

Article

Quality of Sous Vide-Cooked Pork Loin Stored in Refrigerated Conditions

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Abstract: The sous vide cooking method offers advantage in preparing meat dishes in advance. This study aimed to evaluate the effect of refrigerated storage on the quality attributes of pork loin sous vide cooked under selected, optimised temperature and time parameters. Pork loin was cooked at varying temperatures (57–63 °C) and times (3.5–5.5 h), followed by refrigerated storage for up to 7 days. Analytical methods, including TBARS index for lipid oxidation, instrumental colour measurement, texture analysis, and volatile compound profiling, were used to assess changes in meat quality over time. The results indicated that heat treatment and storage time significantly influenced lipid oxidation, colour, and texture. The highest TBARS values were observed at higher cooking temperatures (61 °C and 63 °C), reflecting increased lipid oxidation. Colour changes were also temperature- and time-dependent, with a decrease in redness (a^*) and an increase in lightness (L^*) and yellowness (b^*). Sensory evaluation revealed that juiciness, aroma intensity, tenderness, and flavour acceptability were strongly correlated with overall acceptability, while physical characteristics like colour and texture had a lesser impact. The study highlights the impact of sous vide cooking parameters on the quality and sensory attributes of pork loin, suggesting that optimised heat treatment can help preserve desirable meat characteristics during refrigerated storage.

Keywords: pork loin; sous vide; storage; physicochemical properties; sensory properties



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1. Introduction

Meat processing and storage methods are of great importance for the nutritional value, sensory quality, and safety of meat products. Sous vide heat treatment, which involves vacuum packaging of meat and then cooking it at a relatively low, precisely controlled temperature for a long time, is becoming more and more popular due to its ability to maintain high sensory quality of meat, including its juiciness and tenderness [1–3]. Mild heat treatment conditions used during sous vide cooking help minimise the negative impact of heat treatment on nutrients, such as proteins, lipids, and vitamins [4–6], while vacuum sealing prevents evaporation losses from cooking, preserves the volatile compounds responsible for meat flavour, and minimises generation of off-flavours [7]. In addition, the sous vide method allows the caterers to prepare meat dishes in advance with the intention of using them later due to the lowered risk of recontamination during their storage and handling before consumption [4].

The acceptance of any food product by consumers is related mainly to its sensory characteristics. One of the key parameters for assessing the quality of meat subjected to

heat treatment is its colour, which can be objectively measured, for example, using the CIELAB colour space. The colour of meat changes mainly due to the protein denaturation and oxidative reactions that occur both during cooking and storage. Colour is closely linked to the functional properties of meat, significantly influencing the visual appeal of the cooked product and, as a result, consumers' choices [8].

An important aspect in assessing the quality of cooked meat is also its texture. The moderate cooking parameters applied in sous vide method (low temperature–long time) favour a better retention of fluids in meat compared to traditional methods of cooking, and since water is the main plasticiser of meat, sous vide-cooked meat is more tender than meat prepared using traditional methods [9]. In addition, sous vide cooking, as opposed to traditional methods, enables greater activity of endogenous enzymes like cathepsins, which contribute to meat tenderness by enhancing collagen solubility [10].

The flavour of meat is induced by the presence of water-soluble and nonvolatile (taste) as well as volatile (aroma) compounds. Salts, sugars, organic acids, free amino acids, nucleic acids, and peptides are the main contributors to meat taste, while volatile compounds generated during the thermal degradation of fatty acids and Maillard reactions are responsible for cooked meat aroma [11]. Nevertheless, the importance of Maillard reactions in shaping the aroma of sous vide-cooked meat is limited due to the low temperatures applied in this cooking method; therefore, derivatives of lipid degradation dominate in such meat aroma [11,12].

Lipid oxidation is one of the factors that determine the storage stability and shelf life of food products. In general, oxidative processes lead to the reduction in the nutritional value of meat [13], deterioration of sensory properties [14], and shortening the shelf life of meat products [15]; however, some compounds derived from lipid oxidation also contribute to the flavour characteristic of cooked [16] or dry-cured [17] meat. Lipid degradation begins when the animal is slaughtered and continues gradually until the final product is consumed [18]. The impact of lipid oxidation on meat is particularly important during long storage when oxidation products accumulate, leading to the distinct deterioration of meat quality. Additionally, lipid oxidation poses a potential risk to human health. One of the secondary oxidation products, malondialdehyde (MDA), although prone to the reactions with other compounds present in meat [19], is highly toxic and may show mutagenic and carcinogenic effects on the human organism [20].

In gastronomy, after heat treatment, sous vide-cooked meat can be served immediately or stored for later use. In the latter case, after heat treatment, sous vide-cooked meat should be quickly cooled using ice-water bath or blast chiller. Food safety standards specify that foods must be cooled to below 4 °C within 6 h, with 2 h allocated for cooling from 60 °C to 20 °C and an additional 4 h to lower the temperature from 20 °C to below 4 °C. Due to the risk of *Clostridium botulinum* growth in vacuum-sealed foods, further reduction of temperature and storage at a maximum of 3.3 °C is required. The optimal cooling conditions are even more strict—foods should be cooled to below 3 °C within 2 h, which is consistent with sous vide chefs' recommendations. The maximum storage time in refrigerated conditions for vacuum-packed and fully pasteurised food is 7 days. When longer storage is required, food should be stored in the frozen state. It is also recommended that raw, vacuum-packed food should not be stored for more than two days before pasteurization [21].

Most studies described in the literature were focused on the use of sous vide method in meat preparation for consumption and aimed at assessment of physicochemical properties of meat and/or optimization of cooking parameters in order to obtain the meat product of the best/most balanced eating quality. Only few papers available involved the evaluation of the effect of storage on the quality of sous vide-cooked meat. For example, Diaz et al. [22] investigated quality attributes of pork loin cooked only at 70 °C for 12 h and stored at

2 °C for 0, 5 or 10 weeks. Hong et al. [23] cooked chicken breast at 61 °C for 35 min after reaching the designed temperature and then stored meat samples for 0–14 days at 4 °C. Babür et al. [24] used in their experiment Simmental cattle meat, which was cooked at 70 °C for 2 and 4 h and then was evaluated after 7 days of storage at 2 °C. Gök et al. [25] analysed the quality of Simmental bulls meat, cooked at 80 °C for 75 min, during refrigerated storage at 1 °C for 0, 15 and 30 days. As can be seen above, the data presented in those publications is rather limited. Moreover, the Authors did not present the reasons for their choice of cooking and storage conditions.

Sous vide cooking gives gastronomy additional advantage of preparing meat dishes in advance and their later use after refrigerated storage. Since the literature related to the quality of sous vide-cooked and stored meat is very limited, the aim of the present study was to investigate the effects of refrigerated storage on the quality attributes of pork loin heat treated using the sous vide method. Specifically, the study focused on evaluating changes in key features such as colour, texture, oxidative stability, and sensory properties of meat prepared using optimised cooking temperature, and time parameters.

2. Material and Methods

In order to study the effect of storage on the quality characteristic of sous vide-cooked pork loin, one temperature/time treatment combination from each temperature group was selected on the basis of the results obtained for the samples evaluated shortly after heat treatment in our previous study [26]. That study demonstrated the beneficial impact of mild thermal conditions on meat quality. The optimisation of cooking parameters was conducted to achieve the best balance between sensory quality and physicochemical properties of the final products. Therefore, all meat features evaluated in that study were taken into consideration when selecting the cooking conditions for the present study. The choice of storing meat for 3 and 7 days was based on the potential application of this research in the culinary field, when quality changes are most noticeable and have a direct impact on decisions regarding meat processing, storage, and consumption in culinary practice.

2.1. Preparation of Samples

Pork loins from female pigs were used as research material and details of animals handling are described in Kurp and Danowska-Oziewicz [26]. The meat was obtained 24 h after slaughter from a local meat supplier and transported to the laboratory under refrigerated conditions. After vacuum packaging, meat was subjected to wet aging at 4 °C for 4 days. After that time pork loins were cut into 2.5 cm thick slices, and then the slices were vacuum packed in double layer pouches (15 µm nylon/60 µm polyethylene; heat resistance from −20 °C to +110 °C; Hendi, Lamprechtshausen, Austria) using the Edesa VAC-20 DT vacuum packing device (Barcelona, Spain), set at 99% vacuum. The slices of meat were randomly assigned to specific cooking conditions, which were selected on the basis of our previous study [26]. Therefore, the meat samples were heat-treated at 57 °C/5.5 h, 59 °C/4.5 h, 60 °C/4 h, 61 °C/4 h, and 63 °C/3.5 h, and after processing cooled in an ice-water bath and then stored until analyses, which were performed on days 0, 3, and 7 of storage. The pork loin samples were stored in laboratory refrigerator Liebherr LKexv 3600 MediLine (Ochsenhausen, Germany) set to a temperature of 2 °C, which was monitored using a calibrated temperature logger Testo 175-H2 (Testo SE&Co. KGaA, Titisee-Neustadt, Germany).

2.2. Analytical Methods

Meat samples were analysed for oxidative changes, colour parameters L^* , a^* and b^* , texture attributes, the volatile compounds profile, as well as sensory properties. Physic-

ochemical analyses were carried out in three parallel repetitions when not otherwise stated, and the whole experiment was repeated three times on three different batches of raw material.

2.2.1. Lipid Oxidation

Lipid oxidation was assessed in meat samples using the method outlined by Salih et al. [27] and described in detail in the publication by Kurp et al. [26]. The TBARS value was reported in milligrams of malondialdehyde per kilogram of sample [28].

2.2.2. Colour

Colour measurements were conducted using a CR-400 colorimeter (Konica Minolta Sensing Inc., Osaka, Japan), which featured a standard observer 2° and an illuminant D65. Colour coordinates in the CIELAB colour space were recorded at six randomly chosen locations on the cross-section of both raw and cooked meat samples. From these measurements, the chroma (C^*), hue angle (h°), and total colour difference (ΔE^*) in relation to the raw meat sample, were calculated. The methodology has been described in detail in the publication by Kurp et al. [26].

2.2.3. Instrumental Texture Analysis

Instrumental texture analysis was conducted using the TA.XTplus Texture Analyzer (Stable Micro Systems Ltd., Godalming, UK), which was equipped with a 50 kg load cell. Data collection was facilitated by the Texture Expert 1.21 software.

Shear Test

The maximum force obtained during the shear test was utilised as an indicator of meat hardness. A Warner–Bratzler V-notch blade was used as a cutting device, and it moved at a speed of 250 mm/min during the test. For each treatment, twenty specimens measuring 10 × 10 × 25 mm were cut parallel to the muscle fibers and evaluated.

Texture Profile Analysis (TPA)

The measurements were conducted by placing a meat sample on a fixed bottom plate and subjecting it to two-cycle compression, reducing it to 50% of its initial height with the use of a P/100 platen with a 50 mm diameter, which moved at a constant speed of 50 mm/min. The specimens analysed were cores with a diameter of 16 mm and a height of 20 mm, cut parallel to the muscle fibers; twenty specimens were evaluated for each treatment.

2.2.4. Volatile Compounds

Analyses of volatile compounds present in meat samples were performed using a GC-IMS instrument (FlavorSpec, Gesellschaft für Analytische Sensorsysteme GmbH, Dortmund, Germany) equipped with an autosampler. Chromatographic separation took place on an MXT-5 capillary column (15 m × 0.32 mm × 0.5 µm). One gram of minced meat sample was transferred to a 10 mL glass headspace sampling vial and then incubated at 50 °C for 10 min. Then, 500 µL of headspace was automatically injected into the injector using a heated syringe at 80 °C, splitless. Nitrogen with a purity of 99.99% was used as the carrier gas with a programmed flow as follows: 0 to 10 min, maintaining 2 mL/min, then from 10 to 15 min a linear increase to 10 mL/min, and from 15 to 40 min linear increase to 100 mL/min. The analytes were eluted and separated at 40 °C, and then the analytes were introduced into the ionization chamber for the ionisation in the positive ion mode using a 3H ionisation source with an activity of 370 MBq. The resulting ions were directed to a drift tube (9.8 cm long), which operated at a constant temperature (45 °C) and voltage

(5 kV). The drift gas (nitrogen) was set to 150 mL/min. Each spectrum was described as the average of 12 scans. The retention index of each compound was calculated using C4–C9 n-ketones as external standards. Identification of volatile compounds was performed by comparing the retention index and drift time with the GC-IMS library. Volatile compounds were identified using the software included in the apparatus-GCxIMS Library Search. This tool facilitates the assignment of chemicals to signal peaks in GC-IMS chromatograms based on NITS retention indices (Kovats). Data collection and analysis were performed using VOCal software (0.4.03 rev300) from GAS. This procedure was conducted according to Zhao et al. [29] with minor modifications.

2.2.5. Sensory Analysis

The sensory evaluation of the samples was conducted in a sensory analysis laboratory that featured individual assessment booths. A panel of 15 trained assessors from the Faculty of Food Science, University of Warmia and Mazury in Olsztyn, Poland, with the experience in food sensory analysis, carried out the evaluation [30]. The panel consisted of 10 females, ages 28–59 years, and 5 males, ages 24–54 years.

Before sensory assessment, meat samples were taken from the refrigerator and heated in the water bath at the temperature appropriate for each treatment to achieve the designated temperature. Samples, measuring 1 cm in thickness, were cut diagonally from cooked meat slices and presented to the panelists in a random order on white ceramic plates. A one-way 10 cm structured linear scale, was used following [31] to assess overall appearance, flavour acceptability, and overall acceptability (0—not acceptable, 10—very acceptable), colour uniformity (0—not uniform, 10—highly uniform), aroma intensity and meat flavour intensity (0—low, 10—very intense), tenderness (0—tough, 10—tender), and juiciness (0—low, 10—very high). Each sample evaluation was repeated twice during each experiment, with water and bread provided for the assessors throughout the evaluation process.

2.2.6. Statistical Analysis

Statistical analysis was conducted using the GLM procedure of Statistica 13.0 (TIBCO Software Inc., Tulsa, OK, USA). The mean values and the standard errors of the mean (SEM) for the results of physicochemical analyses and sensory evaluations were computed. The heat treatment and storage time were treated as independent variables. The results were evaluated for normality of the distribution and homogeneity of variances using Shapiro–Wilk test and Levene test, respectively. A two-way analysis of variance was employed to examine the effects of heat treatment and storage time, as well as their interaction, on the characteristics of the meat samples. The significance of differences was evaluated using Tukey's test, with differences deemed statistically significant at $p < 0.05$. Additionally, Pearson's correlation coefficients were calculated to explore potential relationships between overall acceptability and selected attributes of the meat samples.

3. Results and Discussion

The present study describes the changes that take place during refrigerated storage in pork loin sous vide cooked with the application of cooking parameters selected on the basis of our previous experiment [26]. Therefore, the effects of different cooking conditions on the quality of meat are discussed in details in that previous work. Nevertheless, some necessary explanations related to the influence of heating on the quality of meat are also included in this work.

3.1. Lipid Oxidation

Lipids present in processed meat are in great extent responsible for its desirable sensory attributes, such as flavour, texture, and juiciness. Nevertheless, they are susceptible to the oxidative processes caused by elevated temperatures and presence of oxygen [20]. In the present study, lipid oxidation in sous vide-cooked pork loin during refrigerated storage was evaluated with the use of TBARS index, which reflects the presence of thiobarbituric acid reactive substances derived mainly from lipids secondary oxidative reactions and is highly correlated with sensory evaluation scores [32].

Oxidative changes in meat, determined shortly after heat treatment at day 0 and at days 3 and 7 during refrigerated storage, are presented in Figure 1. In general, the increasing tendency in TBARS values was noted with increasing heat treatment temperature, as well as extended time of storage. At day 0, samples cooked at 57 °C/5.5 h, 59 °C/4.5 h, and 60 °C/4 h showed significantly lower TBARS values (1.47–1.59 mg MDA/kg) than samples cooked at 61 °C/4 h and 63 °C/3.5 h (1.75–1.78 mg MDA/kg). At day 3, only sample cooked at the lowest temperature was characterised by the TBARS value significantly lower (1.54 mg MDA/kg) than samples cooked at 61 and 63 °C (1.81–1.83 mg MDA/kg) and the same tendency was observed after 7 days of storage (1.58 mg MDA/kg vs. 1.82–1.84 mg MDA/kg, resp.). The decline in TBARS value observed for 60 °C/4 h treatment after 7 days of storage may result from natural changes occurring in the meat during storage, such as oxidative processes, water loss, or interactions between different compounds present in meat. Malondialdehyde (MDA), which is one of the secondary products of lipid oxidation and one of the main contributors to TBARS value [33], is highly reactive, and while, in general, its amount increases as a result of oxidation, it simultaneously reacts with other compounds present in meat, which makes it not detectable in TBARS assay [34]. Therefore, the TBARS values observed for stored meat products do not change in an unambiguous way but rather fluctuate [35], which presumably might have been the reason for the decrease observed in our study for the sample treated at 60 °C/4 h. Therefore, the highest TBARS values were recorded for samples heated at temperatures of 61 °C and 63 °C, which indicates more intense lipid oxidation at higher temperatures. It was shown that the TBARS values of samples were significantly influenced by treatment conditions ($p < 0.001$) and storage time ($p < 0.01$), but not by the interaction between them. A comparison of the TBARS value of raw meat (0.65 mg MDA/kg) and TBARS values of meat sous vide cooked and stored in refrigerated conditions (1.47–1.84 mg MDA/kg) suggests that heat treatment was the main contributor to the oxidative changes in meat products observed during short term storage in our study. Slight increases in TBARS values during storage of samples could be attributed to the presence of residual oxygen in the packages [36].

Hong et al. [23] observed an accelerated lipid oxidation in sous vide-cooked chicken breast compared to vacuum packed raw meat over the same refrigerated storage period. It can be seen that vacuum storage may delay, but does not completely prevent, lipid oxidation [37,38]. In the study by Diaz et al. [22], pork loin was cooked using sous vide method at 70 °C/12 h, then stored at 2 °C, and evaluated after cooking and after 5 and 10 weeks of storage. The authors observed a significant increase in the TBARS value after 5 weeks storage and a significant decrease in this value after 10 weeks storage, but all TBARS values were below 1 mg MDA/kg. Increasing and fluctuating TBARS values, but lower than 2 mg MDA/kg, were also observed for marinated, sous vide-cooked, and stored up to 8 weeks pork loin by Kim et al. [39]. Research by Roldan [40] showed that the TBARS value, which is used as an indicator of oxidative changes in food products, was significantly influenced by the temperature and time of cooking in lamb meat heated using the sous vide method. This observation was confirmed in our previous study on sous vide-cooked pork loin [26].

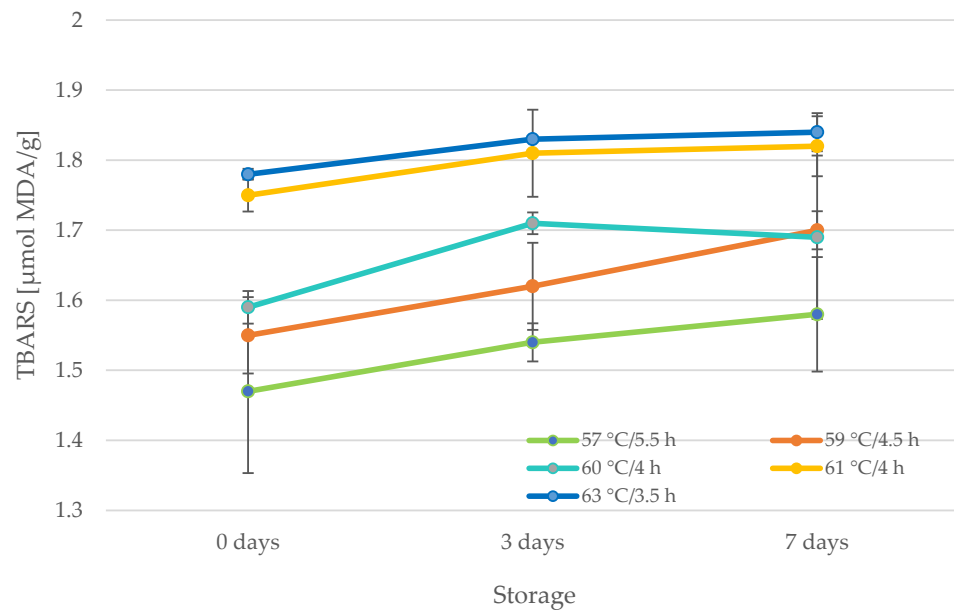


Figure 1. Oxidative changes in sous vide-cooked pork loin stored in refrigerated conditions (mean $\pm$ SD).

The higher values of the TBARS index noted in our study may be caused by different raw meat origins and differences in animal feed [41], as well as a lower antioxidant potential resulting from the presence of endogenous and exogenous antioxidants that naturally occur in meat [42,43]. Nevertheless, in other studies, TBARS values below 1 mg MDA/kg sample were reported for sous vide-cooked chicken breast during 25 days of refrigerated storage [44], turkey breast meat [45], and pork belly [46], but no storage was applied in the last two studies. TBARS values similar to our research, i.e., in the range of 1.8–3.3 mg MDA/kg, were observed for beef steaks subjected to high-pressure processing and then sous vide cooked but not stored [19], and the values in the range of 1.14–3.17 mg MDA/kg were observed for sous vide-cooked poultry during 14 days of refrigerated storage [23]. Lipid oxidation can lead to rancidity and warmed-over-flavour, and several thresholds of off-flavour detection were proposed by other authors, e.g., 0.5 μ g MDA/g [47] in pork, 2 mg MDA/kg [41], and 3.1 μ g MDA/g [48] in beef.

3.2. Colour

Visual appearance, including colour, is the first feature of a cooked meat assessed by the consumer and often has a decisive effect on the acceptance or rejection of the product. The colour of the meat is determined by the light reflecting, scattering, or absorbing [9,49]. The colour of cooked meat differs from that of the raw meat and the change can be attributed to the changes in moisture content [49,50], protein denaturation and aggregation [51], oxidation, enzymatic and nonenzymatic browning [52], and myoglobin denaturation [1,13,53] as well as metmyoglobin formation and its further denaturation [53–55].

The results of the colour coordinate measurements of raw and cooked and then stored pork loin using the CIE $L^*a^*b^*$ colour space are presented in Table 1. All lightness (L^*) values observed for cooked samples (65.23–75.40) were higher than that of raw meat (60.11), which indicates that the colour of meat lightened as a result of heat treatment. Lightness of stored meat samples was significantly affected by treatment and time of storage (both $p < 0.001$), while no significant effect of their interaction was demonstrated. Increasing L^* values were noted with increasing time of storage but the effect of treatment was not so clear since the highest L^* values were observed for samples cooked at 60 °C/4 h. Redness (a^*) values of stored pork loin samples were also significantly affected by treatment and time of storage (both $p < 0.001$), but the effect of their interaction was not significant. It

was shown that with an increase in the heating temperature and the extended storage time, a^* values decreased, which means that the meat became less red due to the higher degree of myoglobin degradation [52]. Redness values of the sample cooked at the lowest temperature (8.07–8.36) remained very close to the value measured for raw meat (8.65) throughout the entire storage period. The lowest a^* values were noted for the sample cooked at the highest temperature (6.38–6.67). Significant changes in a^* value during storage were noted only for samples cooked at 60 °C/4 h and at 61 °C/4 h.

Table 1. Colour parameters of sous vide-cooked pork loin stored in refrigerated conditions (mean $\pm$ SEM; $n = 3$).

Sample		Lightness L^*	Redness a^*	Yellowness b^*	Chroma C^*	Hue Angle h°	ΔE^*
Raw pork loin		60.11 $\pm$ 1.11	8.65 $\pm$ 0.10	5.01 $\pm$ 0.36	10.04 $\pm$ 0.24	29.70 $\pm$ 1.57	-
Treatment	Storage time						
57 °C/5.5 h	0 days	65.23 $\pm$ 0.69 ^a	8.36 $\pm$ 0.11 ^e	12.36 $\pm$ 0.29 ^a	14.93 $\pm$ 0.24 ^a	55.86 $\pm$ 0.72 ^a	8.96
	3 days	66.83 $\pm$ 0.80 ^{ab}	8.24 $\pm$ 0.18 ^{de}	12.28 $\pm$ 0.09 ^a	14.80 $\pm$ 0.11 ^a	56.16 $\pm$ 0.64 ^{ab}	9.91
	7 days	69.00 $\pm$ 0.26 ^{bcd}	8.07 $\pm$ 0.15 ^{de}	12.50 $\pm$ 0.14 ^a	14.88 $\pm$ 0.11 ^a	57.13 $\pm$ 0.63 ^{ab}	11.63
59 °C/4.5 h	0 days	68.19 $\pm$ 1.18 ^{abc}	8.10 $\pm$ 0.14 ^{de}	13.10 $\pm$ 0.23 ^{abc}	15.41 $\pm$ 0.23 ^{ab}	58.26 $\pm$ 0.52 ^{abc}	11.45
	3 days	68.45 $\pm$ 0.25 ^{abcd}	7.86 $\pm$ 0.31 ^{cde}	13.32 $\pm$ 0.19 ^{abcd}	15.48 $\pm$ 0.24 ^{ab}	59.50 $\pm$ 0.99 ^{cde}	11.80
	7 days	68.46 $\pm$ 0.23 ^{abcd}	7.51 $\pm$ 0.23 ^{bcd}	13.42 $\pm$ 0.14 ^{abcd}	15.39 $\pm$ 0.22 ^{ab}	60.81 $\pm$ 0.58 ^{cde}	11.90
60 °C/4 h	0 days	71.85 $\pm$ 0.57 ^{de}	7.76 $\pm$ 0.12 ^{cde}	13.15 $\pm$ 0.20 ^{abcd}	15.27 $\pm$ 0.18 ^{ab}	59.41 $\pm$ 0.53 ^{bcd}	14.31
	3 days	73.56 $\pm$ 0.75 ^{ef}	7.14 $\pm$ 0.12 ^{abc}	13.24 $\pm$ 0.52 ^{abcd}	15.07 $\pm$ 0.44 ^{ab}	61.42 $\pm$ 1.16 ^{cdef}	15.84
	7 days	75.40 $\pm$ 1.13 ^f	6.84 $\pm$ 0.17 ^{ab}	13.54 $\pm$ 0.14 ^{bcd}	15.19 $\pm$ 0.14 ^{ab}	63.21 $\pm$ 0.66 ^{efg}	17.60
61 °C/4 h	0 days	67.23 $\pm$ 1.06 ^{ab}	7.50 $\pm$ 0.11 ^{bcd}	14.01 $\pm$ 0.33 ^{cd}	15.90 $\pm$ 0.29 ^{ab}	61.76 $\pm$ 0.69 ^{def}	11.53
	3 days	68.38 $\pm$ 0.87 ^{abcd}	7.50 $\pm$ 0.10 ^{bcd}	14.07 $\pm$ 0.24 ^{cd}	15.94 $\pm$ 0.22 ^b	61.91 $\pm$ 0.51 ^{def}	12.32
	7 days	68.72 $\pm$ 0.81 ^{bcd}	6.51 $\pm$ 0.33 ^a	14.26 $\pm$ 0.13 ^d	15.70 $\pm$ 0.14 ^{ab}	65.53 $\pm$ 1.17 ^g	12.81
63 °C/3.5 h	0 days	71.00 $\pm$ 0.72 ^{cde}	6.67 $\pm$ 0.11 ^a	13.94 $\pm$ 0.18 ^{cd}	15.46 $\pm$ 0.16 ^{ab}	64.39 $\pm$ 0.53 ^{fg}	14.22
	3 days	71.03 $\pm$ 0.91 ^{cde}	6.51 $\pm$ 0.09 ^a	14.23 $\pm$ 0.16 ^d	15.66 $\pm$ 0.13 ^{ab}	65.38 $\pm$ 0.47 ^g	14.45
	7 days	74.39 $\pm$ 0.51 ^{ef}	6.38 $\pm$ 0.14 ^a	14.29 $\pm$ 0.08 ^d	15.65 $\pm$ 0.09 ^{ab}	65.94 $\pm$ 0.47 ^g	17.18
Storage time							
0 days		68.62 $\pm$ 0.49 ^a	7.68 $\pm$ 0.10 ^b	13.31 $\pm$ 0.14 ^a	15.40 $\pm$ 0.11 ^a	59.91 $\pm$ 0.49 ^a	12.09
3 days		69.89 $\pm$ 0.49 ^{ab}	7.34 $\pm$ 0.11 ^{ab}	13.55 $\pm$ 0.16 ^a	15.44 $\pm$ 0.12 ^a	61.47 $\pm$ 0.56 ^{ab}	12.86
7 days		71.36 $\pm$ 0.49 ^b	7.05 $\pm$ 0.13 ^a	13.60 $\pm$ 0.10 ^a	15.36 $\pm$ 0.08 ^a	62.57 $\pm$ 0.54 ^b	14.22
Level of significance							
Treatment		***	***	***	***	***	nd
Storage time		***	***	NS	NS	***	nd
Treatment $\times$ storage time interaction		NS	NS	NS	NS	NS	nd

^{a,b,c}...—mean values in columns, with different superscripts differ significantly at $p < 0.05$ according to Turkey's test; *** $p < 0.001$, NS—not significant, nd—not determined.

Yellowness (b^*) values of stored meat samples (12.28–14.29) were distinctly higher than b^* value measured for raw meat (5.01). There was a significant effect of treatment conditions on the value of the b^* parameter ($p < 0.001$) of stored samples, but no significant effects of storage time and the interaction between treatment and storage time were demonstrated. The lowest b^* values were observed for the sample cooked at 57 °C/5.5 h and the highest b^* values were noted for the samples cooked at the temperatures 61 °C/4 h and 63 °C/4 h.

The colour is influenced by oxidative processes related mainly to the oxidation of myoglobin, which leads to changes in the tone and intensity of meat redness [13,25,49,52,56]. Sut et al. [57] did not observe significant differences in colour parameters L^* , a^* and b^* of pork loin cooked to the same internal temperature by steaming, vacuum cooking, and sous vide cooking, but they differed from those parameters recorded for meat cooked in the oven. Tathong et al. [58] reported significantly higher b^* values of sous vide-cooked pork meat compared to meat cooked traditionally, but no significant differences were noted for L^* and a^* values.

Saturation (chroma, C^*) and tone (hue angle, h°) of colour are related to the myoglobin concentration in meat and its degree of denaturation. Cooked samples showed

higher values for both chroma (14.48–15.94) and hue angle (55.86–65.94) than raw meat ($C^* = 10.04$ and $h^\circ = 29.70$). An increase in the hue angle indicated the shift of the colour tone from reddish toward yellowish. Treatment conditions significantly influenced the colour saturation ($p < 0.001$) and colour tone ($p < 0.001$), while storage time significantly influenced only the colour tone ($p < 0.001$). There was no significant effect of interaction between treatment and storage time with respect to colour saturation and tone. Chroma values were relatively stable during storage of all samples, and the only significant difference was noted between the sample cooked at 61 °C/4 h and stored for 3 days and samples cooked at 57 °C/5.5 h on all storage days. No significant changes in colour chroma were noted during storage for particular treatments. Regarding the colour tone, the only significant changes (increase) in this parameter were found for samples heat treated at 60 °C/4 h and assessed on days 0 and 7 and for sample heat treated at 61 °C/4 h and assessed on day 7 compared to samples assessed on days 0 and 3.

The total colour difference ΔE^* allows us to evaluate the effects of different technological treatments on colour of food products. In our study, ΔE^* was calculated for cooked and stored samples in relation to the colour parameters of raw meat. It showed high values (>5), which means that regardless of the treatment conditions and storage time applied in the study, the colour changes were recognisable to an inexperienced observer [59]. The lowest values were noted for samples cooked at the lowest temperature (8.96–11.63) and the highest values were obtained for samples cooked at 60 °C/4 h (14.31–17.60). The values observed for the individual treatments tended to increase with prolonged time of storage.

Lightness of cooked meat is related to the structure of the muscle and changes in meat structural proteins, which affect the light reflecting and scattering properties of meat. Colour redness and yellowness are the result of the myoglobin form presence in meat and its ability to absorb light [9,49]. Initial values of colour parameters, measured on day 0, presumably resulted from the meat structural protein denaturation and related changes in moisture content [50,51], reduction in deoxymyoglobin and oxymyoglobin to metmyoglobin form, resulting in the loss of reddish and increase in brownish-green colour [60,61], as well as dull-brown ferrihemochrome appearance from myoglobin form denaturation [62]. Changes in particular colour parameters observed in our study seem to be interrelated since, in general, when higher L^* values were measured, lower a^* and higher b^* values were observed. This phenomenon is probably related to the oxidation of myoglobin to metmyoglobin, which has a brown colour [13,49,61], and its further denaturation due to the heat treatment [52,56,62].

Since the change in colour yellowness in our study was more pronounced upon cooking than the change in redness of meat, it seems that the change in the colour tone is more dependent on myoglobin degree of transformation than its concentration. Changes in meat colour during storage could be attributed to further transformation of myoglobin forms into ferrihemochrome, in spite of vacuum packaging involved. Smiddy et al. [36] reported the presence of residual oxygen in vacuum packages of beef, which may also have been present in packages used in our study and may have contributed to the myoglobin form oxidation and slight changes in colour parameters. According to Han et al. [49], when meat is stored in protective packaging, such as vacuum bags or a modified atmosphere, the presence of oxygen in package is significantly reduced, which limits the rate of colour deterioration.

Unfortunately, there are few studies described in the literature regarding the quality of meat processed using the sous vide method and stored. Nevertheless, fluctuating L^* and a^* values of sous vide-cooked beef during 7 days of storage were reported by Babür et al. [24]. In the study by Diaz et al. [22], no significant differences in colour parameters were observed when samples of sous vide-cooked pork loin were stored in refrigerated

conditions for 5 and 10 weeks. Gök et al. [25] noted lower L^* and a^* values during 30 days storage of sous vide-cooked beef than directly after heat treatment.

3.3. Instrumental Texture Analysis

The texture characteristics of cooked meat depend on the structure of the meat, which changes mainly as a result of protein denaturation during thermal processing. Ángel-Rendón et al. [63] observed that sous vide cooking of meat leads to myofilaments degradation and separation between myofibrils and the sarcolemma membrane. The results of texture analysis are presented in Table 2.

Table 2. Shear force and texture attributes (TPA) of sous vide-cooked pork loin stored in refrigerated conditions (mean $\pm$ SEM; $n = 3$).

Treatment	Storage Time	Shear Force [N]	Hardness [N]	Springiness [cm]	Cohesiveness [-]	Chewiness [N $\times$ cm]
57 °C/5.5 h	0 days	14.66 $\pm$ 0.89 ^{ab}	35.95 $\pm$ 2.72 ^{ab}	0.48 $\pm$ 0.01 ^{ab}	0.55 $\pm$ 0.01 ^{cd}	9.31 $\pm$ 0.69 ^{ab}
	3 days	15.45 $\pm$ 0.72 ^{abc}	41.08 $\pm$ 2.10 ^{abc}	0.44 $\pm$ 0.01 ^a	0.49 $\pm$ 0.02 ^{abc}	9.35 $\pm$ 0.66 ^{ab}
	7 days	15.48 $\pm$ 0.58 ^{ab}	47.19 $\pm$ 3.67 ^{abc}	0.46 $\pm$ 0.01 ^{ab}	0.53 $\pm$ 0.01 ^{bcd}	10.46 $\pm$ 1.57 ^{ab}
59 °C/4.5 h	0 days	18.22 $\pm$ 0.20 ^{cd}	41.30 $\pm$ 3.97 ^{abc}	0.50 $\pm$ 0.01 ^{ab}	0.57 $\pm$ 0.02 ^d	12.89 $\pm$ 1.82 ^{abc}
	3 days	18.31 $\pm$ 0.15 ^{cd}	43.92 $\pm$ 3.63 ^{abc}	0.49 $\pm$ 0.01 ^{ab}	0.53 $\pm$ 0.01 ^{bcd}	12.70 $\pm$ 1.54 ^{abc}
	7 days	18.74 $\pm$ 0.44 ^{cd}	46.95 $\pm$ 2.57 ^{abc}	0.49 $\pm$ 0.01 ^{ab}	0.54 $\pm$ 0.02 ^{cd}	13.86 $\pm$ 1.40 ^{bc}
60 °C/4 h	0 days	15.44 $\pm$ 0.85 ^{abc}	34.71 $\pm$ 2.52 ^a	0.50 $\pm$ 0.02 ^b	0.57 $\pm$ 0.01 ^d	7.68 $\pm$ 0.62 ^a
	3 days	16.89 $\pm$ 1.17 ^{bcd}	44.55 $\pm$ 1.53 ^{abc}	0.46 $\pm$ 0.01 ^{ab}	0.54 $\pm$ 0.02 ^{bcd}	14.12 $\pm$ 1.39 ^{bc}
	7 days	19.91 $\pm$ 0.72 ^d	45.08 $\pm$ 1.31 ^{abc}	0.47 $\pm$ 0.01 ^{ab}	0.56 $\pm$ 0.01 ^{cd}	17.69 $\pm$ 1.53 ^c
61 °C/4 h	0 days	13.41 $\pm$ 0.75 ^a	44.41 $\pm$ 2.55 ^{abc}	0.49 $\pm$ 0.02 ^{ab}	0.55 $\pm$ 0.01 ^{cd}	11.46 $\pm$ 1.53 ^{ab}
	3 days	13.47 $\pm$ 1.01 ^a	49.24 $\pm$ 2.66 ^{bc}	0.46 $\pm$ 0.01 ^{ab}	0.46 $\pm$ 0.02 ^{ab}	10.43 $\pm$ 0.83 ^{ab}
	7 days	18.23 $\pm$ 0.31 ^{cd}	51.59 $\pm$ 1.02 ^c	0.47 $\pm$ 0.01 ^{ab}	0.52 $\pm$ 0.01 ^{bcd}	18.56 $\pm$ 1.32 ^c
63 °C/3.5 h	0 days	14.18 $\pm$ 0.46 ^a	34.72 $\pm$ 3.01 ^a	0.48 $\pm$ 0.01 ^{ab}	0.52 $\pm$ 0.01 ^{bcd}	7.95 $\pm$ 1.29 ^{ab}
	3 days	14.89 $\pm$ 0.47 ^{ab}	48.55 $\pm$ 2.52 ^{abc}	0.44 $\pm$ 0.01 ^{ab}	0.44 $\pm$ 0.03 ^a	9.33 $\pm$ 0.42 ^{ab}
	7 days	16.65 $\pm$ 0.80 ^{bc}	43.98 $\pm$ 2.84 ^{abc}	0.45 $\pm$ 0.01 ^{ab}	0.50 $\pm$ 0.01 ^{abcd}	9.76 $\pm$ 0.54 ^{ab}
Storage time						
0 days		14.80 $\pm$ 0.31 ^a	38.16 $\pm$ 1.41 ^a	0.49 $\pm$ 0.01 ^b	0.55 $\pm$ 0.01 ^b	9.81 $\pm$ 0.61 ^a
3 days		15.69 $\pm$ 0.43 ^a	45.10 $\pm$ 1.24 ^b	0.46 $\pm$ 0.01 ^a	0.49 $\pm$ 0.01 ^a	11.03 $\pm$ 0.55 ^a
7 days		17.51 $\pm$ 0.42 ^b	46.81 $\pm$ 1.16 ^b	0.47 $\pm$ 0.01 ^{ab}	0.53 $\pm$ 0.01 ^b	13.91 $\pm$ 0.86 ^b
Level of significance						
Treatment		***	*	**	***	***
Storage time		***	***	**	***	***
Treatment $\times$ storage time interaction		***	NS	NS	NS	***

^{a,b,c}...—mean values in columns, with different superscripts differ significantly at $p < 0.05$ according to the Turkey's test; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, NS—not significant.

3.3.1. Shear Force

The highest shear force after cooking, on day 0, was noted for the sample cooked at 59 °C/4.5 h (18.22 N) and it was significantly higher than values observed for all other samples (13.41–15.44 N). Samples cooked at 57 °C/5.5 h and 59 °C/4.5 h showed the most stable shear force during the entire storage period, while increasing values, particularly between day 3 and day 7 of storage, were observed for the remaining samples; however, the increase was not always significant. Both the treatment conditions and storage time, as well as their interaction, significantly influenced the shear force value of the tested loin samples (all $p < 0.001$).

Significant increase in shear force of sous vide-cooked chicken breast during 14-day refrigerated storage was reported by Hong et al. [23]. The authors suggested that proteolysis that takes place during meat storage may impair its water holding capacity, which, in turn, leads to an increase in shear force. In the study by Diaz et al. [22] different results were demonstrated as the shear force values of sous vide-cooked pork, measured on days 5 and 10 of storage, were significantly lower than the initial value on day 0. In connection

with the results of sensory evaluation, which showed that the meat became softer and flakier as a result of storage, the authors suggested protein degradation due to chemical and enzymatic reactions as the cause of this phenomenon.

3.3.2. Texture Profile Analysis (TPA)

It was observed that at the beginning of the storage study, regardless of the heat treatment parameters, pork loin samples did not differ significantly in terms of hardness assessed on the basis of the TPA test (34.71–44.41 N). Although the increasing hardness values were noted for all treatments with prolonged time of storage, only the sample heated at 61 °C/4 h on day 7 of storage showed significantly higher hardness than the samples heated at 60 °C/4 h and 63 °C/3.5 h immediately after heat treatment. There were no significant differences in hardness between the remaining samples during the entire storage period, but in general, the highest hardness values were determined for the sample cooked at 61 °C/4 h. The statistical analysis showed that the hardness of stored pork loin was significantly affected by the treatment parameters ($p < 0.05$) and time of storage ($p < 0.001$), but not their interaction. We hypothesise that the increase in hardness may be related to several factors, including changes in muscle proteins and subsequent water loss from meat, which were also pointed out by Hong et al. [23], as a probable reason for the increase in shear force of chicken breast sous vide cooked and stored in refrigerated conditions for 14 days. In the study by Botinestean et al. [3], reduced hardness of sous vide-cooked beef compared to the control sample cooked in a water bath was noted. Shin et al. [64] investigated the effect of different temperature–time combinations of sous vide cooking on duck breast meat quality and found that lower temperatures and shorter times of cooking resulted in increased tenderness of the meat, while Mortensen et al. [65], who studied sensory properties of sous vide-cooked beef, reported increased tenderness when meat was cooked at lower temperatures for longer times. Regarding springiness of stored samples, it tended to decline during storage for all samples, but only minor differences between samples were observed (0.44–0.50), with the only significant one between the sample cooked at 57 °C/5.5 h on day 3 of storage and the sample cooked at 60 °C/4 h on day 0 of storage. Like hardness, springiness was significantly affected by the treatment parameters and the time of storage (both $p < 0.01$), but not their interaction. Changes in meat cohesiveness were also minor during storage and the values were in the range 0.44–0.57. The highest values during storage were noted for meat cooked at 60 °C/4 h, and the lowest for meat cooked at 63 °C/3.5 h. Significant changes in cohesiveness during storage were observed only for samples cooked at 61 °C/4 h and 63 °C/3.5 h. Regarding the chewiness of stored pork loin, the increasing tendency was observed with prolonged storage time, but that increase was significant only for samples cooked at 60 °C/4 h and 61 °C/4 h. Cohesiveness and chewiness were significantly affected by treatment and storage time (both $p < 0.001$) and chewiness was also affected by their interaction ($p < 0.001$).

There are few studies described in the literature on the quality of meat heated using the sous vide method and then stored and, particularly, few studies provide information on the texture of such meat. Nevertheless, Diaz et al. [22] did not find significant differences between the hardness, cohesiveness, gumminess, and chewiness of the sous vide-cooked pork loin samples during 0, 5, and 10 weeks of storage; however, they observed a significant decline in springiness of samples with prolonged time of storage. The authors pointed out a discrepancy between the results of shear force test and TPA hardness. The changes in meat texture during storage was ascribed to protein degradation.

3.4. Volatile Compounds

The flavour of cooked meat is a combined effect of its taste and aroma. Compounds responsible for those meat characteristics are naturally present in meat or are generated during meat heat treatment, mainly as a result of Maillard reactions and oxidation of lipids [11].

The analysis of volatile compounds in pork loin using gas chromatography coupled with ion mobility spectrometry (HS-GC-IMS) allows for the precise identification and qualitative determination of the compounds responsible for the aroma. Changes in the profile of volatile compounds can be directly related to the perception of freshness, storage stability, and sensory quality of meat. The influence of sous vide processing and storage time on these compounds in pork loin was analysed in the context of different temperatures and processing times, and storage periods of 0, 3, and 7 days. Principal component analysis (PCA) was used to understand patterns and relationships between different samples. PCA allowed to reduce the dimensionality of data, while simultaneously highlighting the most important variables influencing differences in meat quality after processing and during storage [66,67].

Only 16 volatile compounds were found in raw meat, while in meat heat-treated at temperatures of 57–63 °C, 29 compounds were identified (Figure 2). Peak intensity for 3-methyl-1-pentene, 2-propanethiol, isobutyl methyl ether, 2,3-butanedione, but-2-enal, 1-butanol, pentanal, 3-methyl-2-butenal, 1,3-butanediol, heptanal, 2-ethyl-6-methylpyrazine, and 2-decanone increased with increasing thermal treatment temperature. Pentanal, hexanal, heptanal, and octanal are linear aldehydes, which were the dominant volatile aldehydes generated in cooked pork. These compounds were formed as a result of lipid oxidation that occurred during meat cooking and storage, as demonstrated by TBARS analysis (Table 1). A significant increase in pentanal, hexanal, heptanal, octanal, and nonanal, in sous vide-cooked lamb loin compared to raw meat was reported by Roldan et al. [40]. Hexanal and heptanal are derived mainly from linoleic and arachidonic acid oxidation, whereas octanal is generated as a product of oleic acid oxidation [46]. These compounds are responsible for the grassy and fruity aromas of meat [68]. It was also suggested that hexanal is a more effective indicator of lipid oxidation in meat than other volatile compounds [32].

Ketone compounds such as acetone, 2,3-butanedione, 2,3-pentanedione, and 2,3-hexanedione were present in raw meat and generally increased in concentration after heat treatment. The increase in ketone levels during cooking can be attributed to the breakdown of fatty acids and amino acids, which is more visible under the influence of heat. Unlike aldehydes, which are formed mainly during lipid oxidation, ketones can originate from both the degradation of unsaturated fatty acids and Maillard reactions [46]. However, in our study, Maillard reactions could have had only a limited contribution to the increase in ketone concentration since the relatively low heat treatment temperatures applied in our study did not favour those reactions [11]. Similar research results were obtained for other types of meat where ketone levels were increased, which additionally contributed to the complex flavour profile of cooked meat. For example, the study by Lorenzo and Dominguez [69] found that the content of ketones, such as 2,3-butanedione and 2,3-pentanedione, increased significantly when meat was cooked, enhancing the buttery and creamy notes of meat aroma. Jiang et al. [46] reported the presence of 2,3-octanedione and 2-cyclopentanone as the main ketones observed in braised pork.

As for alcohols, although they are derived from the oxidation of fatty acids, they have higher aroma thresholds and are generally not considered important factors affecting the aroma of meat products [46].

For comparison, in the study by Zhao et al. [29], a total of 94 compounds were identified in fermented pork, including ketones (10), acids (8), alcohols (19), aldehydes

(15), esters (27), and other compounds (10), while in the experiment of Cheng et al. [68], a total of 93 compounds were identified in Tibetan pork, raw or cooked with the use of different heat treatment methods, including 10 esters, 22 aldehydes, 16 alcohols, 8 ketones, 24 aliphatic hydrocarbons, 3 phenols, and 10 other compounds. Sanchez del Pulgar et al. [16] noted the presence of more than 100 volatile compounds in pork cheeks, sous vide cooked with the use of different combinations of temperature–time of cooking conditions and vacuum level in the package. Roldan et al. [12] found 11 volatile compounds in raw lamb loin, and 57 volatiles in cooked meat, and these were aldehydes, aliphatic and aromatic hydrocarbons, ketones, alcohols, esters, furans, and sulfur compounds. Lorenzo and Dominguez [69] reported an increase in volatile compounds and lipid oxidation with increased cooking temperature of foal meat and found that the main volatile compounds in raw meat were esters, while in cooked meat, the main volatiles were aldehydes. Cheng et al. [68] observed that more intense lipid oxidation in sample led to the higher content of volatile compounds and enriched types of volatiles after heat treatment of pork, suggesting that such treatment may promote the degradation of lipids and proteins and enrich the diversity of volatile flavour compounds in pork. Roldan et al. [12] concluded that volatile compounds derived from lipid oxidation dominated in lamb loin subjected to milder sous vide cooking conditions, namely, 60 °C for 6 or 24 h, 80 °C for 6 h, whereas the presence of volatiles from Strecker degradation was more pronounced when meat was cooked at 80 °C for 24 h. A reduction in the concentration of some volatile compounds generated in lipid oxidation, when the cooking time of pork cheeks at 80 °C was increased from 5 to 12 h, was reported by Sanchez del Pulgar et al. [16].

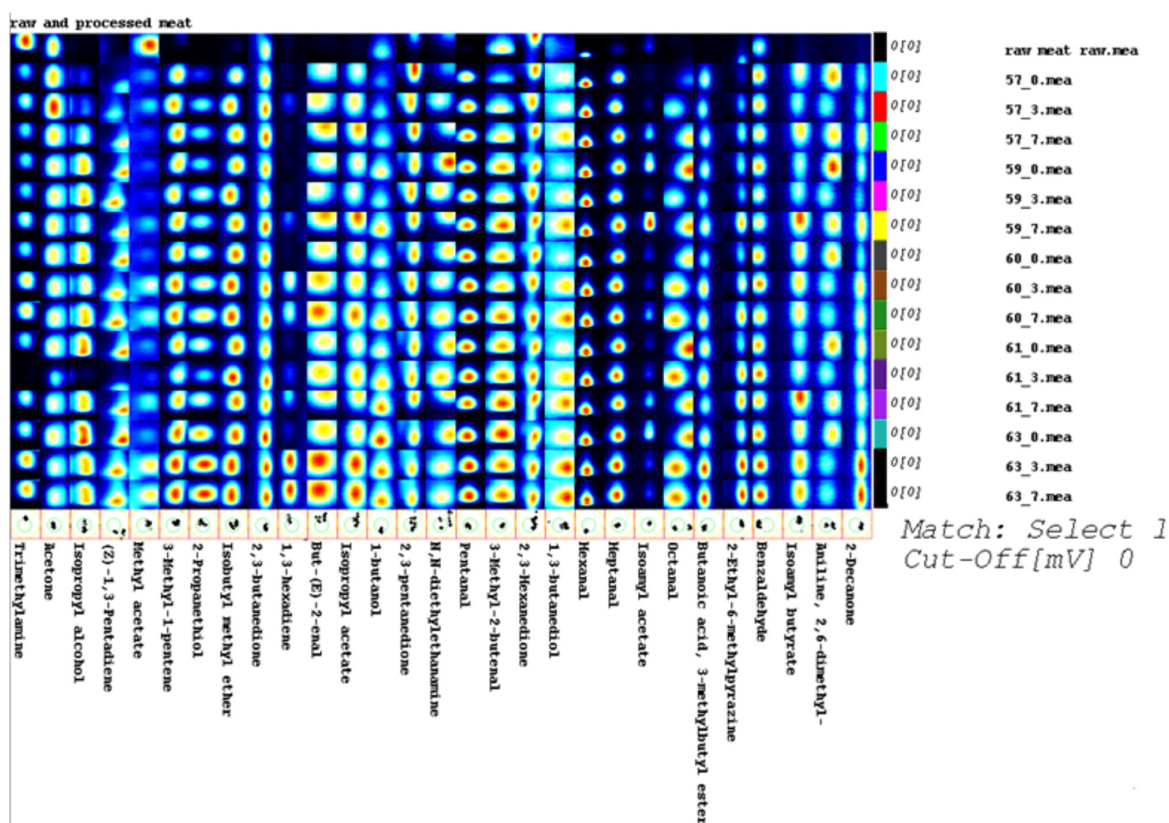


Figure 2. Meat sample fingerprints after incubation at 50 °C.

In order to characterise the profile of volatile compounds in pork and identify potential volatile markers related to the heating of pork, principal component analysis (PCA) was used. The visualisation of the PCA biplot (Figure 3), for which the first two principal components (PC) explained 56% of the data variability, showed that meat, depending

on thermal processing, can be identified and distinguished from others based on the thermal processing temperature. PCA analysis based on the signal intensity of detected volatile compounds showed effective differentiation of samples from different stages into relatively independent spaces. Along PC1, a distinction has been shown from the thermal processing temperature, so raw meat is clearly separated from thermally processed meat, supporting the notion that temperature plays a major role in altering the volatile compound composition. However, the sample processed at 57 °C/0 days showed overlap with other thermally processed samples. This indicates that while temperature drives differentiation to a large extent, some cases display similar volatile profiles, possibly due to limited variability in the data or subtle differences not captured by the first two principal components. Along PC2 in the PCA biplot, the analysis provided additional variation in volatile compound profiles, but this time, likely due to secondary factors beyond cooking temperature. PC2 accounted for 28% of the variability and could highlight differences in specific compounds or reaction products that appear at similar temperatures but vary due to other conditions such as cooking time or specific chemical interactions. For example, some compounds, such as 2,3-hexanedione and trimethylamine, are more distributed along PC2, suggesting that they play a distinct role in defining the aroma profile at different stages of thermal processing, which are not solely determined by temperature. This comprehensive PCA analysis showed that both cooking conditions and certain volatile compounds significantly contribute to the distinct aroma profiles of pork at different stages of the experiment. PC1 successfully distinguished raw meat from thermally processed meat based on cooking temperatures. More nuanced differences emerged with PC2, possibly indicating the influence of specific compounds such as 2,3-hexanedione and trimethylamine on aroma development. In general, while the PCA did not unequivocally distinguish all thermally processed samples, it effectively separated raw samples and highlighted trends associated with different processing conditions. The observed overlap did not negate the value of the PCA but suggested that further analysis, incorporating additional factors or more detailed profiling, may enhance the differentiation of similar treatments.

3.5. Sensory Evaluation

The sensory characteristics of food products have a decisive impact on consumer choices, especially since food is considered not only from the nutritional perspective but, in gastronomy above all, from the hedonic perspective. The results of the sensory evaluation of sous vide-cooked pork loin with the use of selected temperature–time combinations and stored in refrigerated conditions for 7 days are presented in Table 3.

At the initial stage of the storage study (day 0), the highest score for overall appearance was given to the sample cooked at 60 °C/4 h (8.75); similarly, a high score was maintained after 3 days of storage (8.50). The lowest score on day 0 was received by the sample cooked at 61 °C/4 h (7.50). Scores for this attribute tended to decline over storage time, but the only significant difference was observed between the sample cooked at 59 °C/4.5 h and stored for 7 days and the sample cooked at 60 °C/4 h and stored for 0 days. It was noted that the overall appearance was significantly influenced by the storage time ($p < 0.001$). Treatment conditions and storage time significantly affected the juiciness of pork loin samples ($p < 0.001$ and $p < 0.05$, resp.). The high and stable juiciness scores during the entire experiment were observed for the sample cooked at 57 °C/5.5 h (scores in the range 8.00–8.50), but they differed significantly only from the score given to the sample cooked at 63 °C/3.5 h and evaluated on day 3 (score 5.50). During the entire experiment, no significant differences were found between samples with respect to their colour uniformity, aroma intensity, tenderness, meat flavour intensity, and overall acceptability. Nevertheless, statistical analysis showed that the overall acceptability of the samples was significantly

affected by the heat treatment conditions ($p < 0.01$), the tenderness of the samples was significantly affected by the storage time ($p < 0.05$), and the flavour acceptability was significantly affected by the cooking conditions and the time of storage (both $p < 0.05$).

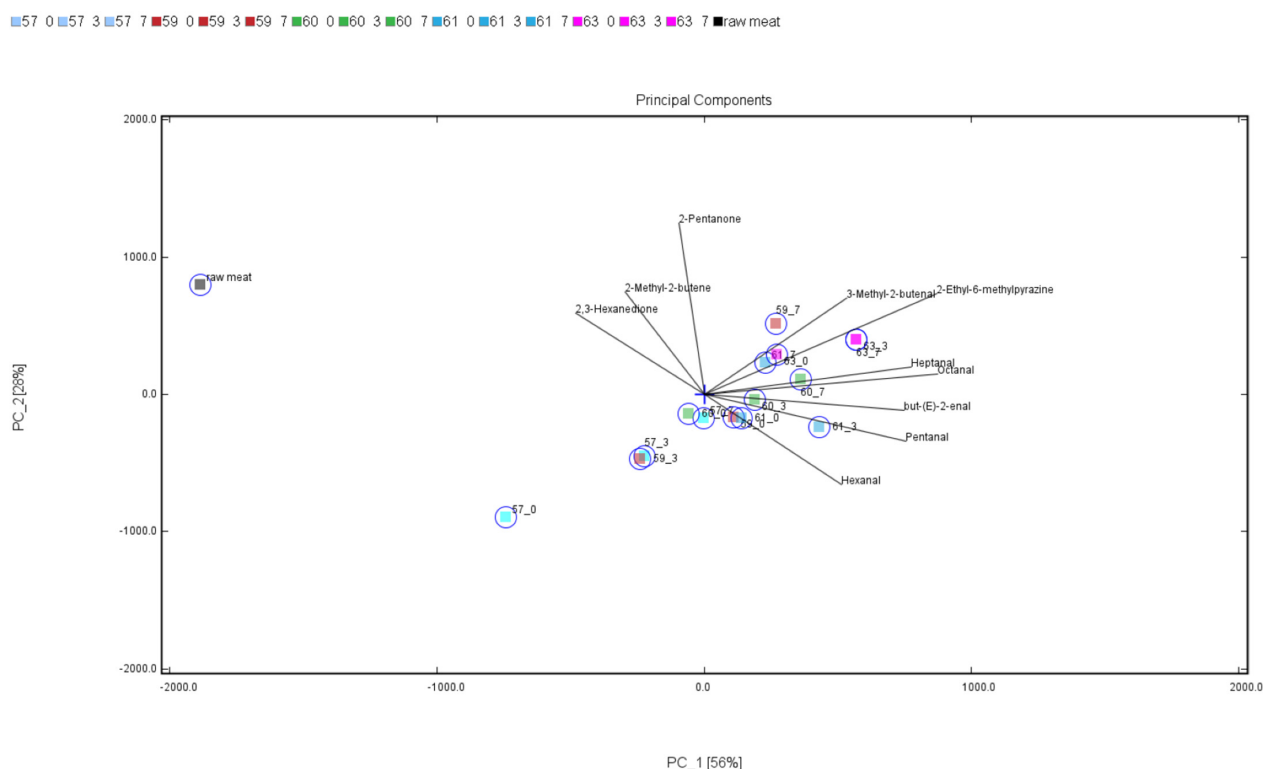


Figure 3. Principle component analysis (PCA) biplot of volatile components of pork loin.

Table 3. Sensory quality of sous vide-cooked pork loin stored in refrigerated conditions (mean $\pm$ SEM; $n = 3$).

Treatment	Storage Time	Overall Appearance ¹	Colour Uniformity ²	Aroma Intensity ³	Tenderness ⁴	Juiciness ⁵	Meat Flavour Intensity ³	Flavour Acceptability ¹	Overall Acceptability ¹
57 °C/5.5 h	0 days	7.75 $\pm$ 0.48 ^{ab}	8.25 $\pm$ 0.63 ^a	7.25 $\pm$ 1.03 ^a	7.00 $\pm$ 1.00 ^a	8.50 $\pm$ 0.87 ^b	8.00 $\pm$ 0.71 ^a	8.25 $\pm$ 0.75 ^a	8.00 $\pm$ 0.91 ^a
	3 days	7.50 $\pm$ 0.85 ^{ab}	7.75 $\pm$ 1.11 ^a	7.25 $\pm$ 0.25 ^a	7.00 $\pm$ 0.41 ^a	8.00 $\pm$ 0.41 ^b	7.25 $\pm$ 1.03 ^a	8.25 $\pm$ 0.48 ^a	8.25 $\pm$ 0.48 ^a
	7 days	7.50 $\pm$ 0.25 ^{ab}	7.50 $\pm$ 0.29 ^a	6.75 $\pm$ 0.75 ^a	6.75 $\pm$ 1.03 ^a	8.00 $\pm$ 0.71 ^b	6.75 $\pm$ 0.48 ^a	7.75 $\pm$ 0.48 ^a	8.50 $\pm$ 0.65 ^a
59 °C/4.5 h	0 days	8.25 $\pm$ 0.25 ^{ab}	7.25 $\pm$ 0.25 ^a	8.75 $\pm$ 0.25 ^a	8.50 $\pm$ 0.65 ^a	8.75 $\pm$ 0.48 ^{ab}	8.00 $\pm$ 0.41 ^a	8.75 $\pm$ 0.75 ^a	8.50 $\pm$ 0.65 ^a
	3 days	6.75 $\pm$ 0.25 ^{ab}	6.00 $\pm$ 0.58 ^a	7.00 $\pm$ 0.71 ^a	6.50 $\pm$ 0.96 ^a	5.75 $\pm$ 0.48 ^{ab}	7.00 $\pm$ 0.71 ^a	6.25 $\pm$ 0.63 ^a	6.00 $\pm$ 0.58 ^a
	7 days	6.25 $\pm$ 0.25 ^a	6.25 $\pm$ 0.48 ^a	6.75 $\pm$ 1.03 ^a	5.75 $\pm$ 0.25 ^a	6.00 $\pm$ 0.46 ^{ab}	6.75 $\pm$ 0.25 ^a	6.00 $\pm$ 0.41 ^a	6.25 $\pm$ 0.75 ^a
60 °C/4 h	0 days	8.75 $\pm$ 0.75 ^b	9.00 $\pm$ 0.58 ^a	7.75 $\pm$ 0.75 ^a	8.00 $\pm$ 1.22 ^a	7.25 $\pm$ 0.75 ^{ab}	8.75 $\pm$ 0.75 ^a	9.00 $\pm$ 0.58 ^a	8.75 $\pm$ 0.75 ^a
	3 days	8.50 $\pm$ 0.29 ^{ab}	8.50 $\pm$ 0.87 ^a	7.75 $\pm$ 0.95 ^a	8.00 $\pm$ 0.71 ^a	6.75 $\pm$ 0.48 ^{ab}	7.75 $\pm$ 1.31 ^a	8.50 $\pm$ 0.65 ^a	8.50 $\pm$ 0.65 ^a
	7 days	7.00 $\pm$ 0.71 ^{ab}	5.25 $\pm$ 1.03 ^a	6.00 $\pm$ 0.91 ^a	6.25 $\pm$ 0.25 ^a	6.25 $\pm$ 0.75 ^{ab}	6.75 $\pm$ 0.48 ^a	6.25 $\pm$ 0.63 ^a	6.75 $\pm$ 0.63 ^a
61 °C/4 h	0 days	7.50 $\pm$ 0.29 ^{ab}	6.50 $\pm$ 0.96 ^a	7.50 $\pm$ 0.87 ^a	6.75 $\pm$ 0.63 ^a	6.75 $\pm$ 0.63 ^{ab}	8.25 $\pm$ 0.25 ^a	6.75 $\pm$ 0.85 ^a	6.50 $\pm$ 0.50 ^a
	3 days	7.00 $\pm$ 0.58 ^{ab}	7.25 $\pm$ 1.18 ^a	7.00 $\pm$ 0.58 ^a	6.75 $\pm$ 0.85 ^a	7.25 $\pm$ 1.03 ^{ab}	7.50 $\pm$ 1.55 ^a	7.75 $\pm$ 0.63 ^a	7.50 $\pm$ 0.29 ^a
	7 days	7.00 $\pm$ 0.41 ^{ab}	6.50 $\pm$ 0.29 ^a	7.25 $\pm$ 0.48 ^a	6.75 $\pm$ 1.25 ^a	7.25 $\pm$ 0.25 ^{ab}	7.25 $\pm$ 0.25 ^a	7.25 $\pm$ 0.85 ^a	7.00 $\pm$ 0.32 ^a
63 °C/3.5 h	0 days	8.25 $\pm$ 0.25 ^{ab}	7.50 $\pm$ 1.04 ^a	7.00 $\pm$ 0.41 ^a	7.50 $\pm$ 1.19 ^a	6.25 $\pm$ 0.63 ^{ab}	7.75 $\pm$ 0.48 ^a	7.00 $\pm$ 0.71 ^a	7.00 $\pm$ 0.41 ^a
	3 days	7.75 $\pm$ 0.63 ^{ab}	8.25 $\pm$ 0.85 ^a	6.75 $\pm$ 0.75 ^a	8.00 $\pm$ 0.58 ^a	6.00 $\pm$ 0.58 ^{ab}	7.50 $\pm$ 1.32 ^a	6.50 $\pm$ 0.29 ^a	7.00 $\pm$ 0.36 ^a
	7 days	7.00 $\pm$ 0.58 ^{ab}	7.50 $\pm$ 0.29 ^a	6.00 $\pm$ 0.41 ^a	6.25 $\pm$ 1.03 ^a	5.50 $\pm$ 0.65 ^a	7.50 $\pm$ 0.50 ^a	6.50 $\pm$ 0.65 ^a	6.75 $\pm$ 0.75 ^a
Storage time									
	0 days	8.10 $\pm$ 0.19 ^b	7.70 $\pm$ 0.36 ^a	7.65 $\pm$ 0.32 ^b	7.55 $\pm$ 0.41 ^b	7.50 $\pm$ 0.35 ^a	8.15 $\pm$ 0.23 ^b	7.95 $\pm$ 0.36 ^b	7.75 $\pm$ 0.33 ^a
	3 days	7.50 $\pm$ 0.24 ^{ab}	7.55 $\pm$ 0.43 ^a	7.15 $\pm$ 0.28 ^{ab}	7.25 $\pm$ 0.32 ^{ab}	6.75 $\pm$ 0.32 ^a	7.40 $\pm$ 0.49 ^{ab}	7.45 $\pm$ 0.30 ^{ab}	7.45 $\pm$ 0.28 ^a
	7 days	6.95 $\pm$ 0.21 ^a	6.60 $\pm$ 0.29 ^a	6.55 $\pm$ 0.32 ^a	6.15 $\pm$ 0.34 ^a	6.40 $\pm$ 0.35 ^a	7.00 $\pm$ 0.18 ^a	6.75 $\pm$ 0.29 ^a	7.05 $\pm$ 0.30 ^a
Level of significance									
Treatment		NS	NS	NS	NS	***	NS	*	**
Storage time		***	NS	NS	*	*	NS	*	NS
Treatment $\times$ storage time interaction		NS	NS	NS	NS	NS	NS	NS	NS

a,b—mean values in columns, with different superscripts differ significantly at $p < 0.05$ according to the Turkey's test; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, NS—not significant; Scale 1 (0—not acceptable, 10—very acceptable), Scale 2 (0—not uniform, 10—highly uniform), Scale 3 (0—not detectable, 10—very intense), Scale 4 (0—tough, 10—tender), Scale 5 (0—low, 10—very high).

Diaz et al. [22] evaluated pork loin sous vide cooked at 70 °C/12 h and stored for up to 10 weeks in refrigerated conditions. The authors reported scores decreased by at least 30% for appearance, meaty odour, meaty flavour, hardness, and overall acceptance after 5 weeks of storage and their further decrease with extended storage time. Smaller negative changes were observed for graininess, juiciness, and chewiness. Increased scores for rancid odour, warmed-over-odour, rancid flavour, warmed-over flavour, and acid flavour were also observed in that study. The pork loin was found unacceptable after 10 weeks of storage. Hasani et al. [44] reported acceptable odour of sous vide-cooked chicken breast during 21 days of refrigerated storage, but that sensory feature was the only one evaluated in the study, and therefore, no further comparisons are possible. The slight changes in the scores for sensory characteristics of meat samples, recorded in our experiment, compared to the work of Diaz et al. [22], can be attributed to relatively small differences in the heat treatment parameters applied in the study, as well as short storage time.

3.6. Relationships Between Overall Acceptability and Selected Attributes of Cooked and Stored Pork Loin Samples

Based on the results of correlation analysis, it can be that noted physicochemical and sensory properties of the stored meat samples influenced their overall acceptability to varying degrees (Table 4). The correlation coefficient observed for TBARS ($r = -0.079$) suggested a very weak, insignificant relationship between the level of lipid oxidation and the meat's acceptability. Similarly, the colour parameter a^* ($r = 0.246$, NS), shear force ($r = 0.134$, NS), hardness ($r = 0.018$, NS), and chewiness ($r = -0.103$, NS) showed very weak correlation coefficients, also without statistical significance, meaning that those parameters did not have a significant effect on the perceived overall acceptability of the evaluated meat samples.

Table 4. Correlation coefficients between overall acceptability and selected attributes of sous vide-cooked pork loin stored for 0, 3, and 7 days.

Attribute	r	p
TBARS	−0.079	NS
Colour a^*	0.246	NS
Shear force	0.134	NS
Hardness	0.018	NS
Chewiness	−0.103	NS
Aroma intensity	0.495	***
Tenderness	0.522	***
Juiciness	0.609	***
Meat flavour intensity	0.448	***
Flavour acceptability	0.770	***

Level of significance: *** $p < 0.001$, NS—not significant.

On the other hand, sensory features such as aroma intensity, tenderness, juiciness, meat flavour intensity, and flavour acceptability were noticeably correlated with the overall acceptability of the meat, and their influence on that feature was statistically significant. Aroma intensity showed a moderately strong, positive correlation ($r = 0.495$, $p < 0.001$), indicating that more intense meat aroma significantly affected its overall acceptability. Meat tenderness ($r = 0.522$, $p < 0.001$) also showed a moderately strong, positive correlation, suggesting that more tender meat was more accepted by the panelists. A stronger relationship was observed for juiciness ($r = 0.609$, $p < 0.001$), suggesting that juiciness was an important factor of the overall acceptability of meat. Meat flavour intensity was also significantly correlated with its overall acceptability ($r = 0.448$, $p < 0.001$). The strongest correlation was noted for flavour acceptability ($r = 0.770$, $p < 0.001$), suggesting that the taste of the meat was the key factor determining its overall rating in our study. These results highlight

that when assessing meat quality, sensory attributes such as aroma intensity, tenderness, juiciness, as well as flavour intensity and acceptability are of key importance. In contrast, physical characteristics such as colour parameter a^* (meat redness), TBARS index, shear force, hardness, and chewiness play a lesser role in shaping the overall acceptability of the product.

To the best of our knowledge, the literature on the correlations between physicochemical and sensory characteristics and the overall quality/acceptability of pork loin cooked using the sous vide method and then stored in refrigerated conditions is very limited. Diaz et al. [22] conducted an analysis of correlation between overall acceptance and sensory features of pork loin sous vide cooked only at 70 °C/12 h and stored up to 10 weeks in refrigerated conditions. The authors reported high and significant correlation coefficients for appearance, meaty odour, and meat flavour and slightly lower coefficients for hardness and juiciness. Negative and significant correlation coefficients were noted for rancid, warmed-over, and acid odours, and rancid and acid flavours. Nevertheless, the results of our present study confirm our earlier findings, related to the pork loin sous vide cooked but not stored, which showed the high correlation coefficients between tenderness and juiciness and overall acceptability of meat [26,70].

4. Conclusions

The findings of the study demonstrate that both sous vide heat treatment parameters and storage time have a significant impact on the physicochemical and sensory properties of pork loin, particularly in terms of lipid oxidation, colour, and texture, which change over time during refrigerated storage. Cooking at higher temperatures led to more pronounced lipid oxidation, as indicated by higher TBARS values. Colour changes noted in lightness and redness were influenced by both cooking parameters and storage duration, while changes in yellowness were affected only by heat treatment parameters. Extended storage time led to increased shear force values of samples cooked at temperatures 60–63 °C. Sensory evaluation and analysis of correlations revealed that attributes such as juiciness, tenderness, and flavour acceptability were critical to the overall acceptability of the products. Although physical properties like texture attributes assessed by the TPA test and colour were less influential on overall acceptability, they can still play a role in the perception of meat's overall quality. The highest scores in sensory evaluation for most attributes were given to the sample cooked at 60 °C/4 h, particularly during 3 days storage. These results underline the importance of optimizing sous vide cooking parameters to maintain high-quality sensory attributes during storage. The study contributes valuable insights into the relationship between cooking methods, storage, and sensory acceptance of sous vide-cooked pork loin.

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Institutional Review Board Statement: The research complied with the guidelines established in Ordinance No. 30/2022 issued by the Rector of the University on 29 April 2022, which governs the ethical conduct of non-invasive research involving human participants. The key points of the ordinance state that non-invasive studies that do not involve biological sample collection, drug administration, or procedures altering the psychological state of participants are exempt from requiring specific ethical committee approval. Instead, such research must adhere to general ethical

principles, including voluntary participation, informed consent, anonymity, and data security. As our study involved only non-invasive sensory evaluation, with procedures that ensured participant anonymity and voluntary participation, formal ethical committee approval was not required. Nevertheless, we confirm that our research adhered to the ethical standards outlined in the ordinance mentioned above.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data is contained within the article.

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