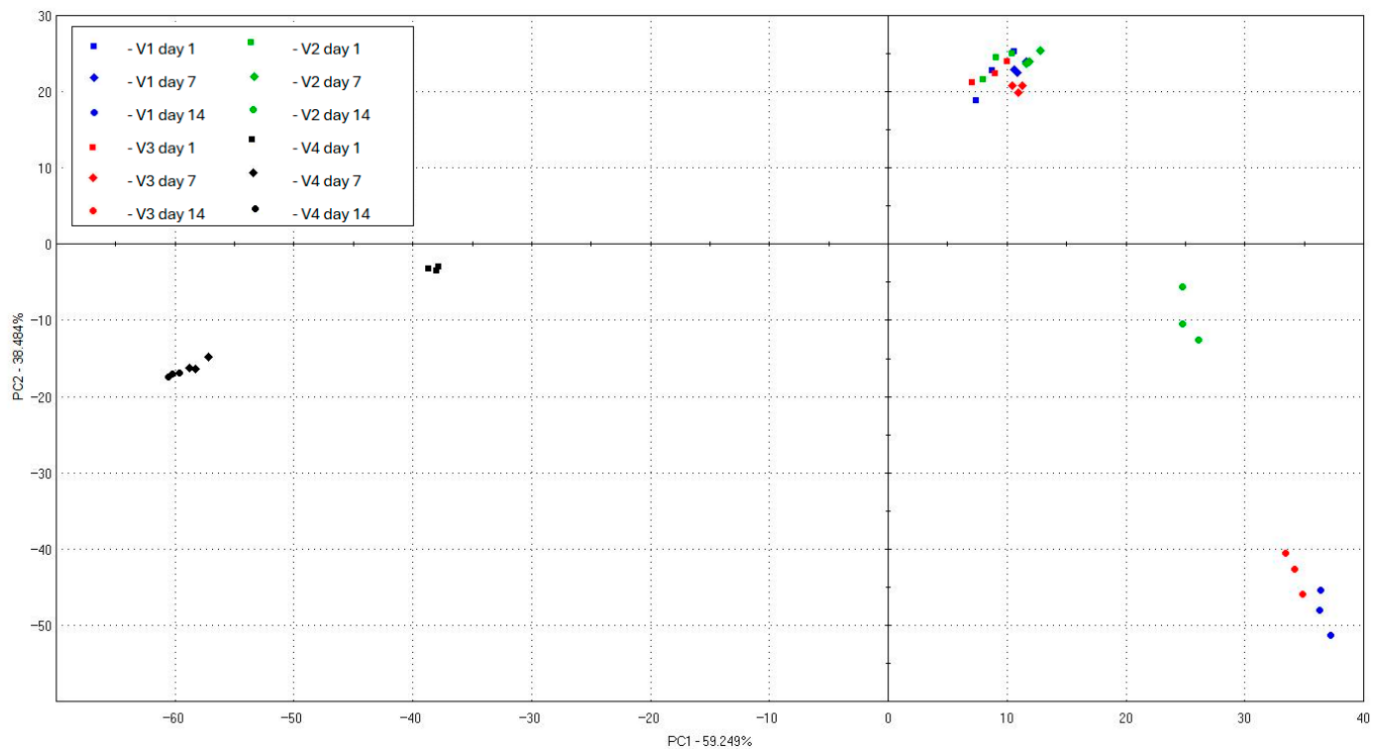


Figure 1. PCA analysis of the quality of ostrich sausages depending on the NaNO_2 content and storage time, blue color—variant1 with 150 mg/kg NaNO_2 , green color—variant 2 with 120 mg/kg NaNO_2 , red color—variant 3 with 60 mg/kg NaNO_2 , black color—variant 4, with NaNO_2 .

The PCA analysis further demonstrated that a notable effect of NaNO_2 on the development of volatile compounds was evident even at 60 mg/kg, emphasizing its crucial role in forming the characteristic cured aroma. This effect is primarily attributed to the reactions of nitric oxide (generated from NaNO_2) with heme pigments and amino acid derivatives, which lead to the formation of nitrogen-containing volatiles responsible for the typical sensory attributes of cured meats [14]. In addition, the antioxidant activity of nitrite may inhibit the formation of oxidation-derived compounds, such as aldehydes and ketones, that could mask or alter the desirable aroma profile of the product. These findings are consistent with previous reports on the influence of nitrite on the volatile profile of cured meats. Marco et al. [42] demonstrated that nitrite inhibited the formation of oxidation-derived aldehydes such as hexanal and 3-methylbutanal, maintaining a more stable aroma profile during ripening. Similar findings were reported by Karwowska et al. [38] and Oral and Sallan [56], who observed reduced lipid oxidation what could stable aroma profile in nitrite-treated meat products. Adequate nitrite levels not only prevent excessive lipid oxidation but also indirectly affect the volatile compound profile by limiting the formation of oxidation-derived aldehydes responsible for rancid off-flavors.

3.3. Semi-Consumer Evaluation

In the semi-consumer evaluation, four formulation variants differing in NaNO_2 content were assessed for color, consistency, aroma, and overall acceptability (Figure 2).

Variant V1 (150 ppm NaNO_2) achieved the highest color score (4.11), followed by V2 (3.85) and V3 (3.63), whereas V4 (without nitrite) obtained a markedly lower rating (1.74). This confirms the crucial role of NaNO_2 in the development and stability of cured color, resulting from the formation of nitrosylmyochromogen. The lack of this pigment leads to a dull gray appearance that consumers typically perceive as less appealing or “uncooked.” Nitrosylmyochromogen is responsible for the characteristic pink-red color of cured meat

products, which consumers perceive as an indicator of freshness and quality [57]. Similar effects were reported by Deniz and Serdaroğlu [43], who showed that higher nitrite levels produce a stable pink color in cooked poultry rolls, while its absence results in a pale, unattractive surface.

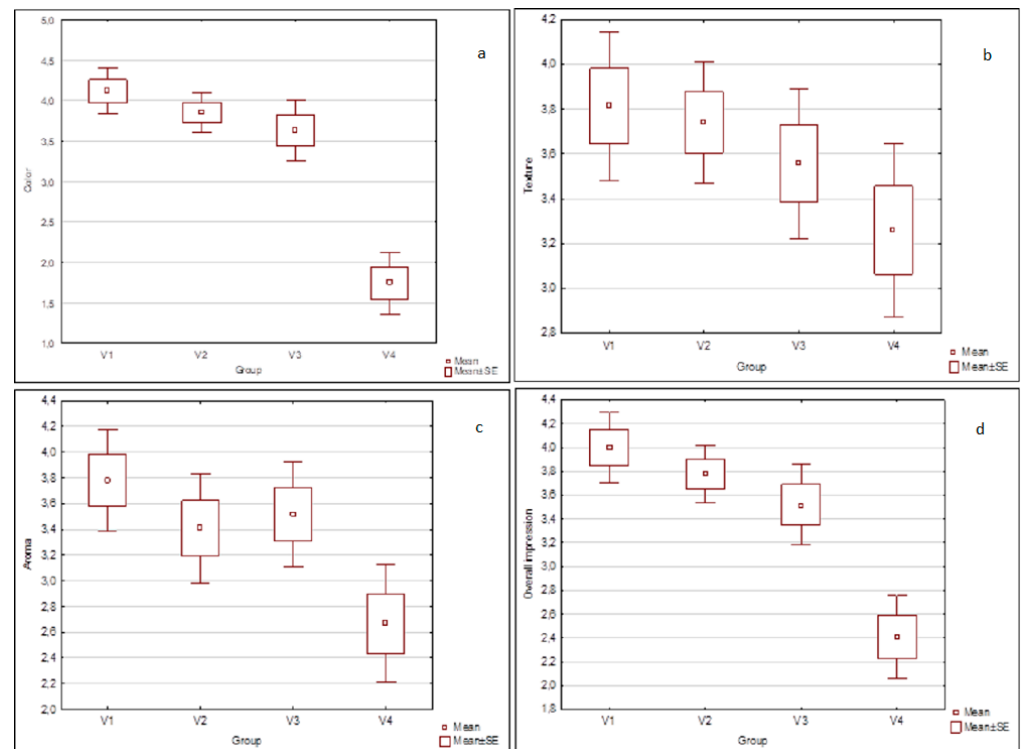


Figure 2. The effect of the applied level of NaNO₂ on the assessment of the sensory characteristics of boiled sausage in a semi-consumer study: color (a), texture (b), aroma (c) and overall impression (d). V1—meat products with 150 ppm NaNO₂ added; V2—meat products with 120 ppm NaNO₂ added; V3—meat products with 60 ppm NaNO₂ added; V4—meat products without NaNO₂ added.

Differences in texture were less pronounced, with V1 (3.81) and V2 (3.74) receiving comparable ratings, while V4 (3.26) scored slightly lower. These differences may reflect minor variations in protein network stability, as nitrite can influence water binding and emulsion properties, although this effect is generally weaker than its impact on color or aroma [41].

In contrast, more distinct differences were observed in the aroma assessment. Variant V1 (3.78) received the highest score, followed by V3 (3.52) and V2 (3.41), whereas V4 (2.67) obtained the lowest rating. The reduction in aroma quality may result from the loss of the characteristic “cured” flavor, which originates from reactions of nitrite-derived nitrogen compounds with lipids and proteins during heat treatment. Al Marazzeq et al. [44] demonstrated that beef mortadella produced with olive leaf extract instead of nitrite had significantly lower flavor scores compared to conventional formulations containing NaNO₂. Likewise, Dissanayake et al. [47] reported that cooked hams produced without nitrite exhibited higher levels of aldehydes associated with rancid odor, leading to decreased aroma and flavor acceptability.

The overall acceptability followed a consistent pattern: V1 (4.00) > V2 (3.78) > V3 (3.52) > V4 (2.41). This demonstrates that moderate nitrite reduction (to 60–120 ppm) maintains satisfactory consumer acceptance, while complete omission substantially lowers sensory quality. Rocha et al. [58], in a review of nitrite and nitrate functions in meat products, emphasized that consumers often perceive nitrite-free products as having color and flavor defects, confirming that the presence of nitrite remains critical for sensory appeal.

It is also noteworthy that NaNO_2 contributes not only to the cured color but also indirectly stabilizes aroma through its antioxidant and antimicrobial properties, limiting the formation of rancidity-associated volatiles. Similarly, Wójciak et al. [41] demonstrated that nitrite levels of 100–150 mg/kg provide optimal oxidative stability and product quality, indirectly contributing to better sensory perception.

Obtained results indicate that NaNO_2 concentration has a decisive effect on the sensory characteristics of analyzed ostrich sausages, especially color and aroma. While a moderate reduction in nitrite content allows for acceptable sensory quality, complete elimination causes significant deterioration in consumer perception. These findings are consistent with current literature emphasizing that successful nitrite reduction strategies require compensatory approaches (such as the use of natural antioxidants, starter cultures, or modified-atmosphere packaging) to preserve product quality and consumer acceptance [47,58].

4. Conclusions

Most previous studies on NaNO_2 have focused on its antimicrobial and antioxidant activity or on searching for natural alternatives with similar effects. In this study, these aspects were not analyzed, as all formulations contained NaNO_2 within the limits allowed by European Union law. This research instead focused on parameters that are important from the consumer's perspective: color, texture, volatile compound profile, and the relationship between residual nitrite and the potential formation of nitrosamines.

The results of this study showed that NaNO_2 has an important role in shaping the physicochemical and sensory properties of ostrich sausages. Reducing its level from 150 to 60 mg/kg caused only slight changes in pH and color but did not markedly affect the texture of stored products. Sausages containing 120 and 150 mg/kg of NaNO_2 had similar color stability, texture, and consumer acceptance, while samples with 60 mg/kg were slightly paler and scored lower in sensory evaluation. Nonetheless, the PCA analysis of volatile compounds confirmed that all nitrite-containing variants (60–150 mg/kg) had a similar and stable volatile profile during 14 days of storage. In contrast, samples without nitrite showed greater variation and lacked the characteristic cured-meat aroma. Importantly, residual nitrite levels in all variants remained below the maximum legal limits, confirming compliance with European regulations and ensuring product safety. However, even legally permitted doses of NaNO_2 may not be fully accepted by all consumers, which increases the need for developing formulations that combine safety, sensory quality, and clean-label expectations.

Overall, the findings indicate that a moderate reduction in NaNO_2 to about 120 mg/kg can maintain the desired sensory and technological properties of ostrich sausages while minimizing residual nitrite content and potential nitrosamine formation. This level can be considered a practical and safe compromise between product quality, consumer acceptance, and regulatory compliance.

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