

Article

The Effect of Apple Vinegar Addition on the Quality and Shelf Life of Cooked Sausage during Chilling Storage

Anna Okoń ¹, Dorota Zielińska ^{2,*}, Piotr Szymański ¹, Anna Łepecka ¹, Urszula Siekierko ¹, Katarzyna Neffe-Skocińska ², Monika Trzaskowska ², Katarzyna Kajak-Siemaszko ², Barbara Sionek ², Marcelina Karbowiak ², Danuta Kołożyn-Krajewska ² and Zbigniew J. Dolatowski ¹

¹ Department of Meat and Fat Technology, Prof. Wacław Dąbrowski Institute of Agriculture and Food Biotechnology—State Research Institute, 02-532 Warsaw, Poland; anna.okon@ibprs.pl (A.O.); piotr.szymanski@ibprs.pl (P.S.); anna.lepecka@ibprs.pl (A.Ł.); urszula.siekierko@ibprs.pl (U.S.); zbigniew.dolatowski@ibprs.pl (Z.J.D.)

² Department of Food Gastronomy and Food Hygiene, Institute of Human Nutrition Sciences, Warsaw University of Life Sciences-SGGW, 02-776 Warsaw, Poland; katarzyna_neffe_skocinska@sggw.edu.pl (K.N.-S.); monika_trzaskowska@sggw.edu.pl (M.T.); katarzyna_kajak_siemaszko@sggw.edu.pl (K.K.-S.); barbara_sionek@sggw.edu.pl (B.S.); marcelina_karbowiak@sggw.edu.pl (M.K.); danuta_kolozyn_krajewska@sggw.edu.pl (D.K.-K.)

* Correspondence: dorota_zielinska@sggw.edu.pl; Tel.: +4822-593-70-65

Abstract: As more and more consumers are becoming conscious of the safety and taste of meat products, the use of natural additives and innovative processing techniques has gained significant attention. Naturally fermented fruit vinegar is rich in organic acids and antioxidant phenolic compounds. In addition, it contains amino acids, minerals, vitamins, and provitamin beta-carotene, and the presence of acetic acid bacteria may have a positive effect on consumer health. The study aimed to assess the impact of different concentrations of apple vinegar addition on the quality of cooked sausage, focusing on physicochemical parameters, including fatty acid profile and oxidative stability, as well as microbiological quality and sensory changes after production and during chilling storage. Four variants of sausage were prepared: C—sausage without apple vinegar; V1—sausage with 1% of apple vinegar; V3—sausage with 3% of apple vinegar; and V5—sausage with 5% of apple vinegar. All of the tests were carried out after production, as well as after 7 and 14 days of refrigeration storage. The addition of apple vinegar decreased the pH value and increased the oxidation-reduction potential and lipid oxidation in the samples V1, V3, and V5. The sausage with the 5% addition of apple vinegar (V5) was characterized by significantly more intensive brightness (parameter $L^* = 54.67$) in comparison to the C sample (parameter $L^* = 52.78$). The sausages that were tested showed good microbiological quality concerning the total number of microorganisms, lactic acid bacteria, and the absence of pathogenic bacteria. The addition of apple vinegar contributed to the reduction in the intensity of the cured meat flavor and the fatty flavor. Therefore, according to the results presented in this work, it can be concluded that 3% of vinegar is the optimal addition, which may be used in the next step of investigation, taking into account color formation abilities as well as microbiological quality and lipid oxidation processes.

Keywords: organic sausage; microbial assessment; fruit vinegar



Citation: Okoń, A.; Zielińska, D.; Szymański, P.; Łepecka, A.; Siekierko, U.; Neffe-Skocińska, K.; Trzaskowska, M.; Kajak-Siemaszko, K.; Sionek, B.; Karbowiak, M.; et al. The Effect of Apple Vinegar Addition on the Quality and Shelf Life of Cooked Sausage during Chilling Storage. *Appl. Sci.* **2024**, *14*, 4027. <https://doi.org/10.3390/app14104027>

Academic Editor: Alessandro Genovese

Received: 9 April 2024

Revised: 3 May 2024

Accepted: 6 May 2024

Published: 9 May 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Cooked sausages are one of the most popular in Poland as well as worldwide ready-to-eat products made from a variety of meats including pork, beef, and chicken [1,2]. Nitrite is a common food additive that plays a crucial role in the production of sausages. Its primary function is to prevent the growth of harmful bacteria, particularly *Clostridium* spp. Nitrite also plays a crucial role in giving sausages their characteristic pink color. Furthermore, it is effective in inhibiting the oxidation of lipids, which can lead to the development of rancid

and unpleasant flavors [3–5]. A high intake of nitrites can pose a health risk since it may lead to the formation of cancer-causing N-nitroso compounds [6,7]. Hence, it is imperative to minimize or eliminate the use of nitrites in meat products. Therefore, researchers are investigating natural substitutes to reduce or eliminate the addition of nitrite in meat. In contemporary times, it has become apparent that consumers are increasingly inclined towards meat products that are minimally processed and incorporate natural additives. These natural additives comprise a range of ingredients, including but not limited to salt, vinegar, herbs, spices, and acerola [8–10]. As a result, meat producers need to adapt to this trend and offer meat products that meet the preferences of the modern-day consumer.

Fruit vinegar, mainly apple, has been known since ancient times and is used in many cultures around the world. The production of apple vinegar involves a natural fermentation process of crushed apples. Apple vinegar is considered to be a rich source of various organic acids, including acetic, citric, lactic, and apple. In addition to these acids, apple cider vinegar also contains enzymes, pectins, and antioxidant phenolic compounds such as gallic acid, caffeic acid, chlorogenic acid, catechins, and epicatechins [11–14]. All of these components have been proven to have health-promoting properties. In addition to its other properties, it comprises all the crucial elements that are indispensable for the functioning of complex mechanisms of life [15,16]. These components comprise amino acids and mineral elements like iron, fluorine, potassium, calcium, copper, magnesium, sodium, phosphorus, sulfur, and silicon. In addition to these essential components, it also contains a variety of important vitamins such as A1, B1, B2, B6, C, E, P, and pro-vitamin beta-carotene, which play critical roles in maintaining good health, including supporting immunity. Moreover, naturally fermented vinegar provides environmental acetic acid bacteria with potentially health-promoting properties. Consuming vinegar has health benefits, including antimicrobial and antioxidant effects, positive effects on the cardiovascular system and metabolism, and reducing fatigue [12,17,18]. Natural fruit vinegar is high quality, safe, and nutritious, with characteristic sensory, microbiological, and physicochemical properties. However, some researchers have found that the addition of apple vinegar could affect the sensory quality of the final meat product, especially in terms of its color and consistency characteristics [19,20]. Therefore, this study aimed to assess the impact of different concentrations of apple vinegar addition on the quality of cooked sausage, focusing on changes in the fatty acid profile, oxidative stability, physicochemical parameters, as well as microbiological and sensory qualities after production and during chilling storage. The research presented here is part of a broader investigation project that involves searching for new, natural solutions to ensure the safety of meat products and their appropriate quality in light of the limitations of nitrite additions to meat products.

2. Materials and Methods

2.1. Materials

2.1.1. Apple Vinegar

Apple vinegar was made according to the protocol presented by Łepecka et al. [11]. Briefly, vinegar was created by the natural fermentation of apple juice; the first stage was alcoholic fermentation (anaerobic decomposition of sugars carried out by Tokaj wine yeast), and then, in the process of acetic fermentation, acetic acid bacteria (AAB): *Acetobacter pasteurianus* O4 (KKP 674; access to GenBank OM200034) and *Acetobacter pasteurianus* MW3 (KKP 2997; GenBank accession OM212983) converted alcohol into acetic acid were added. The obtained apple vinegar had been naturally cloudy, unfiltered, and unpasteurized.

2.1.2. Preparation of Cooked Organic Sausage

Four groups of cooked meat sausages samples were produced which differed in the various additions of apple vinegar (0, 1, 3, 5%). The sample groups were listed as C—a cooked sausages sample with curing salt (0.8%) without apple vinegar; V1—a cooked sausages sample with curing salt (0.8%) and apple vinegar (1%); V3—a cooked sausages sample with curing salt (0.8%) and apple vinegar (3%); and V5—a cooked sausages sample

with curing salt (0.8%) and apple vinegar (5%). The raw material for the sausages' production was pork and beef from an organic farm in the Masovian Voivodeship. Organic sausage production prioritizes sustainable systems that rely on natural life cycles and reduce the use of chemicals, GMOs, and additives. The experimental material was sausage, which included 25% of pork shoulder, 25% of skinless pork belly, and 50% of lean beef. The meat was minced and divided into four fillings, and the ingredients were added in the following order: curing salt 0.8%, water 10%, apple vinegar (0, 1, 3, 5%), and water to make up for vinegar (5, 4, 2, 0%, respectively). The processing of sausages is shown in Figure 1, and in Table 1, the presentation of the formula of model sausages was included. The photography of the samples of sausages is shown in Appendix A.

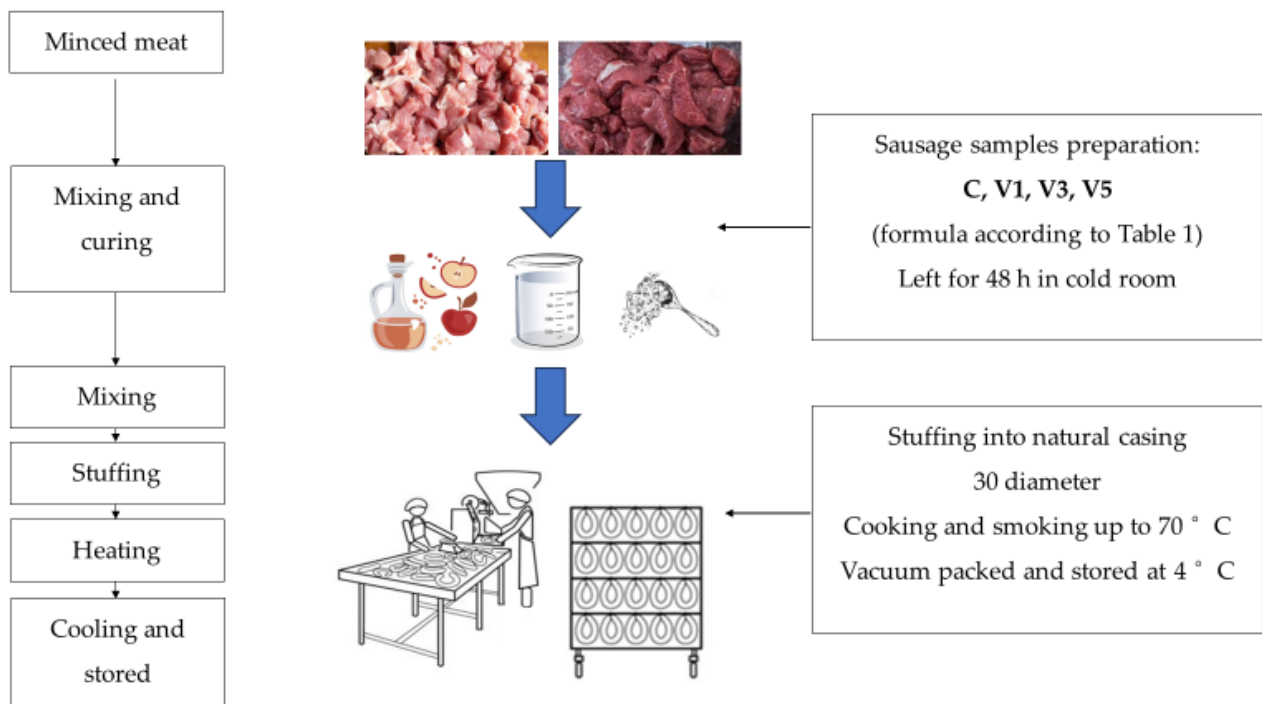


Figure 1. Processing of cooked sausages.

Table 1. Formula of model sausages.

Component	Treatment			
	C	V1	V3	V5
Pork shoulder (kg)	25	25	25	25
Skinless pork belly (kg)	25	25	25	25
Lean beef (kg)	50	50	50	50
Curing salt (99.5% NaCl, 0.5% NaNO ₂) (kg)	0.8	0.8	0.8	0.8
Apple vinegar (kg)	-	1	3	5
Water (kg)	15	14	12	10

Explanatory notes: C—control sausage without apple vinegar; V1, V3, V5—sausage with apple vinegar 1, 3, and 5%, respectively.

After mixing, the stuffings were left for 48 h in a cold room, and then the stuffings were lightly mixed and stuffed into natural casings. The sausages prepared in this way were subjected to the smoking and cooking process at temperatures of up to 70 °C in a traditional smokehouse with the parameters of the smokehouse and the product controlled. A traditional smokehouse was used for smoking, featuring a brick chamber measuring 100 × 100 × 250 cm, lined with clinker. A hearth, situated at a distance of 100 cm from

the chamber, was employed to generate smoke from beech wood billets that had been stripped of their bark, with meticulous control of the air supply. The smoke was directed from the fireplace to the bottom of the chamber during a smoking process that was carried out in an open circuit. After cooling, the samples were hermetically sealed using vacuum packaging and stored at a temperature of 4 °C. The products were analyzed immediately after production and after 7 and 14 days of refrigerated storage (4 °C).

2.2. Methods

2.2.1. Microbiological Analysis

The lactic acid bacteria (LAB) count was determined according to PN ISO 15214:2002 [21]. The acetic acid bacteria (AAB) count was determined using a modified solid medium GCA (glucose calcium carbonate agar) containing the following: 2% glucose, 0.3% K-peptone, 0.3% yeast extract, 0.7% calcium carbonate, 2% ethanol, and nystatin (Sigma-Aldrich, Piekary Śląskie, Poland) [11]. The plates were incubated for 72 h at 25 °C. Selected pathogenic bacteria were also assayed. The assaying of *L. monocytogenes* (LM) was performed based on PN-EN ISO 11290-1:2017 [22], whereas *Salmonella* (SAL) was performed based on PN-EN ISO 6579 [23] (the samples were tested in terms of the presence in 25 g of the product). The Enterobacteriaceae family (ENT) was enumerated according to ISO 21528-2:2017 [24]. *Escherichia coli* (EC) were enumerated according to ISO 16649-1:2018 [25]. The coagulase-positive staphylococci (SA) were performed according to ISO 6888-1:2021 [26]. Microbial tests to determine total viable counts (TVC) were performed according to PN-EN ISO 4833-1:2013 [27]. The results were reported as colony-forming units per gram of the product [log cfu/g].

2.2.2. Chemical Composition Analyses

The analysis of the chemical composition of the sausages included the determination of the moisture content according to ISO 1442:1997 [28]; the total protein content according to ISO 937:1978 [29], carried out by the Kjeldahl titration method; the fat content according to ISO 1444:1996 [30], determined by the Soxhlet method; and the carbohydrate content according to the IBPRS-PIB laboratory's own procedure (PA/09, Issue 3 of 8 June 2021), which is based on the PN-A-82059:1985 [31,32], determined by the titration method. The values are given in %.

2.2.3. pH Value

To evaluate the pH of the samples, they were ground and homogenized with distilled water for 1 min using a blender (MSM 66120, BSH Hausgeräte GmbH, Munich, Germany). The pH of the resulting suspension was measured using a FiveEasy F20 digital pH meter (Mettler Toledo, Schwerzenbach, Switzerland) equipped with a pH In Lab Cool electrode (Mettler Toledo, Greifensee, Switzerland). Before measurements, the electrode was calibrated with standardized buffers at pH 2.0, 4.0, 7.0, and 10.0.

2.2.4. Oxidation-Reduction Potential (ORP), TBARS (Thiobarbituric Acid Reactive Substances) Index

The oxidation-reduction potential (ORP) was determined following the method outlined by Ahn and Nam [33]. A digital pH meter (Delta 350, Mettler Toledo, Schwerzenbach, Switzerland) equipped with an In Lab Redox Pro electrode (Mettler Toledo, Greifensee, Switzerland) was used. Measurements were conducted at 20 °C and the standard hydrogen electrode EH(mV) was used. The results were calculated into the value of ORP. The ORP value of the reference electrode at a temperature of 20 °C $E_{ref} = 207$ mV was summed up with the value obtained with the equipment.

The lipid oxidation in the sausages was assessed according to Pikul et al. [34]. The amount of thiobarbituric acid reactive substances (TBARS) was measured. The absorbance at 532 nm at approx. 20 °C using a Nicolet Evolution 300 spectrophotometer (Thermo

Electron Corp., Waltham, MA, USA) was read. The values were expressed as mg of malondialdehyde (MDA) per kilogram of sample, as shown in the following equation:

$$\text{TBARS [mg MDA/kg]} = 5.5 \times \text{absorbance value of the tested sample}$$

2.2.5. Fatty Acid Profile

Gas chromatography with a flame ionization detector (HP/Agilent 6890 II-FID) was used to determine fatty acids, following ISO 12966-1:2014 [35] and according to the methodology of Łepecka et al. [11].

2.2.6. Color Measurements

The color was measured with a Konica Minolta CR-300 colorimeter using the CIELab system to determine lightness (L^*), greenness/redness ($-a^*$, $+a^*$), and blueness/yellowness ($-b^*$, $+b^*$). The results are presented as the means with $\pm$ standard deviation from forty independent trials.

2.2.7. Sensory Analysis

Sensory evaluations were carried out using the Quantitative Descriptive Analysis (QDA) method. The tests were performed following the requirements of the ISO 13299:2016 standard by a trained team of assessors [36,37]. The QDA assessments were carried out with the participation of an 8-person team of employees of the Department of Food Gastronomy and Food Hygiene of the Warsaw University of Life Sciences—SGGW. Members of the evaluation team were trained in the methodology of the analyses performed and tested for sensory sensitivity. The sensory features examined were selected in a panel discussion and concerned smell, color, consistency, and taste. The average results were based on 10 unit assessments. Samples of 15–20 g of cold cuts were placed in disposable, colorless plastic boxes, covered with lids, and coded with letter and numerical codes. After 15 min, the samples were given to the evaluators for evaluation along with a previously prepared evaluation card. The obtained results were presented using polar plots. The analyzed products were analyzed after 14 days of refrigerated storage. The study was conducted in accordance with the Declaration of Helsinki, and approved by the Rector's Committee for the Ethics of Scientific Research Involving Humans at WULS-SGGW (Resolution No. 28/RKE/2023/U of 6 July 2023).

2.2.8. Statistical Analysis

The experiments were conducted in three independent production batches. Measurements were repeated at least three times for each production batch. The results obtained from the physicochemical and microbiological analyses underwent statistical analysis using a two-way ANOVA model that accounted for the effects of the treatments (0%, 1%, 3%, and 5% of apple vinegar), storage time (0, 7, and 14 days), and the interaction between the treatments and storage time. Furthermore, the sensory analysis data underwent a one-way ANOVA (between treatments) after 14 days. The mean values and standard deviations were calculated, and the Fisher post-hoc test was used to determine the significance of the mean values for multiple comparisons ($p < 0.05$). The calculations were performed using the Statistica package, version 13 (StatSoftPolska Sp. z o.o, Cracov, Poland).

3. Results and Discussion

3.1. Chemical Composition

Four types of sausage were produced under the manufacturing conditions. Table 2 presents the chemical composition of the tested sausages. The moisture content of the sausage was 61.3–63.4%, the protein content was 21.2–22.6%, the fat content was 9.8–10.3%, and the carbohydrate content was $<0.50\%$. Upon analysis, the chemical composition of the sausage products was determined to be in accordance with the typical profile of sausages, as indicated in other studies [38].

Table 2. Chemical composition of sausage (means $\pm$ standard deviation error).

Treatment	Moisture (%)	Carbohydrates (%)	Protein (%)	Fat (%)
C	62.6 $\pm$ 0.82 ^b	<0.5 ^a	21.7 $\pm$ 0.59 ^a	9.9 $\pm$ 0.56 ^{ab}
V1	63.4 $\pm$ 0.26 ^b	<0.5 ^a	21.2 $\pm$ 0.40 ^a	9.8 $\pm$ 0.05 ^a
V3	62.8 $\pm$ 0.58 ^b	<0.5 ^a	21.7 $\pm$ 0.32 ^a	10.1 $\pm$ 0.05 ^{ab}
V5	61.3 $\pm$ 0.36 ^a	<0.5 ^a	22.6 $\pm$ 0.18 ^b	10.3 $\pm$ 0.11 ^b

^{a,b} Means in the same columns with different superscript small letters differ significantly ($p < 0.05$); C—control sausage without apple vinegar; V1, V3, V5—sausage with apple vinegar 1, 3, and 5%, respectively.

3.2. Microbiological Quality

All of the tested products were of good microbiological quality in accordance with the Regulation (EC) No. 1441/2007 [39], which is presented in Table 3.

Table 3. Microbiological analysis of sausage.

Treatment		Storage Time (Days)			Treatment	Time	Treatment $\times$ Time
		0	7	14	<i>p</i>	<i>p</i>	<i>p</i>
TVC (log CFU/g)	C	1.36 $\pm$ 0.10 ^{bB}	1.36 $\pm$ 0.10 ^{aB}	1.00 $\pm$ 0.01 ^{aA}	***	**	***
	V1	1.10 $\pm$ 0.17 ^{aA}	1.52 $\pm$ 0.07 ^{aB}	1.86 $\pm$ 0.03 ^{cC}			
	V3	1.46 $\pm$ 0.15 ^{bcA}	1.75 $\pm$ 0.08 ^{bB}	1.63 $\pm$ 0.05 ^{bAB}			
	V5	2.36 $\pm$ 0.10 ^{dB}	2.27 $\pm$ 0.08 ^{cB}	2.07 $\pm$ 0.09 ^{dA}			
LAB (log CFU/g)	C	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}	NS	NS	NS
	V1	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}			
	V3	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}			
	V5	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}			
AAB (log CFU/g)	C	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}	***	*	***
	V1	<1.00 ^{aA}	<1.00 ^{aA}	1.20 $\pm$ 0.06 ^{bB}			
	V3	1.96 $\pm$ 0.08 ^{bA}	2.07 $\pm$ 0.09 ^{bA}	1.83 $\pm$ 0.28 ^{cA}			
	V5	2.99 $\pm$ 0.14 ^{cA}	3.02 $\pm$ 0.16 ^{cA}	2.82 $\pm$ 0.11 ^{dA}			
ENT (log CFU/g)	C	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}	NS	NS	NS
	V1	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}			
	V3	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}			
	V5	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}			
EC (log CFU/g)	C	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}	NS	NS	NS
	V1	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}			
	V3	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}			
	V5	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}			
SA (log CFU/g)	C	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}	NS	NS	NS
	V1	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}			
	V3	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}			
	V5	<1.00 ^{aA}	<1.00 ^{aA}	<1.00 ^{aA}			
SAL	C	nd	nd	nd	NS	NS	NS
	V1	nd	nd	nd			
	V3	nd	nd	nd			
	V5	nd	nd	nd			
LM	C	nd	nd	nd	NS	NS	NS
	V1	nd	nd	nd			
	V3	nd	nd	nd			
	V5	nd	nd	nd			

^{a–d} Means in the same columns with different superscript small letters differ significantly ($p < 0.05$); ^{A–C} Means in the same row with different superscript capital letters differ significantly ($p < 0.05$); TVC—total viable count; LAB—lactic acid bacteria, AAB—acetic acid bacteria, ENT—bacteria *Enterobacteriaceae*, EC—*Escherichia coli*, SA—coagulase-positive staphylococci (*Staphylococcus aureus* and other species), SAL—*Salmonella* spp., LM—*Listeria* spp. including *Listeria monocytogenes*; <1.00—counts below the detection limit of the plating method; nd—not detected in 25 g; the values are expressed as means $\pm$ SD. *p*: significance of effects; treatment; time; treatment–time interaction; NS—not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

During the storage period, the total viable counts in all of the samples were between 1.00 log cfu/g and 2.36 log cfu/g. Throughout the duration of the storage period, the counts of LAB, *Enterobacteriaceae*, *Escherichia coli*, and *Staphylococcus aureus* in the model sausages remained below 1.0 log cfu/g. The samples with apple cider vinegar (V1, V3, and V5)

contained AAB (acetic acid bacteria), the higher concentrations of which were due to the greater amount of vinegar added. According to Table 2, there was no confirmed presence of *L. monocytogenes* and *Salmonella* spp. in the products. The obtained results confirmed the high hygienic status of the production process. The heat treatment of the model products and the addition of apple vinegar, which lowered the pH, likely contributed to the low number of total viable microorganisms (TVC). However, the slightly higher count of TVC in samples with higher concentrations of apple vinegar indicates that probably the acetic acid bacteria, which were present in apple vinegar at a level above 6 log cfu/mL, could survive and grow in the samples. Similar results were obtained by Łepecka et al. [11].

3.3. Oxidation-Reduction Potential, pH, and TBARS Index

The physicochemical parameters of model meat products (pH, ORP, and TBARS) were affected by the addition of apple vinegar. Table 4 presents the physicochemical properties of model sausages.

Table 4. The values of oxidation-reduction potential, pH, and TBARS index of sausage (means $\pm$ standard deviation error).

	Treatment	Storage Time (Days)			Treatment	Time	Treatment $\times$ Time
		0	7	14	<i>p</i>	<i>p</i>	<i>p</i>
pH	C	5.83 $\pm$ 0.09 ^{cA}	5.82 $\pm$ 0.02 ^{cA}	5.85 $\pm$ 0.09 ^{bA}	***	**	*
	V1	5.69 $\pm$ 0.04 ^{bA}	5.69 $\pm$ 0.02 ^{bA}	5.75 $\pm$ 0.17 ^{abA}			
	V3	5.50 $\pm$ 0.03 ^{aA}	5.73 $\pm$ 0.07 ^{bB}	5.69 $\pm$ 0.05 ^{aB}			
	V5	5.46 $\pm$ 0.04 ^{aA}	5.57 $\pm$ 0.02 ^{aB}	5.63 $\pm$ 0.01 ^{aC}			
ORP (mV)	C	377.08 $\pm$ 5.67 ^{aB}	376.05 $\pm$ 2.91 ^{aB}	358.50 $\pm$ 5.16 ^{aA}	***	**	***
	V1	371.50 $\pm$ 4.63 ^{aA}	382.43 $\pm$ 4.29 ^{bB}	379.55 $\pm$ 7.42 ^{bAB}			
	V3	392.58 $\pm$ 1.06 ^{bB}	382.23 $\pm$ 2.08 ^{bA}	384.43 $\pm$ 6.35 ^{bcA}			
	V5	390.10 $\pm$ 4.06 ^{bA}	396.15 $\pm$ 1.14 ^{cB}	389.55 $\pm$ 3.59 ^{cA}			
TBARS (mg/kg)	C	0.58 $\pm$ 0.09 ^{abA}	0.54 $\pm$ 0.06 ^{aA}	0.89 $\pm$ 0.08 ^{aB}	*	***	**
	V1	0.61 $\pm$ 0.04 ^{abA}	0.71 $\pm$ 0.04 ^{cB}	0.86 $\pm$ 0.04 ^{aC}			
	V3	0.67 $\pm$ 0.05 ^{bA}	0.64 $\pm$ 0.01 ^{bA}	0.86 $\pm$ 0.03 ^{aB}			
	V5	0.55 $\pm$ 0.04 ^{aA}	0.69 $\pm$ 0.03 ^{bcB}	0.91 $\pm$ 0.05 ^{aC}			

^{a-c} Means in the same columns with different superscript small letters differ significantly ($p < 0.05$); ^{A-C} Means in the same row with different superscript capital letters differ significantly ($p < 0.05$); C—control sausage without apple vinegar; V1, V3, V5—sausage with apple vinegar 1, 3, and 5%, respectively. *p*: significance of effects; treatment; time; treatment–time interaction; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

The sausages were analyzed for their pH levels, which varied between 5.46 and 5.85, and an ORP index ranging from 358.50 to 396.15 mV. The TBARS values were between 0.54 and 0.91 mg MDA/kg. Table 3 shows the pH changes in sausages that were treated with apple vinegar during refrigerated storage at 4 °C.

The samples containing vinegar experienced a decrease in pH values immediately after production (0 days). However, these pH values steadily increased as the samples were stored for a longer period. This was associated with the presence of organic acids in naturally fermented apple vinegar absorbed by sausage in the process of curing. At the highest concentration of vinegar (V5), the pH level was significantly reduced. Aktas and Kaya [40] found that marinating beef *Longissimus dorsi* muscle with weak organic acids and salts impacted its quality. According to their findings, the type and concentration of the organic acid used had a significant influence on the pH values and weight changes. Acid treatment caused lower pH values, denaturing proteins below the isoelectric point and altering their water-binding ability. Previous studies have shown that marinating meat with organic acids significantly lowers its pH value [41,42]. These results have important implications for the food industry, as controlling the pH level is crucial to ensuring the quality and safety of meat products. In a study conducted by Jones et al. [41], it was observed that the addition of vinegar to biltong caused a decrease in the pH value from 5.64 to 4.91. Similarly, Seong et al. [42] found that the pH values of beef, which varied between 5.51 and 5.60, decreased and varied between 5.11 and 5.37 after undergoing the marination

process with vinegar. The acidity level of meat affects its ability to hold water. Generally, meat can retain more water when its pH level is either above or below the isoelectric point of the meat proteins. It is worth noting that processed meat products with a lower pH level are less likely to develop pathogenic microbial growth, which ultimately improves their safety and extends their shelf life [43]. The pH of all samples increased throughout the refrigerated storage period, similar to Rahman et al.'s findings [44]. The elevation in the pH level of meat and its derived products is linked to the liberation of basic compounds, which include the imidazole, sulfhydryl, and hydroxyl groups, during processing and storage. We observed the treated batches (V3, V5) as the storage period progressed.

The study revealed a noteworthy impact of treatment and storage time on the oxidation-reduction potential value with a p -value of less than 0.001. Furthermore, an interaction between the treatment and storage time was observed for the oxidation-reduction potential, as indicated in Table 4. The sausage treated with apple vinegar at the 3% and 5% levels showed a significantly higher level of oxidation-reduction potential (ORP) with a range of 13–16 mV compared to the control treatments, immediately after the production process. The lowest ORP value was recorded in the V1 and C treatment at 371.50 mV and 377.08 mV, respectively. However, the addition of apple vinegar at a 1% level did not significantly affect the ORP values, which were similar to the control sample. After seven days of storage, a significant decrease in the ORP value was observed only in the V3 treatment, while a significant increase in the V1 and V5 treatments was recorded (Table 4). The ORP index value further decreased by 18 mV and 6.6 mV in the C and V5 treatment, respectively, after 14 days of storage compared to the value measured after 7 days of storage ($p > 0.05$). Acetic acid bacteria are a type of bacteria that undergo oxidative metabolism ("oxidative bacteria"). This is because they tend to oxidize certain compounds like ethanol, carbohydrates, and sugar alcohols, resulting in the creation of diverse organic acids, aldehydes, and ketones. The products of these transformations may influence the increase in the oxidation-reduction potential and the amount of secondary fat oxidation products produced [45,46].

The efficacy of food preservation techniques and the impact of processing on the quality and safety of food can be gleaned through the quantification of secondary products. The TBARS value, which is considered an indicator of the lipid oxidation level, is generally correlated with the off-flavor intensity [47,48]. The TBARS value of the samples is reported in Table 4.

Table 4 shows that both apple vinegar and the storage time separately as well as in combination have a significant effect ($p < 0.05$) on TBARS values. The V3 treatment (with 3% apple vinegar) showed the highest TBARS value of $0.67 \text{ mg MDA kg}^{-1}$ ($p < 0.05$), while significantly lower values were found in the V5 treatment (0.55 MDA kg^{-1}) directly after production ($p < 0.05$). After being stored for seven days, the treatment with C showed a lower TBARS value ($p < 0.05$). However, the treatments with V1 and V5 showed a significant increase ($p < 0.001$) in the TBARS index value, with the value being higher by 0.1 MDA kg^{-1} and 0.14 MDA kg^{-1} , respectively, compared to the value measured right after production. After fourteen days, no significant differences in the TBARS values ($p > 0.05$) were found between treatments. However, all treatments showed a significant increase in the TBARS values ($p < 0.05$) after fourteen days of storage compared to seven days. During the marinating process, free unsaturated fatty acids are oxidized, resulting in secondary oxidation products. These products can have adverse effects on the taste, smell, and safety of the meat. The nutritional value of meat is also reduced due to the loss of essential fatty acids and vitamins resulting from oxidation. Additionally, lipid oxidation produces toxic compounds that are harmful to health. The first change observed due to oxidation is a gradual reduction in the quality of the meat, leading to color, texture, and appearance changes and the development of rancid odors and flavors that affect consumer acceptance. The study did not exceed the threshold for detecting oxidized taste aroma, which in beef is 2 mg/kg [49,50]. Fencioglu et al. [51] studied the impact of marinating beef steak with different vinegars on its texture, protein profile, and formation of heterocyclic aromatic amines when cooked. However, the marinated and cooked beef steaks did not

show any significant differences in the TBARS value. According to the authors, the study results can be explained by the reactivity of thiobarbituric acid reactive substances (TBARS) with several compounds present in meat, including protein and amino acids. The reactive nature of TBARS leads to an interaction with these compounds, which sheds light on the observed outcomes. On the other hand, Rahman et al. [44] reported that fortifying fresh meat with 5% and 10% of vinegar for preservation at 4 °C is highly effective.

3.4. Fatty Acid

The fatty acid composition of the sausage after production and storage is shown in Table 5.

Table 5. Fatty acid composition of sausage (means $\pm$ standard deviation error).

Treatment		Storage Time (Days)			Treatment	Time	Treatment $\times$ Time
		0	7	14	<i>p</i>	<i>p</i>	<i>p</i>
SFA	C	37.25 $\pm$ 0.09 ^{abA}	37.20 $\pm$ 0.19 ^{aA}	37.33 $\pm$ 0.18 ^{aA}	*	NS	NS
	V1	37.13 $\pm$ 0.22 ^{aA}	37.25 $\pm$ 0.15 ^{aA}	37.23 $\pm$ 0.29 ^{aA}			
	V3	37.38 $\pm$ 0.08 ^{bA}	37.48 $\pm$ 0.27 ^{aA}	37.35 $\pm$ 0.05 ^{aA}			
	V5	37.13 $\pm$ 0.04 ^{aA}	37.18 $\pm$ 0.04 ^{aA}	37.10 $\pm$ 0.12 ^{aA}			
MUFA	C	44.68 $\pm$ 0.15 ^{aA}	45.05 $\pm$ 0.27 ^{aB}	45.10 $\pm$ 0.00 ^{aB}	*	NS	NS
	V1	45.25 $\pm$ 0.25 ^{cA}	45.15 $\pm$ 0.05 ^{aA}	45.15 $\pm$ 0.29 ^{aA}			
	V3	45.08 $\pm$ 0.04 ^{bcA}	45.13 $\pm$ 0.15 ^{aA}	45.20 $\pm$ 0.24 ^{aA}			
	V5	44.93 $\pm$ 0.04 ^{abA}	45.08 $\pm$ 0.04 ^{aA}	45.03 $\pm$ 0.18 ^{aA}			
PUFA	C	18.03 $\pm$ 0.19 ^{bB}	17.70 $\pm$ 0.19 ^{aAB}	17.58 $\pm$ 0.18 ^{aA}	**	NS	NS
	V1	17.60 $\pm$ 0.23 ^{aA}	17.60 $\pm$ 0.17 ^{aA}	17.58 $\pm$ 0.22 ^{aA}			
	V3	17.55 $\pm$ 0.05 ^{aA}	17.38 $\pm$ 0.39 ^{aA}	17.45 $\pm$ 0.23 ^{aA}			
	V5	17.95 $\pm$ 0.09 ^{bA}	17.70 $\pm$ 0.00 ^{aA}	17.83 $\pm$ 0.25 ^{aA}			

^{a-c} Means in the same columns with different superscript small letters differ significantly ($p < 0.05$). ^{A,B} Means in the same row with different superscript capital letters differ significantly ($p < 0.05$); C—control sausage without apple vinegar; V1, V3, V5—sausage with apple vinegar 1, 3, and 5%, respectively. *p*: significance of effects; treatment; time; treatment–time interaction; NS—not significant; * $p < 0.05$; ** $p < 0.01$.

It was found that the changes in the fatty acid profile in individual samples are small but statistically significant. Treatment significantly affected the total saturated fatty acid (SFA), monounsaturated fatty acid (MUFA), and polyunsaturated fatty acid (PUFA) proportions of the sausage ($p < 0.05$). Analysis of the fatty acid profile in the C treatment after production (time 0) revealed the highest PUFA content (18.03%) and lowest MUFA content (44.68%), significantly ($p < 0.05$). The opposite trend was observed in the V1 and V3 treatments, where the lowest PUFA content (17.60% and 17.55%, respectively) and the highest MUFA content (45.25% and 45.08%, respectively) were observed. In the V3 treatment, the SFA content was higher than in the V1 and V5 treatments after production ($p < 0.05$) (Table 4). The significantly higher SFA and lowest MUFA content in the control (C) treatment after production was mainly caused by oxidative changes because unsaturated fatty acids are oxidized faster [49]. The composition of fatty acids in food is subject to change during processing and storage, thereby influencing both the taste and nutritional quality of the food. Unsaturated fatty acids are particularly susceptible to oxidation [48]. In light of our study, it is observed that the use of apple vinegar treatment (V1, V3, V5) resulted in lowered levels of PUFA, coupled with increased levels of TBARS and ORP immediately after production. This observation suggests that vinegar fails to provide adequate protection against lipid oxidation, unlike sodium nitrite employed in the C treatment. Sodium nitrite provides better lipid protection, which is supported by the existing literature [48]. According to a study conducted by Toomik et al. [52], the inclusion of acetic acid in pork marinades is reported to promote the oxidation of the free polyunsaturated fatty acids present in the meat. However, no significant differences in the PUFA content were found among the tested samples in other studies [11]. These results confirm that vinegar and curing salt protect polyunsaturated fatty acids against oxidative changes. There are many factors which determine the susceptibility of meat

to lipid oxidation. These factors include, but are not limited to, the balance between antioxidant and pro-oxidant factors, as well as the fatty acid composition of the meat lipid fractions [48,49]. The processing of meat has the potential to disrupt cell structures which can result in the interaction of polyunsaturated fatty acids and prooxidants, leading to lipid oxidation [48,49].

3.5. Color

The sausage with 5% added apple vinegar (V5) had the highest brightness parameter L^* (54.67–55.34) immediately after production and throughout storage ($p < 0.05$) (Table 6).

Table 6. Color parameters of sausage (means $\pm$ standard deviation error).

Treatment		Storage Time (Days)			Treatment	Time	Treatment $\times$ Time
		0	7	14	<i>p</i>	<i>p</i>	<i>p</i>
L^*	C	52.78 $\pm$ 0.64 ^{aA}	52.29 $\pm$ 1.34 ^{aA}	54.42 $\pm$ 1.27 ^{aB}	***	***	**
	V1	53.94 $\pm$ 2.07 ^{bcB}	51.78 $\pm$ 2.27 ^{aA}	53.97 $\pm$ 2.11 ^{aB}			
	V3	53.60 $\pm$ 1.62 ^{abB}	52.27 $\pm$ 1.73 ^{aA}	55.49 $\pm$ 1.42 ^{bcC}			
	V5	54.67 $\pm$ 1.96 ^{cB}	52.47 $\pm$ 1.72 ^{aA}	55.34 $\pm$ 1.33 ^{bB}			
a^*	C	18.58 $\pm$ 0.44 ^{aB}	18.91 $\pm$ 0.94 ^{aB}	16.93 $\pm$ 1.10 ^{aA}	***	***	***
	V1	18.90 $\pm$ 0.91 ^{abA}	18.75 $\pm$ 1.09 ^{aA}	18.88 $\pm$ 0.98 ^{bA}			
	V3	19.21 $\pm$ 0.74 ^{bcA}	19.63 $\pm$ 0.84 ^{bB}	19.23 $\pm$ 0.77 ^{bcA}			
	V5	19.57 $\pm$ 1.37 ^{cA}	19.70 $\pm$ 0.82 ^{bA}	19.52 $\pm$ 0.76 ^{cA}			
b^*	C	1.82 $\pm$ 0.44 ^{aA}	2.77 $\pm$ 0.94 ^{bB}	2.52 $\pm$ 1.10 ^{bB}	***	***	*
	V1	1.83 $\pm$ 0.47 ^{aA}	2.40 $\pm$ 0.72 ^{aB}	1.91 $\pm$ 0.58 ^{aA}			
	V3	2.47 $\pm$ 0.54 ^{bA}	3.38 $\pm$ 0.46 ^{cB}	2.68 $\pm$ 0.55 ^{bA}			
	V5	3.01 $\pm$ 0.57 ^{cA}	3.56 $\pm$ 0.59 ^{cB}	3.18 $\pm$ 0.64 ^{cA}			

^{a–c} Means in the same columns with different superscript small letters differ significantly ($p < 0.05$); ^{A–C} Means in the same row with different superscript capital letters differ significantly ($p < 0.05$); C—control sausage without apple vinegar; V1, V3, V5—sausage with apple vinegar 1, 3, and 5%, respectively. *p*: significance of effects; treatment; time; treatment–time interaction; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Sausage C was the darkest (52.78–54.42). Treatments V3 and V5 had significantly higher shades of red (a^* 19.21–19.70; $p < 0.05$). Treatment V3 showed significant reddening after 7 days of storage (a^* 19.63; $p < 0.05$). Only control sausages had the intensity of yellow color that increased during storage ($p < 0.05$). Sausage V5 was the most yellow (b^* 3.01–3.56; $p < 0.05$). The color of meat depends on heme pigments and their oxidation-reduction changes. The redox status of iron in the myoglobin molecule determines the pinkish-red color of meat [47,53]. The formation of nitrosyl myoglobin (NO-myoglobin) is responsible for this color, which occurs when myoglobin (Fe^{2+}) binds with NO, formed previously from N_2O_3 . Nitrosyl myoglobin (NO-myoglobin) formation causes the color, and heat treatment causes unstable NO-myoglobin to degrade to form nitrosomyochromogen. The color of meat is subject to deterioration as a result of exposure to ultraviolet (UV) light and harmful bacteria. The redness of meat products is largely dependent on the presence of nitric oxide (NO), which serves as a source of nitrite [53]. Based on the analysis of the color (parameter a^*) of the tested sausages, we can assume that the addition of apple cider vinegar promoted the formation of NO-myoglobin. The pH plays a crucial role in nitric oxide formation from nitrite. As acidity increases, the reactivity of nitrous acid (HNO_2) and nitrite increases. As the pH level is reduced by 0.2–0.3 units, the rate of nitric oxide (NO) formation doubles [54,55]. According to Pohlman et al. [56], a solution containing 1% ozonated water and 5% acetic acid can effectively reduce the redness and oxymyoglobin content, and improve the color stability of displayed beef. Acetic acid promotes pigment oxidation by lowering the muscle pH. The pH levels play a crucial role in ensuring the optimal quality of meat products.

3.6. Sensory Quality

The Quantitative Descriptive Analysis method was used to conduct a sensory evaluation of the experimental sausage samples after 14 days, and the results are presented in Figure 2.

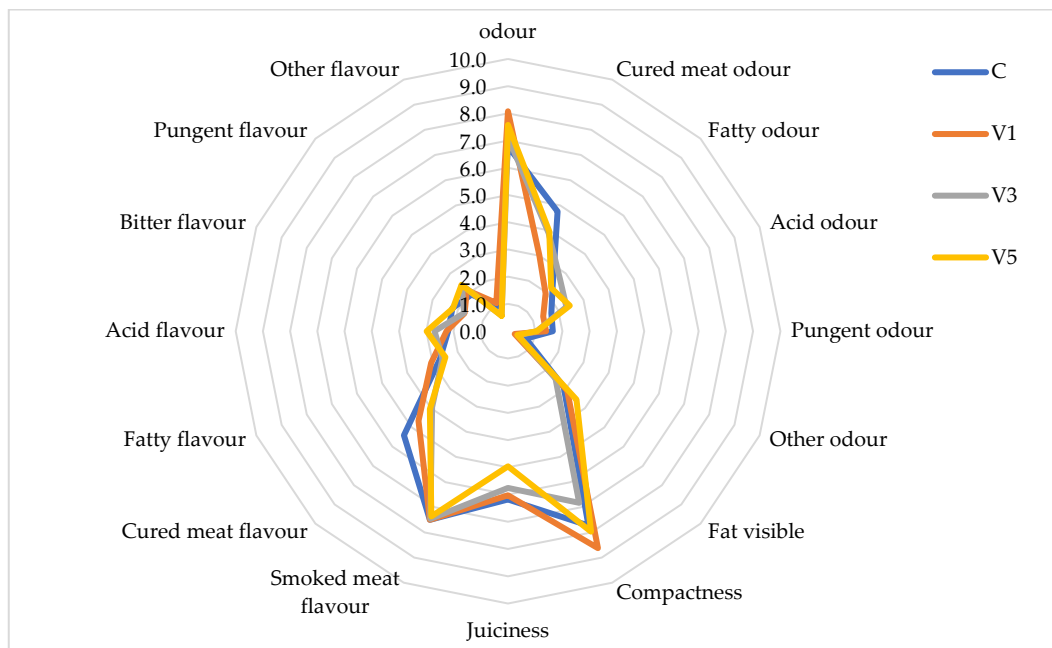


Figure 2. Sensory profile of the sausage after 14 days. Explanatory notes: C—control sausage without apple vinegar; V1, V3, V5—sausage with apple vinegar 1, 3, and 5%, respectively.

Sensory characteristics such as taste, appearance, texture, color, and smell are essential motivating factors that drive consumers toward the shopping and consumption of food products [49,57]. The products exhibited a pronounced smoked meat flavor profile, with a comparatively lower intensity of cured meat notes. The sensory analysis further revealed the presence of fatty, acidic, and pungent odors, amongst others, albeit at a lesser intensity. A slice of sausage showed the pink color of the meat and the bright white color of the fat. The V1 treatment showed the highest compactness of sausage slice, while significantly lower values were found in the V3 treatment. The juiciness and intensity of the smoked meat flavor were highly evaluated in all treatments, with around 5.7 c.u. and 7.2 c.u., respectively. However, no significant differences were found between the particular samples ($p > 0.05$). The addition of apple vinegar to the sausage lowered the intensity of the cured meat flavor. The flavor of food is a manifestation of the complex interactions between aroma, taste, and oral sensations. Aroma, in particular, is associated with volatile compounds, while taste is linked with non-volatile, high-molecular-weight components [58]. Lipids, which are present in most food items, play a crucial role in determining the taste and aroma of food. However, lipid oxidation can also lead to the production of off-flavors and volatile compounds that can negatively impact the sensory quality of food. Notably, the number of compounds formed as a result of oxidative transformations in the V1, V3, and V5 treatments was insufficient to cause any significant differences in the sensory quality. The addition of apple vinegar to the sausage decreased the intensity of the fatty flavor, which was probably masked by peptides and free amino acids that could have affected the sensory perceptions of the evaluators [44,57]. There were no statistically significant differences in the intensity of the acid, bitter, pungent, and other flavors between treatments ($p > 0.05$).

4. Conclusions

In the conclusions, it could be assumed that our study demonstrated the possibility of 1%, 3%, and 5% apple vinegar addition to the sausages during production to improve the quality of the final product. It was found that the addition of apple vinegar to the process of sausage production did not affect significantly the microbiological and sensory quality of the final meat products, but resulted in a slight reduction in the intensity of the cured meat flavor and the fatty flavor, as well as had an impact on color. The sausages with the addition of

apple vinegar were characterized by greater redness. The exploration of vinegar's effects on the production process presents the opportunity to discover a natural and healthier method for adjusting the color of meat products. This avenue of research has the potential to identify and develop alternative methods that are both more environmentally friendly and cost-effective. Therefore, it is believed that the use of vinegar allows for the reduction of the addition of nitrites in the product. However, it should be noticed that the weakness of this solution is undesirable changes in fatty acid composition as well as some physicochemical parameters of model meat products (ORP and TBARS), due to the oxidative fermentation processed by the acetic acid bacteria included in unfiltered vinegar. Therefore, according to the results presented in this work, it can be concluded that 3% of vinegar is the optimal addition, which may be used in the next step of investigation. Further research addressing the use of apple vinegar as a color modulator is needed to better understand the role of oxidative changes in meat products. Moreover, research is warranted to explore the potential of this solution in sausages made from diverse sources, such as poultry, pork, and game. Additionally, it is recommended to examine the effectiveness of other kinds of vinegar, including wine and different fruit vinegar, in this context. Such investigations would provide valuable insights into the versatility of this solution and its potential applicability in a broader range of sausages and vinegar types.

Author Contributions: Conceptualization, P.S. and Z.J.D.; methodology, P.S., A.O., A.L., U.S., D.Z., K.N.-S., M.T., K.K.-S., B.S. and M.K.; software, A.O.; validation, P.S. and D.Z.; formal analysis, P.S.; investigation, P.S., A.O., A.L., U.S., D.Z., K.N.-S., M.T., K.K.-S., B.S. and M.K.; resources, A.O.; data curation, A.O.; writing—original draft preparation, A.O., P.S. and D.Z.; writing—review and editing, Z.J.D. and D.K.-K.; visualization, A.O.; supervision, Z.J.D. and D.K.-K.; project administration, P.S. and Z.J.D.; funding acquisition, P.S. and Z.J.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Minister of Agriculture and Rural Development from a subsidy for organic farming research, grant number JPR.re.027.8.2021.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Rector's Committee for the Ethics of Scientific Research Involving Humans at WULS-SGGW (Resolution No. 28/RKE/2023/U of 6 July 2023).

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A



Figure A1. Cont.



Figure A1. The photography of cooked meat sausages samples.

References

1. Khodayari, M.; Basti, A.A.; Khanjari, A.; Misaghi, A.; Kamkar, A.; Shotorbani, P.M.; Hamed, H. Effect of poly (lactic acid) films incorporated with different concentrations of Tanacetum balsamita essential oil, propolis ethanolic extract and cellulose nanocrystals on shelf life extension of vacuum-packed cooked sausages. *Food Packag. Shelf Life* **2019**, *19*, 200–209. [\[CrossRef\]](#)
2. Mendoza, E.; García, M.L.; Casas, C.; Selgas, M.D. Inulin as fat substitute in low fat, dry fermented sausages. *Meat Sci.* **2001**, *57*, 387–393. [\[CrossRef\]](#)
3. Choi, Y.S.; Kim, T.K.; Jeon, K.H.; Park, J.D.; Kim, H.W.; Hwang, K.E.; Kim, Y.B. Effects of preconverted nitrite from red beet and ascorbic acid on quality characteristics in meat emulsions. *Korean J. Food Sci. Anim. Resour.* **2017**, *37*, 288. [\[CrossRef\]](#)
4. Lee, E.; Choe, J.; Shin, D.J.; Yong, H.I.; Choi, Y.; Yoon, Y.; Jo, C. Combined effect of high pressure and vinegar addition on the control of *Clostridium perfringens* and quality in nitrite-free emulsion-type sausage. *Innov. Food Sci. Emerg. Technol.* **2019**, *52*, 429–437. [\[CrossRef\]](#)
5. Xiang, R.; Cheng, J.; Zhu, M.; Liu, X. Effect of mulberry (*Morus alba*) polyphenols as antioxidant on physiochemical properties, oxidation and bio-safety in Cantonese sausages. *LWT* **2019**, *116*, 108504. [\[CrossRef\]](#)
6. Ma, L.; Hu, L.; Feng, X.; Wang, S. Nitrate and nitrite in health and disease. *Aging Dis.* **2018**, *9*, 938. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Šojić, B.; Pavlič, B.; Ikonić, P.; Tomović, V.; Ikonić, B.; Zeković, Z.; Kocić-Tanackov, S.; Jokanović, M.; Škaljac, S.; Ivić, M. Coriander essential oil as natural food additive improves quality and safety of cooked pork sausages with different nitrite levels. *Meat Sci.* **2019**, *157*, 107879. [\[CrossRef\]](#) [\[PubMed\]](#)

8. Campêlo, M.; Medeiros, J.; Silva, J. Natural products in food preservation. *Int. Food Res. J.* **2019**, *26*, 41–46.
9. Carballo, D.E.; Giráldez, F.J.; Andrés, S.; Caro, I.; Fernández-Gutiérrez, M.; Mateo, J. Effects of dietary astaxanthin supplementation on the oxidative stability of meat from suckling lambs fed a commercial milk-replacer containing butylated hydroxytoluene. *Meat Sci.* **2019**, *156*, 68–74. [\[CrossRef\]](#)
10. Karam, L.; Roustom, R.; Abiad, M.G.; El Obeid, T.; Savvaidis, I.N. Combined effects of thymol, carvacrol and packaging on the shelf-life of marinated chicken. *Int. J. Food Microbiol.* **2019**, *291*, 42–47. [\[CrossRef\]](#)
11. Łepecka, A.; Szymański, P.; Okoń, A.; Siekierko, U.; Zielińska, D.; Trzaskowska, M.; Neffe-Skocińska, K.; Sionek, B.; Kajak-Siemaszkó, K.; Karbowiak, M.; et al. The Influence of the Apple Vinegar Marination Process on the Technological, Microbiological and Sensory Quality of Organic Smoked Pork Hams. *Foods* **2023**, *12*, 1565. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Neffe-Skocińska, K.; Karbowiak, M.; Kruk, M.; Kołożyn-Krajewska, D.; Zielińska, D. Polyphenol and antioxidant properties of food obtained by the activity of acetic acid bacteria (AAB)—A systematic review. *J. Funct. Foods* **2023**, *107*, 105691. [\[CrossRef\]](#)
13. Liu, Q.; Tang, G.-Y.; Zhao, C.-N.; Gan, R.-Y.; Li, H.-B. Antioxidant Activities, Phenolic Profiles, and Organic Acid Contents of Fruit Vinegars. *Antioxidants* **2019**, *8*, 78. [\[CrossRef\]](#)
14. Ousaaïd, D.; Imtara, H.; Laaroussi, H.; Lyoussi, B.; Elarabi, I. An Investigation of Moroccan Vinegars: Their Physicochemical Properties and Antioxidant and Antibacterial Activities. *J. Food Qual.* **2021**, *2021*, 6618444. [\[CrossRef\]](#)
15. Kalembe-Drożdż, M.; Kwiecień, I.; Szewczyk, A.; Cierniak, A.; Grzywacz-Kisieleska, A. Fermented Vinegars from Apple Peels, Raspberries, Rosehips, Lavender, Mint, and Rose Petals: The Composition, Antioxidant Power, and Genoprotective Abilities in Comparison to Acetic Macerates, Decoctions, and Tinctures. *Antioxidants* **2020**, *9*, 1121. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Ousaaïd, D.; Mechchate, H.; Laaroussi, H.; Hano, C.; Bakour, M.; El Ghouizi, A.; Conte, R.; Lyoussi, B.; El Arabi, I. Fruits Vinegar: Quality Characteristics, Phytochemistry, and Functionality. *Molecules* **2022**, *27*, 222. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Xia, T.; Kang, C.; Qiang, X.; Zhang, X.; Li, S.; Zhang, X.; Wang, Y.; Wang, J.; Cao, H.; Wang, M. Beneficial effect of vinegar consumption associated with regulating gut microbiome and metabolome. *Curr. Res. Food Sci.* **2023**, *8*, 100566. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Ousaaïd, D.; Laaroussi, H.; Bakour, M.; ElGhouizi, A.; Aboulghazi, A.; Lyoussi, B.; ElArabi, I. Beneficial Effects of Apple Vinegar on Hyperglycemia and Hyperlipidemia in Hypercaloric-Fed Rats. *J. Diabetes Res.* **2020**, *2020*, 9284987. [\[CrossRef\]](#)
19. Laranjo, M.; Potes, M.E.; Gomes, A.; Véstia, J.; Garcia, R.; Fernandes, M.J.; Fraqueza, M.J.; Elias, M. Shelf-life extension and quality improvement of a Portuguese traditional ready-to-eat meat product with vinegar. *Int. J. Food Sci. Technol.* **2019**, *54*, 132–140. [\[CrossRef\]](#)
20. Unal, K.; Alagöz, E.; Çelik, İ.; Sarıçoban, C. Marination with citric acid, lemon, and grapefruit affects the sensory, textural, and microstructure characteristics of poultry meat. *Br. Poult. Sci.* **2022**, *63*, 31–38. [\[CrossRef\]](#)
21. ISO 15214:2002; Microbiology of Food and Animal Feeding Stuffs—Horizontal Method for the Enumeration of Mesophilic Lactic Acid Bacteria—Colony-Count Technique at 30 Degrees C. ISO: Geneva, Switzerland, 2002.
22. ISO 11290-1:2017; Microbiology of the Food Chain—Horizontal Method for the Detection and Enumeration of *Listeria monocytogenes* and of *Listeria* spp.—Part 1: Detection Method. ISO: Geneva, Switzerland, 2017.
23. ISO 6579-1:2017; Microbiology of the Food Chain—Horizontal Method for the Detection, Enumeration and Serotyping of *Salmonella*—Part 1: Detection of *Salmonella* spp. ISO: Geneva, Switzerland, 2017.
24. ISO 21528-2:2017; Microbiology of the Food Chain—Horizontal Method for the Detection and Enumeration of Enterobacteriaceae—Part 2: Colony-Count Technique. ISO: Geneva, Switzerland, 2017.
25. ISO 16649-1:2018; Microbiology of the Food chain—Horizontal Method for the Enumeration of Beta-Glucuronidase-Positive *Escherichia coli*—Part 1: Colony-Count Technique at 44 Degrees C Using Membranes and 5-Bromo-4-Chloro-3-Indolyl Beta-D-Glucuronide. ISO: Geneva, Switzerland, 2018.
26. ISO 6888-1:2021; Microbiology of the Food Chain—Horizontal Method for the Enumeration of Coagulase-Positive Staphylococci (*Staphylococcus aureus* and Other Species)—Part 1: Method Using Baird-Parker Agar Medium. ISO: Geneva, Switzerland, 2021.
27. ISO 4833-1:2013; Microbiology of the Food Chain—Horizontal Method for the Enumeration of Microorganisms—Part 1: Colony Count at 30 °C by the Pour Plate Technique. ISO: Geneva, Switzerland, 2013.
28. ISO 1442:1997; Meat and Meat Products—Determination of Moisture Content (Reference Method). ISO: Geneva, Switzerland, 1997.
29. ISO 937:1978; Meat and Meat Products—Determination of Nitrogen Content (Reference Method). ISO: Geneva, Switzerland, 1978.
30. ISO 1444:1996; Meat and Meat Products—Determination of Free Fat Content. ISO: Geneva, Switzerland, 1996.
31. IBPRS-PIB Procedura Laboratorium nr PA/04, Wydanie 7 z Dnia 08.06.2021 r. (Certyfikat Akredytacji Laboratorium Badawczego nr AB 553 Wydanym Przez Polskie Centrum Akredytacji). Available online: <https://www.pca.gov.pl/akredytowane-podmioty/akredytacje-aktywne/laboratoria-badawcze/AB%20553,plik.html> (accessed on 5 May 2024).
32. PN-A-82059:1985; Przetwory Mięsne—Wykrywanie i Oznaczanie Zawartości Skrobi. Available online: <https://sklep.pkn.pl/pn-a-82059-1985p.html> (accessed on 5 May 2024).
33. Ahn, D.U.; Nam, K.C. Effect of ascorbic acid and antioxidants on color, lipid oxidation and volatiles of irradiated ground beef. *Radiat. Phys. Chem.* **2003**, *71*, 149–154.
34. Pikul, J.; Leszczynski, D.E.; Kummerow, F.A. Evaluation of three modified TBA methods for measuring lipid oxidation in chicken meat. *J. Agric. Food Chem.* **1989**, *37*, 1309–1313. [\[CrossRef\]](#)

35. ISO 12966-1:2014; Animal and Vegetable Fats and Oils—Gas Chromatography of Fatty Acid Methyl Esters—Part 1: Guidelines on Modern Gas Chromatography of Fatty acid Methyl Esters. ISO: Geneva, Switzerland, 2014.
36. ISO 13299:2016; Sensory Analysis—Methodology—General Guidance for Establishing a Sensory Profile. ISO: Geneva, Switzerland, 2016.
37. ISO 8586:2023; Sensory Analysis—Selection and Training of Sensory Assessors. ISO: Geneva, Switzerland, 2023.
38. Surówka, K.; Maciejaszek, I.; Walczak, K.; Walczycka, M.; Surówka, B.; Rzepka, M.; Banaś, J. Chemical composition, safety and quality attributes of traditional cottage sausage. *Czech J. Food Sci.* **2019**, *37*, 325–331. [\[CrossRef\]](#)
39. European Commission. Commission Regulation (EC) No 1441/2007 of 5 December 2007 amending Regulation (EC) No 2073/2005 on microbiological criteria for foodstuffs. *Off. J. Eur. Union* **2007**, *322*, 12–29.
40. Aktas, N.; Kaya, M. The influence of marinating with weak organic acids and salts on the intramuscular connective tissue and sensory properties of beef. *Eur. Food Res. Technol.* **2001**, *213*, 88–94. [\[CrossRef\]](#)
41. Jones, M.; Arnaud, E.; Gouws, P.; Hoffman, L.C. Effects of the addition of vinegar, weight loss and packaging method on the physicochemical properties and microbiological profile of biltong. *Meat Sci.* **2019**, *156*, 214–221. [\[CrossRef\]](#)
42. Seong, P.-N.; Kim, J.-H.; Cho, S.-H.; Kang, G.-H.; Park, B.-Y.; Park, K.-M.; Kim, D.-H.; Kim, D. The effects of marinating with commercial vinegars on the quality characteristics of biceps femoris muscle on Hanwoo. *Ann. Anim. Resour. Sci.* **2012**, *23*, 26–32.
43. Sengun, I.Y.; Turp, G.Y.; Cicek, S.N.; Avci, T.; Ozturk, B.; Kilic, G. Assessment of the effect of marination with organic fruit vinegars on safety and quality of beef. *Int. J. Food Microbiol.* **2021**, *336*, 108904. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Rahman, M.; Sarker, M.; Hashem, M.A.; Azad, M.A.K.; Rahman, M. Food grade vinegar acts as an effective tool for short-term meat preservation. *Meat Res.* **2021**, *1*, 1–9.
45. Lynch, K.M.; Zannini, E.; Wilkinson, S.; Daenen, L.; Arendt, E.K. Physiology of acetic acid bacteria and their role in vinegar and fermented beverages. *Compr. Rev. Food Sci. Food Saf.* **2019**, *18*, 587–625. [\[CrossRef\]](#) [\[PubMed\]](#)
46. Mamlouk, D.; Gullo, M. Acetic acid bacteria: Physiology and carbon sources oxidation. *Indian J. Microbiol.* **2013**, *53*, 377–384. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Feng, X.; Li, C.; Jia, X.; Guo, Y.; Lei, N.; Hackman, R.M.; Chen, L.; Zhou, G. Influence of sodium nitrite on protein oxidation and nitrosation of sausages subjected to processing and storage. *Meat Sci.* **2016**, *116*, 260–267. [\[CrossRef\]](#) [\[PubMed\]](#)
48. Sampaio, G.R.; Saldanha, T.; Soares, R.A.M.; Torres, E.A.F.S. Effect of natural antioxidant combinations on lipid oxidation in cooked chicken meat during refrigerated storage. *Food Chem.* **2012**, *135*, 1383–1390. [\[CrossRef\]](#)
49. Domínguez, R.; Pateiro, M.; Gagaoua, M.; Barba, F.J.; Zhang, W.; Lorenzo, J.M. A Comprehensive Review on Lipid Oxidation in Meat and Meat Products. *Antioxidants* **2019**, *8*, 429. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Campo, M.; Nute, G.; Hughes, S.; Enser, M.; Wood, J.; Richardson, R. Flavour perception of oxidation in beef. *Meat Sci.* **2006**, *72*, 303–311. [\[CrossRef\]](#)
51. Fencioğlu, H.; Oz, E.; Turhan, S.; Proestos, C.; Oz, F. The Effects of the Marination Process with Different Vinegar Varieties on Various Quality Criteria and Heterocyclic Aromatic Amine Formation in Beef Steak. *Foods* **2022**, *11*, 3251. [\[CrossRef\]](#)
52. Toomik, P.; Lepp, K.; Lepasalu, L.; Püssa, T. The effect of tenderizing acids on linoleic acid oxidation during marination of pork. *Meat Sci.* **2012**, *92*, 870–873. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Szymański, P.; Łaszkiewicz, B.; Kern-Jędrychowska, A.; Siekierko, U.; Kołożyn-Krajewska, D. The Use of the Mixed Bacteria *Limosilactobacillus fermentum* and *Staphylococcus carnosus* in the Meat Curing Process with a Reduced Amount of Sodium Nitrite. *Appl. Sci.* **2021**, *11*, 904. [\[CrossRef\]](#)
54. Skibsted, L.H. Nitric oxide and quality and safety of muscle based foods. *Nitric Oxide* **2011**, *24*, 176–183. [\[CrossRef\]](#)
55. Gassara, F.; Kouassi, A.P.; Brar, S.K.; Belkacemi, K. Green alternatives to nitrates and nitrites in meat-based products—A review. *Crit. Rev. Food Sci. Nutr.* **2016**, *56*, 2133–2148. [\[CrossRef\]](#)
56. Pohlman, F.W.; Stivarius, M.R.; Mcelyea, K.S.; Johnson, Z.B.; Johnson, M.G. The effects of ozone, chlorine dioxide, cetylpyridinium chloride and trisodium phosphate as multiple antimicrobial interventions on microbiological, instrumental color, and sensory color and odor characteristics of ground beef. *Meat Sci.* **2002**, *61*, 307–313. [\[CrossRef\]](#) [\[PubMed\]](#)
57. Neffe-Skocińska, K.; Okoń, A.; Kołożyn-Krajewska, D.; Dolatowski, Z. Amino acid pro-file and sensory characteristics of dry fermented pork loins produced with a mixture of probiotic starter cultures. *J. Sci. Food Agric.* **2017**, *97*, 2953–2960. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Shahidi, F.; Hossain, A. Role of Lipids in Food Flavor Generation. *Molecules* **2022**, *27*, 5014. [\[CrossRef\]](#) [\[PubMed\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.