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Quality of Pork Loin Subjected to Different Temperature–Time Combinations of Sous Vide Cooking

Lidia Kurp and Marzena Danowska-Oziewicz *

Department of Human Nutrition, Faculty of Food Science, University of Warmia and Mazury in Olsztyn, 10-718 Olsztyn, Poland; lidia.kurp@uwm.edu.pl

* Correspondence: marzena.danowska@uwm.edu.pl; Tel.: +48-89-523-37-60

Abstract: Cooking with the sous vide method preserves nutritional value and maintains desirable sensory qualities of food, thanks to vacuum-sealed heat treatment at controlled low temperatures. In meat, the right combination of temperature and time is critical for texture, juiciness, and flavour, all essential features for consumer acceptance of cooked meat. This study assessed the impact of sous vide heat treatment on selected quality attributes of pork loin using various low temperature–time combinations. Pork loins were sliced, vacuum-sealed, and cooked in a water bath at temperatures of 57 °C to 63 °C for 3 to 5.5 h. The meat was evaluated for cooking loss, proximate composition, pH, water activity, oxidative changes, colour, texture, and sensory characteristics. The results showed that cooking losses increased with higher temperatures and longer times of cooking. Likewise, the oxidative changes were significantly affected by both cooking parameters. Temperature of cooking influenced only meat redness (a^*), but cooking time had no significant effect on colour parameters. The lowest hardness was observed for samples cooked at 59 °C/4.5 h and at 60 °C/4–5 h. Sensory analysis indicated that cooking at 59 °C for 4.5 h provided the most acceptable sensory characteristics of pork loin.

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

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1. Introduction

Meat cooking is a necessary procedure to make it acceptable, palatable, and as result nutritious for humans [1]. Several cooking methods can be applied for meat preparation for consumption including conventional ones such as dry or moist roasting, boiling, steaming, frying, stewing, and grilling, and those more technologically advanced such as sous vide [2] or even ohmic heating [3].

The sous vide method involves the heat treatment of food placed in vacuum-sealed packaging at a relatively low, controlled temperature for an extended time. The use of a vacuum bag increases food safety by eliminating the risk of recontamination during handling and storage of food, and prevents the loss of volatile flavour substances caused by evaporation, while low cooking temperatures limit the loss of nutrients and improve the sensory quality of food [2]. Meat prepared in this way can be eaten immediately after preparation or cooled quickly, stored in the fridge for a few days, and, before serving, warmed up to the temperature of consumption [4]. The precise control of temperature and time of cooking during the sous vide procedure leads to improved food quality, including colour, flavour, and texture, as well as reduced loss of nutrients [1,4,5]. Reducing the temperature during sous vide cooking improves the juiciness of the meat, while extending the heating time gives the cooked meat the desired aroma and taste characteristics [1,6]. In addition, the prolonged heating time causes a greater weakening of the myofibrils' holding forces, which is particularly important in meat with a lower content of connective tissue, where as a result the degree of softening is relatively high when cooking takes place at a temperature of 50–60 °C [1]. Other advantages of this method of heating are lower changes of protein, amino acids, and fatty acids compared to conventional methods of cooking; reduction of lipid oxidation; and non-dilution of meat juices [7–10]. Haghighi et al. [11] reported that the low heating temperature minimised the oxidative changes (TBARS values) of meat and keep them under the sensory threshold of detection. Heating and then storage of meat packed in a vacuum bag avoids the risk of its recontamination, while inhibiting the growth of anaerobic bacteria during storage [12].

The uniform heating of food products together with repeatability and adequate control of process parameters, as well as high cooking yield [13], are important from the manufacturer's point of view. For consumers, the benefits of sous vide-cooked food are good retention of nutrients [4,14] and desirable sensory properties [4,14,15]. Nevertheless, this technique is not commonly known to consumers, and when presented in relation to convenience food it raised doubts in regard to food processing in plastic bags and the possible use of food additives [15].

The catering industry has been using the sous vide method since the beginning of the 21st century. Consumers have known about the possibility of using this method of heat treatment at home since around 2010. Despite the availability of home circulators on the market, this method is mainly widespread on an industrial scale [2,16]. It is worth considering that heat treatment using the sous vide method can contribute to reducing food waste in households and catering establishments through better use of low-value co-products of main ingredients [17]. In addition, cooking in thermostable vacuum bags in controlled conditions extends the shelf life of food, so overproduction can be avoided and thus a further reduction of food waste can be achieved [18]. This is particularly important in catering facilities, where it is difficult to predict the demand for certain menu items. Using the sous vide method, meat previously prepared and stored in vacuum bags can be reheated and then seared on both sides to induce Maillard reactions, which make meat more tasteful and therefore more acceptable to consumers [2,19]. In order to meet the demands of modern consumers and thus increase the development of the food market, sous vide heat treatment can be combined with existing food trends, such as organic, healthy and clean-label food [7].

Choosing the right combinations of temperature and time plays an important role in sous vide cooking, reducing the risk of overcooking, as well as the loss of volatile compounds and heat-sensitive nutrients [6]. In addition, for catering establishments, the microbiological safety of the final product is also important [20], as well as energy consumption during cooking [8,21] and the speed of food preparation, which should be taken into account when choosing the temperature and time of sous vide cooking.

Our previous research, in which we sous vide cooked pork loin at temperatures 60, 65, 70, and 75 °C for 1–4 h, showed that sous vide cooking of pork loin slices at 60 or 65 °C for 4 h resulted in the most acceptable eating quality of meat, which was partially confirmed by the results of physicochemical and instrumental analyses [20]. As lower heat treatment temperatures have a beneficial effect on the preservation of the nutritional value as well as the texture and juiciness of meat, and to explore the effects of temperatures closer to the range which assured the best quality of pork loin, our team undertook a further study in which partially lower temperatures (57 °C, 59 °C, 60 °C, 61 °C, 63 °C) with smaller temperature and time intervals (3, 3.5, 4, 4.5, 5, 5.5 h) were investigated. Therefore, the objective of the present study was a detailed analysis of the impact of sous vide treatment parameters on the physicochemical and sensory characteristics, including proximate composition, colour, and texture features, as well as oxidative changes of pork loin, and to determine the optimal cooking parameters that guarantee high product quality, so that the results can be useful for both the food and catering industries.

2. Materials and Methods

2.1. Preparation of Samples

The research material was pork loin of female pigs from a commercial breeding program (PIC), obtained 24 h after slaughter from a local meat supplier. The animals at the time of slaughter weighed about 110 kg and were 5–6 months old. Before slaughter they were kept under the same environmental conditions, were fed equally, and had unlimited access to water. Meat was transported to the laboratory under refrigerated conditions, then vacuum packed and stored at 4 °C for 4 days.

Heat treatment of meat was carried out using the sous vide technique (circulator with a temperature sensor, Diamond Z, Julabo GmbH, Seelbach, Germany). Before cooking meat was cut into slices of 2.5 cm thickness and then slices were individually weighed and vacuum packed using double layer pouches (15 µm polyamide/60 µm polyethylene; heat resistance of −20 °C/+110 °C; Hendi, Lamprechtshausen, Austria) and the chamber vacuum sealer Edesa VAC-20 DT (Barcelona, Spain). Meat slices were randomly assigned to the particular cooking conditions. The vacuum-packed meat slices were heat treated at 57 °C, 59 °C, 60 °C, 61 °C, and 63 °C for 3 to 5.5 h. The temperature range and heating times were established based on publications and publicly available materials regarding recommendations for using this method in practice [2,22,23], as well as on the results of our previous study [20].

Directly after the heat treatment, the meat samples were served to sensory evaluation panellists, while those intended for physicochemical analyses were rapidly cooled in an ice-water bath and then kept at 4 °C until analyses which took place during two consecutive days after processing. The scope of the analyses included the determination of cooking loss; water, protein, and fat contents in meat; water activity; active acidity (pH); oxidative changes; and instrumental measurement of colour and texture. Sensory evaluation using a 10-point structured linear scale was also carried out. Where not otherwise stated, the physicochemical analyses were conducted in three parallel repetitions. The experiment was repeated three times (three different batches of raw material) in order to limit the impact of raw material variability on the studied phenomena.

2.2. Analytical Methods

2.2.1. Cooking Loss

Cooking loss was calculated on the basis of the difference in meat weight before and after heat treatment.

$$\text{Cooking loss } (\%) = [(W_0 - W_1)/W_0] \times 100 \tag{1}$$

where

W_0—weight of raw meat (g)

W_1—weight of cooked meat (g).

2.2.2. Proximate Composition

Moisture content was determined by weighing 5 g of minced meat in a glass weighing bottle and drying in a laboratory oven with forced draft (UF55; Memmert, Schwabach, Germany), at 105 °C until constant weight was achieved [24].

Fat content was determined by the Soxhlet method [25] with the use of petroleum ether with a boiling point of 40–60 °C. The extraction was carried out in an Extraction Unit E-816 (BÜCHI Labortechnik AG, Flawil, Switzerland).

Protein content was determined by the Kjeldahl method [26]. The process of meat samples' mineralisation was carried out using a Kjeldahl digestion system SpeedDigester K-436 (BÜCHI Labortechnik AG, Flawil, Switzerland), and the distillation process was conducted using the Distillation Unit K-355 (BÜCHI Labortechnik AG, Flawil, Switzerland).

2.2.3. pH Value

Meat samples of 5 g were homogenised with the addition of 45 mL of distilled water in the HO 4A homogeniser (Edmund Bühler GmbH, Hechingen, Germany) for 2 min at 5000 rpm. Then, the electrode of the pH meter (pH 210, Hanna Instruments, Woonsocket, RI, USA) was inserted into the homogenate and readings were taken after the pH value was stabilised. Before measurements, the pH meter was calibrated using pH4 and pH7 buffers.

2.2.4. Water Activity

Comminuted meat placed in a measuring cup was inserted into the chamber of a water activity analyser (AWC-200, Novasina, Pfäffikon, Switzerland), calibrated with a set of Novasina moisture sources. Readings of aw were made at 20 °C ± 0.1 °C.

2.2.5. Lipid Oxidation

Oxidative changes in meat samples were determined according to the procedure described by Salih et al. [27]. In short, meat samples were homogenised with chilled perchloric acid and alcoholic BHT solution. Five mL of filtered homogenate was heated with 5 mL of 0.02 M aqueous solution of 2-thiobarbituric acid (TBA reagent) in a boiling water bath for 1 h and then cooled under cold running water. The absorbance of samples was measured against a blank sample (perchloric acid and TBA reagent) at a wavelength of 532 nm using a Optizen POP UV/VIS spectrophotometer (Metasys Co., Ltd., Deajeon, Republic of Korea). The TBARS value was calculated according to Equation (1) presented below and expressed in mg of malondialdehyde per kg of the sample [28].

$$\text{TBARS} = \text{A} \times \text{K}\ [\text{mg MDA/kg}] \tag{2}$$

where

A—absorbance of the investigated sample
K—conversion factor of 5.5.

2.2.6. Colour

Colour measurements were made using a CR-400 colorimeter (Konica Minolta Sensing Inc., Osaka, Japan), equipped with a standard observer 2° and an illuminant D65, calibrated with white ceramic tile before measurements. Colour space *L*a*b** (lightness, redness, and yellowness, resp.) coordinates were recorded at six randomly selected locations on the cross-section of meat samples. Based on the measurements results, the chroma (*C**), hue angle (*h*°), and total colour difference (Δ*E**) in relation to the raw meat sample were calculated according to the following formulas:

$$C^* = \sqrt{a^{*2} + b^{*2}} \tag{3}$$

$$h^\circ = \text{arctg}(b^*/a^*) \times (360^\circ/2 \times 3.14) \tag{4}$$

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \tag{5}$$

where

$\Delta L^* = L^*_{cookedsample} - L^*_{rawsample}$
$\Delta a^* = a^*_{cookedsample} - a^*_{rawsample}$
$\Delta b^* = b^*_{cookedsample} - b^*_{rawsample}$

2.2.7. Instrumental Texture Analysis

The instrumental texture analysis was performed with the use of a TA.XTplus Texture Analyzer (Stable Micro Systems Ltd., Godalming, UK) equipped with a 50 kg load cell. The Texture Expert 1.21 software was used to collect the data.

2.3. Shear Test

The maximum force recorded during the shear test was used as a measure of meat hardness. A Warner–Bratzler V-notch blade moved during the test with the speed 250 mm/min. Twenty specimens (10 × 10 × 25 mm) were cut parallel to the muscle fibres and evaluated for each treatment.

2.4. Texture Profile Analysis (TPA)

The measurement was made by placing a meat sample on the fixed bottom plate and setting its two-cycle compression to 50% of its original height with a P/100 platen of 50 mm diameter, which moved at a constant speed of 50 mm/min. The specimens for measurement were the cores of 16 mm diameter and 20 mm height, cut parallel to the muscle fibres and 20 specimens were analysed for each heat treatment.

Sensory Analysis

Sensory evaluation of investigated material was carried out in a sensory analysis laboratory equipped with individual assessment booths. The evaluation was performed by 15 panellists who were employees of the Faculty of Food Science and experienced in sensory analysis of food [29]. Samples of 1 cm thickness were cut diagonally from cooked meat slices and served to panellists in random order on white ceramic plates. A one-way 10 cm structured linear scale was used to carry out the assessment for 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 and 10–very high) according to ISO 4121:2003 [30]. The evaluation of the samples was repeated twice during each experiment. Water and unsalted bread were available to the assessors during evaluation.

2.5. Statistical Analysis

Statistical analysis was performed using the GLM procedure of Statistica 13.0 (TIBCO Software Inc., Tulsa, OK, USA). Mean values and the standard error of the mean (SEM) of the results of physicochemical analyses and sensory evaluation were calculated. Temperature and time of sous vide treatment were used as independent variables. The influence of temperature and time of cooking and their interaction on the features of meat samples was examined with the use of a two-way analysis of variance. The significance of differences was assessed using the Tukey's test and differences were considered statistically significant at $p < 0.05$. In order to investigate potential relationships between selected attributes of meat samples, the Pearson's correlation coefficients were calculated.

3. Results and Discussion

3.1. Cooking Loss

The cooking loss resulting from heat treatment of meat affects its eating quality; it is also a key factor in meat processing in terms of production economy. In the present study, it was noted that the weight loss of the tested meat after sous vide heat treatment was between 12.70 and 25.20%, with a significant increase in weight loss with increasing temperature and time of heating ($p < 0.001$, Table 1). Similar relationships have been shown in the study of Hwang et al. [31], who observed an increased cooking loss with elevated temperature when heat treatment took place at 50, 55, and 60 °C, while the effect of cooking time was observed only at 50 °C and lower cooking loss was noted with increasing time of cooking. Christensen et al. [23] observed such effects for chicken meat, but in most studies conducted on pork, only the effect of temperature was significant [22,23,32]. Supaphon et al. [33] reported a significant effect of cooking time and an increase in cooking loss with extended cooking time when beef was sous vide-cooked at the temperature of 60 °C and partially at 70 °C, but no significant effect of cooking time on cooking loss was found at 80 °C.

Table 1. Cooking loss and proximate composition of raw and sous vide-cooked pork loin (mean ± SEM; n = 3).

Sample		Cooking Loss (%)	Moisture Content (%)	Fat Content (%)	Protein Content (%)
Raw pork loin		nd	71.98 ± 0.09	4.28 ± 0.10	22.89 ± 0.13
57 °C	3 h	12.70 ± 0.26 ^{a}	70.39 ± 0.04 ^{fh}	4.14 ± 0.05 ^{a}	24.55 ± 0.01 ^{abc}
	3.5 h	14.59 ± 0.15 ^{abc}	69.79 ± 0.10 ^{efgh}	4.11 ± 0.01 ^{a}	24.57 ± 0.10 ^{abc}
	4 h	15.02 ± 0.19 ^{ab}	70.10 ± 0.18 ^{fh}	3.96 ± 0.06 ^{a}	24.85 ± 0.24 ^{abc}
	4.5 h	14.86 ± 0.73 ^{ab}	69.69 ± 0.21 ^{fh}	3.87 ± 0.03 ^{a}	24.84 ± 0.21 ^{abc}
	5 h	16.60 ± 0.13 ^{abc}	69.68 ± 0.24 ^{fh}	3.88 ± 0.06 ^{a}	25.14 ± 0.05 ^{abc}
	5.5 h	16.56 ± 0.49 ^{abc}	68.22 ± 0.39 ^{abcd}	3.77 ± 0.07 ^{a}	25.48 ± 0.21 ^{abcde}
59 °C	3 h	18.19 ± 0.36 ^{abcd}	70.35 ±0.15 ^{h}	4.02 ± 0.02 ^{a}	24.67 ± 0.25 ^{a}
	3.5 h	18.76 ± 0.98 ^{bcde}	70.29 ± 0.10 ^{h}	3.98 ± 0.08 ^{a}	24.73 ± 0.18 ^{ab}
	4 h	21.53 ± 0.70 ^{defg}	70.13 ± 0.10 ^{fh}	3.93 ± 0.05 ^{a}	24.90 ± 0.14 ^{abc}
	4.5 h	23.20 ± 0.81 ^{fgh}	69.58 ± 0.10 ^{efh}	3.85 ± 0.11 ^{a}	25.42 ± 0.17 ^{abcd}
	5 h	22.79 ± 0.27 ^{fgh}	69.51 ± 0.21 ^{efh}	3.85 ± 0.02 ^{a}	25.57 ± 0.24 ^{bcde}
60 °C	3 h	21.67 ± 0.92 ^{efg}	69.17 ± 0.33 ^{defg}	3.96 ± 0.12 ^{a}	25.31 ± 0.05 ^{abcde}
	3.5 h	22.01 ± 0.66 ^{efgh}	68.42 ± 0.24 ^{abcdg}	3.97 ± 0.10 ^{a}	25.85 ± 0.45 ^{cdefgh}
	4 h	22.93 ± 0.54 ^{fgh}	68.02 ± 0.21 ^{abc}	3.90 ± 0.15 ^{a}	26.22 ± 0.04 ^{defghij}
	4.5 h	24.05 ± 0.47 ^{gh}	68.00 ± 0.18 ^{abc}	3.85 ± 0.11 ^{a}	26.29 ± 0.04 ^{defghij}
	5 h	24.37 ± 0.40 ^{gh}	68.05 ± 0.17 ^{abc}	3.83 ± 0.12 ^{a}	26.69 ± 0.14 ^{ghij}
61 °C	3 h	21.38 ± 0.93 ^{defg}	68.62 ± 0.15 ^{cdeg}	3.88 ± 0.16 ^{a}	25.59 ± 0.20 ^{abcdef}
	3.5 h	20.09 ± 0.41 ^{cdef}	68.46 ± 0.06 ^{bcdg}	3.86 ± 0.07 ^{a}	26.15 ± 0.12 ^{defghi}
	4 h	21.44 ± 0.55 ^{defg}	67.82 ± 0.32 ^{abc}	3.87 ± 0.03 ^{a}	26.37 ± 0.18 ^{efghij}
	4.5 h	23.66 ± 0.42 ^{gh}	68.07 ± 0.09 ^{abc}	3.78 ± 0.06 ^{a}	26.65 ± 0.14 ^{gij}
	5 h	24.00 ± 0.43 ^{gh}	67.67 ± 0.21 ^{abc}	3.71 ± 0.09 ^{a}	26.73 ± 0.12 ^{gij}
63 °C	3 h	21.45 ± 0.90 ^{defg}	68.58 ± 0.09 ^{cdeg}	3.87 ± 0.05 ^{a}	25.71 ± 0.24 ^{cdefh}
	3.5 h	22.01 ± 0.68 ^{efgh}	67.83 ± 0.23 ^{abc}	3.84 ± 0.04 ^{a}	26.52 ± 0.11 ^{fghij}
	4 h	23.72 ± 0.88 ^{gh}	67.63 ± 0.23 ^{abc}	3.84 ± 0.09 ^{a}	26.88 ± 0.05 ^{gij}
	4.5 h	24.78 ± 0.84 ^{gh}	67.47 ± 0.17 ^{ab}	3.75 ± 0.05 ^{a}	27.07 ± 0.04 ^{ij}
	5 h	25.20 ± 0.97 ^{h}	67.37 ± 0.08 ^{a}	3.67 ± 0.08 ^{a}	27.15 ± 0.20 ^{j}
Level of significance					
Temperature		***	***	*	***
Time		***	**	**	**
Temperature × time interaction		NS	NS	NS	NS

$^{a, b, c}$ …—mean values in columns for cooked samples; different superscripts indicate significant differences at $p < 0.05$ according to the Tukey's test; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, NS—not significant, nd—not determined.

It was noted in our study that the initial 3 h heating resulted in 12.70–21.67% cooking losses, while a further 2 h cooking increased those losses by another 2.7–4.6%. This observation confirmed the findings of other authors, reported by Dominguez-Hernandez et al. [6]. In our study, the highest increase in that feature with prolonged time of cooking was observed when heating took place at 59 °C. The application of cooking parameters higher than 59 °C/3.5 h caused cooking losses above 20%. Kovaleva et al. [34] observed a sharp increase in the degree of myofibrillar proteins' denaturation between 55 and 60 °C. They concluded that the temperature of 50–60 °C in the meat centre during cooking minimised cooking losses and prepared a juicy final product with preserved nutritional value.

Myofibrils are responsible for the majority of cooking loss, since they retain most of the water in the muscle. Water is released during muscle fibre shrinkage. Apart from water release, the cooking loss is enhanced by the fat melting [35] and the loss of soluble compounds [21,34], and as a result the weight of the meat decreases. Myofibrillar proteins denature and shrink mainly at temperatures between 40 °C and 80 °C [13,34,36–39]. According to Pathare and Roskilly [21], the reduced cooking loss contributes to higher thermal hydrolysis of collagen which in turn results in better meat tenderisation, and the most intense cooking loss is observed between 50 and 70 °C. Likewise, Botinestean et al. [40] showed that softer consistency of meat is related to reduced cooking losses.

3.2. Proximate Composition

The moisture content in raw pork loin was 71.98% and in the cooked meat it was in the range of 67.37–70.39% (Table 1). The lowest moisture level was found in the meat heated at 63 °C/5 h and the highest in the meat heated at 57 °C/3 h. The loin samples differed significantly depending on the heating temperature ($p < 0.001$) and time ($p < 0.01$) applied. In general, the higher the cooking temperature and the longer the cooking time used, the lower the moisture content in the pork samples. Our results confirm the observations noted in other studies [20,22,41,42]. In the review by Tornberg [39], it was reported that with increasing temperature, the transverse shrinkage of muscle fibres at 40–60 °C and then collective longitudinal shrinkage of the connective tissue network and the muscle fibres at 60–70 °C cause expulsion of water, which is held in the spaces between the thick and thin filaments in the muscle, and which represents most of the water present in the muscle [35]. Another reason for water loss from meat during cooking is protein denaturation, which leads to less water held by capillary forces within protein structures [43]. The heat treatment of meat causes a decrease in the number of acidic and basic groups of proteins, which in turn affects the pH value of meat and the change in the isoelectric point of proteins, and, as a result, the moisture-holding capacity of proteins [34]. James and Yang [36] reported that the low temperature used during sous vide cooking of meat helped to preserve cellular structure and increase water retention capacity compared to traditional cooking, which in turn promoted solubilisation and gelation of the connective tissue and ensured that the final products are tender and juicy.

The fat content in the cooked meat samples ranged from 3.67 to 4.14%, with the lowest fat content recorded in pork loin heated at 63 °C/5 h, and the highest in pork loin heated at 57 °C/3 h (Table 1). It was shown that temperature and time of cooking were factors that significantly influenced the fat content in the examined meat ($p < 0.05$ and $p < 0.01$, resp.). The fat content in the samples decreased with increasing temperature and time of heating. Similar relationships were demonstrated in the studies of Jiang et al. [44], and the authors ascribed that change to the melting and leakage of fat from meat samples, which could also be a reason for the fat content change in our study. The small changes in fat content recorded in the present study may be due to the low fat content in pork loin and its even distribution in the muscle structure which limited the fat loss from the meat. In addition, Ismail et al. [42] pointed out the presence of volatile organic compounds originated from fatty acids degradation in meat sous vide cooked at 60 °C, which might have also affected the fat content in samples tested our study. A contrary observation—an increase in fat content after sous vide cooking of poultry compared to raw meat—was noted by Głuchowski et al. [8]. In the study by Rezler et al. [45], a reduced fat content after 6 h/60 °C sous vide cooking of pork compared to raw meat and then mostly higher fat content than in raw meat when cooking took place for 8–18 h at 60 °C, was reported.

It was observed that the protein content in meat after sous vide heat treatment (24.55–27.15%) was higher than in a raw meat (22.89%), with an increase noted with increasing temperature and time of heating (Table 1). Statistical analysis of the results has shown that both above-mentioned cooking parameters were the factors significantly influencing the protein content in the tested meat samples ($p < 0.001$ and $p < 0.01$, resp.). Our results confirm the findings of Głuchowski et al. [8], who reported that the protein content change in poultry, cooked by sous vide, steaming, and boiling, depended on the intensity of the thermal treatment, and those of Rezler et al. [45] who noted higher protein content in pork loin sous vide cooked at 60 °C/6–18 h than in raw meat, although the increase in protein content was not regular with increased time of cooking. Changes in meat proteins during cooking, such as denaturation and solubilisation, occur gradually depending on the temperature of treatment, and affect the water-holding capacity of meat [36,39,43]. At lower temperatures (around 57–59 °C), denaturation of muscle proteins occurs more slowly, which may lead to less impact on the structural integrity of the meat and less changes in water content. In addition, the sous vide method minimises protein losses compared to other methods because there is no direct contact of meat with water (as in traditional cooking), which prevents protein from washing out. The increase in protein content after cooking in our study can be ascribed to the change in its concentration caused by the moisture and fat contents reduction due to the heat treatment.

3.3. pH Value

Most pH values of heat-treated samples were slightly higher than those of the raw meat, but no significant differences were observed in pH values of cooked meats ($p > 0.05$; Table 2). This confirmed our earlier findings, even though, in general, higher temperatures (60–75 °C) and shorter cooking times (1–4 h) were applied in that study [20].

Table 2. pH value, water activity, and oxidative changes (TBARS) of raw and sous vide-cooked pork loin (mean ± SEM; n = 3).

Sample		pH	Water Activity	TBARS (mg MDA/kg)
Raw pork loin		5.72 ± 0.02	0.987 ± 0.003	0.56 ± 0.04
57 °C	3 h	5.97 ± 0.01 ^{a}	0.983 ± 0.008 ^{a}	0.43 ± 0.04 ^{a}
	3.5 h	6.01 ± 0.03 ^{a}	0.997 ± 0.007 ^{a}	0.92 ± 0.15 ^{abcd}
	4 h	5.73 ± 0.07 ^{a}	0.998 ± 0.007 ^{a}	1.40 ± 0.19 ^{bcde}
	4.5 h	5.75 ± 0.06 ^{a}	0.995 ± 0.007 ^{a}	1.41 ± 0.19 ^{bcde}
	5 h	5.78 ± 0.04 ^{a}	0.984 ± 0.007 ^{a}	1.50 ± 0.17 ^{bcde}
	5.5 h	5.78 ± 0.08 ^{a}	0.989 ± 0.009 ^{a}	1.48 ± 0.21 ^{bcde}
59 °C	3 h	5.77 ± 0.02 ^{a}	0.995 ± 0.005 ^{a}	0.71 ± 0.09 ^{a}
	3.5 h	5.80 ± 0.01 ^{a}	0.997 ± 0.005 ^{a}	0.91 ± 0.02 ^{ab}
	4 h	5.78 ± 0.02 ^{a}	0.995 ± 0.006 ^{a}	1.10 ± 0.06 ^{abc}
	4.5 h	5.83 ± 0.02 ^{a}	0.996 ± 0.005 ^{a}	1.39 ± 0.07 ^{bcde}
	5 h	5.81 ± 0.02 ^{a}	0.984 ± 0.006 ^{a}	1.57 ± 0.07 ^{cde}
60 °C	3 h	5.72 ± 0.02 ^{a}	0.983 ± 0.010 ^{a}	1.54 ± 0.01 ^{bcde}
	3.5 h	5.81 ± 0.01 ^{a}	0.980 ± 0.011 ^{a}	1.57 ± 0.02 ^{cde}
	4 h	5.76 ± 0.03 ^{a}	0.987 ± 0.011 ^{a}	1.53 ± 0.02 ^{bcde}
	4.5 h	5.78 ± 0.03 ^{a}	0.984 ± 0.010 ^{a}	1.90 ± 0.06 ^{e}
	5 h	5.81 ± 0.01 ^{a}	0.998 ± 0.009 ^{a}	1.87 ± 0.01 ^{e}
61 °C	3 h	5.81 ± 0.03 ^{a}	0.992 ± 0.003 ^{a}	1.38 ± 0.03 ^{bcde}
	3.5 h	5.82 ± 0.04 ^{a}	0.990 ± 0.003 ^{a}	1.52 ± 0.06 ^{bcde}
	4 h	5.82 ± 0.04 ^{a}	0.999 ± 0.003 ^{a}	1.75 ± 0.13 ^{cde}
	4.5 h	5.84 ± 0.04 ^{a}	0.991 ± 0.004 ^{a}	1.83 ± 0.11 ^{e}
	5 h	5.88 ± 0.04 ^{a}	0.993 ± 0.003 ^{a}	1.91 ± 0.04 ^{e}
63 °C	3 h	5.87 ± 0.06 ^{a}	0.996 ± 0.005 ^{a}	1.60 ± 0.25 ^{cde}
	3.5 h	5.87 ± 0.06 ^{a}	0.997 ± 0.005 ^{a}	1.78 ± 0.09 ^{de}
	4 h	5.87 ± 0.09 ^{a}	0.984 ± 0.004 ^{a}	1.87 ± 0.20 ^{e}
	4.5 h	5.83 ± 0.02 ^{a}	0.997 ± 0.005 ^{a}	1.84 ± 0.08 ^{de}
	5 h	5.85 ± 0.07 ^{a}	0.983 ± 0.006 ^{a}	1.72 ± 0.10 ^{de}
Level of significance				
Temperature		NS	NS	***
Time		NS	NS	***
Temperature × time interaction		NS	NS	NS

^{a}, ^{b}, ^{c} . . .—mean values in columns for cooked samples; different superscripts indicate significant differences at $p < 0.05$ according to the Tukey's test *** $p < 0.001$, NS—not significant.

The increase in the pH value of meat upon cooking has been recently reported in poultry by Głuchowski et al. [8] and Haghighi et al. [11], and in beef by Jung et al. [46]. The latter authors explained the change in pH value by the alteration of electric charge of acid groups, separation of peptide chains, and formation of new compounds of an alkaline nature. Other probable causes for the higher pH value of cooked meat compared to raw meat, suggested in the literature, are the loss of acidic amino groups [35], formation of free hydrogen sulfide [47], structural changes in muscle proteins [48], and breaking of bonds involving imidazole, sulphydryl, and hydroxyl groups [49]. Significant differences in the pH value of meat, depending on the cooking method, were noted in rabbit meat by Abdel-Naeem et al. [50] and in beef by Xu et al. [51]. Bıyikli et al. [52] reported a significant increase in pH with increasing temperature and time of sous vide cooking of turkey meat.

3.4. Water Activity

There were no significant differences between the samples with regard to water activity (Table 2). The values were within the range of 0.983–0.999 for heat-treated meat and 0.987 for raw meat, and were in agreement with those reported in our previous study [20]. There is little data in the literature on the water activity of pork loin heated with the sous vide technique. Diaz et al. [53] obtained slightly different results, as for pork loin shortly roasted at 300 °C and then heated with the sous vide technique at 70 °C for 12 h the water activity value was 0.92. In the experiment of ul Haq et al. [54], water activity values of around 0.95 for buffalo steaks sous vide cooked at 55, 65, and 95 °C for 8 h, 5 h, and 45 min, resp., and no significant effect of cooking conditions on that parameter, were observed. Likewise, no significant effect of cooking method (sous vide, grilling, and steaming) on veal steaks' water activity was noted by Kaliniak-Dziura et al. [55]. It can be assumed that differences in water activity of cooked meats may result from differences in heating parameters/cooking method as well as from the origin of meat samples analysed in the studies presented above. It is known that the reduction of water activity of food products increases the lag phase and reduces the growth of microorganisms [56,57], but the effect of water activity on oxidative and browning reactions is more complex [57]. Nevertheless, the cooking parameters applied in our study did not cause the differences in the water activity of samples; therefore, their similar storage stability can be assumed.

3.5. Lipid Oxidation

The TBARS (thiobarbituric acid reactive substances) value is an indicator of oxidative changes in food. It reflects the degree of secondary oxidative reactions on the basis of the presence of the secondary products resulting from the oxidative breakdown of unsaturated fatty acids [44].

In the present study, the TBARS value of raw meat was 0.56 mg MDA/kg and after thermal processing the values were in the range 0.43–1.91 mg MDA/kg (Table 2). The statistical analysis has shown that the content of TBARS in the tested samples of pork loin was significantly influenced by the sous vide heating temperature and its exposure time ($p < 0.001$). Nevertheless, the significant differences in TBARS values of samples heated at different times were observed when cooking took place at 57 and 59 °C, while all samples cooked at higher temperatures did not differ significantly with respect to the TBARS value, regardless of the cooking times applied.

Bıyıklı et al. [52] reported significantly higher TBARS values for turkey meat sous vide cooked at higher temperatures, when cooking parameters applied were 65/70/75 °C for 20/40/60 min, but the effects of cooking time and interaction of temperature and time were not significant. In the research of Jiang et al. [44] on pork sous vide cooked at 65/70/75 °C for 8/10/12 h, the content of TBARS increased with increasing temperature and time of sous vide cooking, and in addition it was observed that the sous vide cooking of pork significantly reduced the lipid oxidation compared to the meat stewed traditionally. In both studies, all TBARS values remained below 1.0 mg MDA/kg sample, while in our study, despite the use of lower temperatures and intermediate heating times compared to the above-mentioned studies, most recorded TBARS values were in the range 1–2 mg MDA/kg. Higher TBARS values observed in our study could be explained by the additional effect of the type of animal feed on the intensity of oxidative changes in meat [58]. Campo et al. [58] also indicated a TBARS value of 2 mg MDA/kg as a limiting threshold value for rancidity perception and oxidation acceptability in beef; however, the authors pointed out the importance of personal experience and sensitivity of panellists in threshold perception. In other studies, the rancidity thresholds of 0.5 µg MDA/g in pork [59] and 3.1 µg MDA/g in beef [60] were reported.

3.6. Instrumental Colour Measurement

The colour of meat is an important criterion for its quality evaluation by the consumer, and the cooked meat colour can have a decisive effect on the product acceptance [40,61]. While in some groups of consumers/countries, consumption of rare or medium-rare meat is a matter of tradition or preference, in other groups/countries the reddish or pinkish colour of meat may be perceived as an undercooked state of product [62,63].

In the present study, when determining the colour of sous vide-cooked pork in the CIE $L^*a^*b^*$ system (Table 3), it was shown that the lightness (L^*) of raw meat was 52.16, while that of heated meat was from 66.33 (cooking at 57 °C/3.5 h) to 71.98 (cooking at 60 °C/3.5 h). Cooked samples did not differ significantly in terms of their lightness and no significant effect of temperature and heating time as well as their interaction on the lightness (L^*) of the examined pork loin was found. Likewise, no significant differences in L^* values for lamb sous vide cooked at 60/70/80 °C were reported by Roldan et al. [38]. In addition, Roldan et al. [38] and Sanchez del Pulgar et al. [64] observed slightly higher L^* values for lamb and pork, respectively, cooked at lower temperatures, which they explained by the differences in water presence on the meat surface. Jeong et al. [22] noted an increase in the L^* value of pork ham when the heating temperature increased from 61 °C to 71 °C and attributed this observation to the differences in moisture content in samples which affects the depth of light penetration in the tissue and thus the colour of the meat surface [65], as well as an increased protein denaturation and aggregation at higher temperatures, which leads to increased light scattering and increases the lightness of the meat [66].

In our study, higher cooking temperatures led to a slight reduction in meat redness (a^*), which was also observed in other studies [21,38,67,68]. The meat redness was affected by the cooking temperature ($p < 0.001$); however, the significant differences were observed mainly between some of the samples cooked at 61 °C and 57 °C. The share of redness in the overall colour of heated meat products is inversely related to the degree of myoglobin denaturation, and as the cooking temperature increases, the degree of myoglobin denaturation increases causing the reduction in meat redness [4,38]. As a consequence, the pork loin samples cooked at a lower temperature showed a more intense red colour (higher a^* values) than those cooked at a higher temperature, indicating higher myoglobin degradation with increasing cooking temperature. In addition, García-Segovia et al. [67] observed that sous vide-cooked meat showed a more reddish colour than meat cooked by other methods and suggested that packaging used in sous vide treatment could protect myoglobin from degradation. It was confirmed by Sanchez del Pulgar et al. [64], who showed that the a^* value was higher for pork cooked with sous vide method at 60 °C and 80 °C than for meat cooked traditionally in water.

It was noted in the present experiment that the b^* values of heat-treated samples were higher than those of raw meat; however, no significant differences were observed between cooked samples. Contrary to our results, higher b^* values with increasing temperature and time of lamb loin sous vide cooking have been reported in the study by Roldán et al. [38], but in that study temperatures 60–80 °C and times 6–24 h were applied as cooking parameters. In the literature, the increase in yellowness values of meat upon cooking is attributed to the formation of metmyoglobin and its further heat denaturation, giving meat a brownish colour [38,40,62].

Table 3. CIE $L^*a^*b^*$ colour parameters of raw and sous vide-cooked pork loin (mean ± SEM; n = 3).

Sample		Colour L^*	Colour a^*	Colour b^*	Hue Angle $h°$	Chroma C^*	ΔE^*
Raw pork loin		52.16 ± 0.65	8.56 ± 0.12	4.29 ± 0.12	34.88 ± 0.63	7.49 ± 0.15	nd
57 °C	3 h	69.19 ± 1.12 ^{a}	8.36 ± 0.45 ^{bcd}	13.09 ± 0.44 ^{a}	57.46 ± 1.60 ^{ab}	15.58 ± 0.47 ^{a}	19.50
	3.5 h	66.33 ± 1.13 ^{a}	8.35 ± 0.27 ^{bcd}	14.30 ± 0.26 ^{a}	59.73 ± 0.97 ^{abcd}	16.58 ± 0.25 ^{a}	18.30
	4 h	70.09 ± 0.74 ^{a}	8.35 ± 0.36 ^{d}	13.47 ± 0.31 ^{a}	58.47 ± 0.89 ^{a}	15.89 ± 0.42 ^{a}	21.00
	4.5 h	69.43 ± 0.72 ^{a}	8.35 ± 0.23 ^{d}	13.57 ± 0.15 ^{a}	58.53 ± 0.53 ^{a}	15.94 ± 0.24 ^{a}	20.40
	5 h	69.31 ± 1.17 ^{a}	8.00 ± 0.27 ^{cd}	13.42 ± 0.29 ^{a}	59.34 ± 0.63 ^{abc}	15.65 ± 0.36 ^{a}	20.20
	5.5 h	69.32 ± 0.81 ^{a}	7.39 ± 0.34 ^{abcd}	13.56 ± 0.25 ^{a}	61.79 ± 0.74 ^{bcdefg}	15.47 ± 0.38 ^{a}	20.30
59 °C	3 h	69.33 ± 0.59 ^{a}	7.98 ± 0.25 ^{cd}	13.39 ± 0.21 ^{a}	59.35 ± 0.54 ^{abc}	15.60 ± 0.29 ^{a}	21.30
	3.5 h	70.75 ± 1.02 ^{a}	7.24 ± 0.33 ^{abcd}	13.01 ± 0.36 ^{a}	61.20 ± 0.59 ^{abcde}	14.91 ± 0.47 ^{a}	22.30
	4 h	68.54 ± 2.78 ^{a}	6.80 ± 0.25 ^{abc}	13.15 ± 0.30 ^{a}	62.84 ± 0.53 ^{defg}	14.82 ± 0.36 ^{a}	20.40
	4.5 h	68.89 ± 2.32 ^{a}	7.11 ± 0.26 ^{abcd}	13.36 ± 0.27 ^{a}	62.14 ± 0.56 ^{cdefg}	15.15 ± 0.34 ^{a}	20.80
	5 h	70.12 ± 0.48 ^{a}	6.94 ± 0.31 ^{abcd}	13.35 ± 0.36 ^{a}	62.80 ± 0.54 ^{defg}	15.06 ± 0.45 ^{a}	21.90
60 °C	3 h	71.27 ± 0.83 ^{a}	7.28 ± 0.25 ^{abcd}	13.48 ± 0.27 ^{a}	61.74 ± 0.59 ^{bcdef}	15.34 ± 0.33 ^{a}	21.50
	3.5 h	71.98 ± 0.93 ^{a}	6.97 ± 0.33 ^{abcd}	13.01 ± 0.34 ^{a}	62.19 ± 0.68 ^{cdefg}	14.78 ± 0.45 ^{a}	22.00
	4 h	69.87 ± 0.72 ^{a}	7.27 ± 0.25 ^{abcd}	13.92 ± 0.25 ^{a}	62.58 ± 0.57 ^{defg}	15.72 ± 0.32 ^{a}	20.50
	4.5 h	69.16 ± 0.75 ^{a}	7.41 ± 0.27 ^{abcd}	13.99 ± 0.22 ^{a}	62.29 ± 0.63 ^{cdefg}	15.86 ± 0.31 ^{a}	19.90
	5 h	68.76 ± 0.62 ^{a}	6.90 ± 0.23 ^{abc}	13.83 ± 0.21 ^{a}	63.63 ± 0.59 ^{defg}	15.47 ± 0.27 ^{a}	19.40
61 °C	3 h	69.03 ± 0.69 ^{a}	7.36 ± 0.25 ^{abcd}	13.84 ± 0.23 ^{a}	62.16 ± 0.60 ^{cdefg}	15.69 ± 0.30 a	17.70
	3.5 h	68.54 ± 0.57 ^{a}	7.45 ± 0.22 ^{abcd}	14.19 ± 0.18 ^{a}	62.41 ± 0.52 ^{cdefg}	16.04 ± 0.24 ^{a}	17.50
	4 h	69.80 ± 0.73 ^{a}	6.31 ± 0.27 ^{a}	13.28 ± 0.24 ^{a}	64.84 ± 0.68 ^{fg}	14.73 ± 0.32 ^{a}	18.00
	4.5 h	68.26 ± 0.48 ^{a}	6.65 ± 0.22 ^{abc}	13.83 ± 0.22 ^{a}	64.47 ± 0.56 ^{fg}	15.36 ± 0.27 ^{a}	17.20
	5 h	68.27 ± 0.55 ^{a}	6.53 ± 0.23 ^{ab}	13.90 ± 0.23 ^{a}	64.94 ± 0.56 ^{g}	15.37 ± 0.28 ^{a}	17.10
63 °C	3 h	70.70 ± 0.57 ^{a}	7.31 ± 0.25 ^{abcd}	13.77 ± 0.28 ^{a}	62.18 ± 0.55 ^{cdefg}	15.61 ± 0.34 ^{a}	19.60
	3.5 h	71.11 ± 0.65 ^{a}	6.41 ± 0.30 ^{ab}	13.20 ± 0.31 ^{a}	64.36 ± 0.65 ^{efg}	14.69 ± 0.40 ^{a}	19.70
	4 h	69.24 ± 0.67 ^{a}	7.15 ± 0.25 ^{abcd}	13.96 ± 0.23 ^{a}	63.06 ± 0.64 ^{defg}	15.70 ± 0.30 ^{a}	18.40
	4.5 h	70.12 ± 0.64 ^{a}	7.28 ± 0.31 ^{abcd}	14.30 ± 0.29 ^{a}	63.27 ± 0.67 ^{defg}	16.07 ± 0.38 ^{a}	19.30
	5 h	69.54 ± 0.49 ^{a}	6.95 ± 0.25 ^{abcd}	13.99 ± 0.29 ^{a}	63.77 ± 0.48 ^{defg}	15.63 ± 0.36 ^{a}	18.60
Level of significance							
Temperature		NS	***	NS	***	NS	nd
Time		NS	NS	NS	**	NS	nd
Temperature × time interaction		NS	NS	NS	NS	NS	nd

^{a}, ^{b}, ^{c} …—mean values in columns for cooked samples; different superscripts indicate significant differences at $p < 0.05$ according to the Tukey's test; ** $p < 0.01$, *** $p < 0.001$, NS—not significant, nd—not determined.

According to Jeong et al. [22], the temperature applied during sous vide heat treatment affects the meat's $L^*a^*b^*$ colour characteristics, while cooking time may have a limited effect. Naveena et al. [69] and Park et al. [68] pointed out that cooked meat colour depends on the degree of protein denaturation in myoglobin, and the domineering form of myoglobin in vacuum-packed meat is deoxymyoglobin, which is more heat resistant than other forms, namely oxymyoglobin and metmyoglobin. Denaturation/unfolding of the globin part of myoglobin forms upon heat treatment leads to the exposure of heme moiety and its susceptibility to oxidation. Formation of dull-brown ferrihemochrome from metmyoglobin and pink-red ferrohemochrome from deoxy- and oxymyoglobin, which is further oxidised to ferrihemochrome, occurs [62]. Latoch et al. [70] suggested that sous vide heat treatment can reduce myoglobin oxidation and increase its thermal stability. As the protein denaturation in myoglobin takes place between 55 °C and 65 °C and continues till 75 °C–80 °C [38], the relatively small intervals between temperatures and times applied in our study could explain the lack of significant differences in the L^* and b^* colour values and only minor variability in the a^* values.

The tone of the pork samples' colour, expressed as hue angle ($h°$), was significantly affected by temperature and time of cooking ($p < 0.001$ and $p < 0.01$, resp.). The $h°$ value is related to the chemical state of the myoglobin and is inversely proportional to the a^* value. Therefore, pork samples cooked at 57 °C showed lower $h°$ values than those cooked at 63 °C, which can be explained by the lower degree of myoglobin denaturation mentioned above. The colour intensity (saturation or chroma, C^*) of meat is also influenced by the concentration of myoglobin and degree of its denaturation, and is more dominant at higher concentrations of myoglobin and at a lower degree of myoglobin denaturation [13]. In the present study, no significant differences were observed for C^* values between cooked samples. When determining the overall colour difference (ΔE^*) of the cooked meat samples in relation to the raw meat, high values were noted (17.10–22.30), which means a large colour difference [22], recognisable by an inexperienced observer [71].

3.7. Instrumental Texture Analysis

The texture of meat is an important feature influencing its acceptance by consumers. This is also the feature that chefs pay the most attention to, and indicating the appropriate sous vide heat treatment parameters that give the meat the desired organoleptic properties and microbiological safety would greatly facilitate the work of the catering industry. In order to assess the texture of the tested pork loin, a shear test and texture profile analysis (TPA) were performed.

3.8. Shear Force

The shear force (SF) parameter is considered a good indicator of initial bite tenderness [13], which correlates well with sensory tests [2,39]. In general, the value of this parameter declines when meat temperature changes from 50 °C to 65 °C and then it increases at temperatures up to 80 °C [2,39].

It was confirmed in our study as the pork loin samples cooked at 57 °C showed higher shear force values than those cooked at higher temperatures (Table 4). It was shown that the factors that significantly influenced the shear force of meat samples were the temperature and the interaction between temperature and time of cooking (both $p < 0.001$). Naqvi et al. [72] also showed a decrease in shear force with increasing temperature and heating time. According to the above authors, the decrease in shear force resulted from the solubility of connective tissue in the tested steaks. A similar trend was observed in the study of Hwang et al. [31], who reported a significant effect of cooking temperature when pork loin treatment took place for 12 h at 50, 55, or 60 °C. A significant effect of cooking time (12 or 24 h) was noted only for samples cooked at 50 °C. Likewise, Botinestean et al. [40] did not observe a significant effect of sous vide cooking time on the shear force of beef steaks. The SF values reported in that study were between 31 and 39 N, and samples were considered relatively tender. Destefanis et al. [73] suggested an SF value below 42.87 N for the perception of beef steaks as tender by the consumers. The SF values noted in our study did not exceed 22 N, which confirms desirable tenderness of our meat samples.

The texture of cooked meat is a result of heat-induced changes which take place in myofibrillar proteins and connective tissue [74]. Denaturation of myofibrillar proteins leads to meat toughening but solubilisation of connective tissue results in meat tenderisation [13]. Apart from a solubilisation of connective tissue, meat tenderisation can be also attributed to a change from viscoelastic to elastic properties of meat upon cooking, which is related to the gelation of aggregated sarcoplasmic proteins [2,39] as well as a residual activity of endogenous proteolytic enzymes [39,66,75]. Dominguez-Hernandez and Ertbjerg [76] reported a residual activity of some cathepsins under low-temperature long-time heat treatment of pork and its negative correlation with the presence of large aggregates of myofibrillar proteins. The authors suggested that the changes in myofibrillar proteins' aggregation due to the cathepsins activity affect the meat texture through the changes in gel formation by those proteins. According to Kathuria et al. [77], the stability of cathepsin is higher than that of calpain between 50 and 70 °C and when the temperature is above 70 °C, the enzymes are inactivated.

Table 4. Texture characteristics of sous vide-cooked pork loin on the basis of shear force and TPA tests (mean ± SEM; n = 3).

Sample		Shear Force (N)	Hardness (N)	Springiness (cm)	Cohesiveness (-)	Chewiness (N × cm)
57 °C	3 h	20.60 ± 0.62 abcd	102.87 ± 2.63 h	0.39 ± 0.01 a	0.45 ± 0.01 a	19.51 ± 1.60 fgh
	3.5 h	20.25 ± 0.68 abcd	88.35 ± 1.65 gh	0.48 ± 0.01 abc	0.55 ± 0.01 abcd	21.33 ± 2.08 fgh
	4 h	18.54 ± 0.84 bcd	50.20 ± 1.19 abcde	0.49 ± 0.02 bc	0.55 ± 0.01 cd	15.05 ± 1.14 cdefg
	4.5 h	18.34 ± 0.89 bcd	52.08 ± 1.53 abcdef	0.45 ± 0.01 ab	0.55 ± 0.00 cd	12.67 ± 0.42 abcdeg
	5 h	18.20 ± 0.78 abcd	58.90 ± 2.14 defg	0.47 ± 0.01 abc	0.54 ± 0.00 bcd	13.44 ± 1.21 abcdefg
	5.5 h	17.42 ± 1.16 abcd	55.46 ± 2.11 bcdef	0.44 ± 0.01 ab	0.51 ± 0.01 abc	11.88 ± 0.83 abcde
59 °C	3 h	14.17 ± 0.60 abc	58.15 ± 3.94 defg	0.47 ± 0.01 abc	0.51 ± 0.00 abc	14.21 ± 1.04 bcdefg
	3.5 h	16.84 ± 1.07 abcd	57.42 ± 4.05 defg	0.49 ± 0.01 bc	0.54 ± 0.00 bcd	15.58 ± 1.11 defg
	4 h	16.12 ± 1.00 abcd	56.19 ± 4.10 bcdef	0.48 ± 0.01 bc	0.53 ± 0.01 abcd	14.15 ± 0.91 bcdefg
	4.5 h	17.49 ± 1.23 bcd	38.66 ± 2.54 a	0.50 ± 0.01 bc	0.55 ± 0.01 bcd	10.43 ± 0.70 abc
	5 h	21.76 ± 0.59 d	47.46 ± 1.57 abcd	0.47 ± 0.01 abc	0.53 ± 0.01 abcd	11.63 ± 0.33 abcd
60 °C	3 h	16.38 ± 1.11 abcd	54.23 ± 2.14 abcdef	0.48 ± 0.01 abc	0.53 ± 0.01 abcd	13.47 ± 0.39 abcdefg
	3.5 h	14.35 ± 0.61 abc	50.72 ± 3.41 abcdef	0.49 ± 0.02 bc	0.54 ± 0.00 bcd	13.30 ± 0.80 abcdefg
	4 h	14.03 ± 0.55 ab	39.68 ± 2.28 abc	0.47 ± 0.01 abc	0.53 ± 0.01 abcd	9.77 ± 0.67 ab
	4.5 h	11.66 ± 0.41 a	50.48 ± 3.99 abcde	0.47 ± 0.01 abc	0.51 ± 0.01 abc	12.07 ± 0.91 abcde
	5 h	14.19 ± 0.76 abc	39.78 ± 3.21 ab	0.47 ± 0.01 abc	0.52 ± 0.01 abcd	9.42 ± 0.67 a
61 °C	3 h	20.07 ± 1.02 cd	52.21 ± 1.77 abcdef	0.48 ± 0.01 abc	0.54 ± 0.01 bcd	14.39 ± 0.74 bcdefg
	3.5 h	21.05 ± 0.79 d	49.73 ± 3.95 abcde	0.48 ± 0.01 bc	0.57 ± 0.01 d	13.75 ± 0.83 abcdefg
	4 h	16.94 ± 0.64 abcd	63.76 ± 1.38 defg	0.48 ± 0.01 bc	0.51 ± 0.00 abc	15.84 ± 0.60 defgh
	4.5 h	18.32 ± 1.19 bcd	55.80 ± 1.81 cdef	0.48 ± 0.01 abc	0.52 ± 0.00 abcd	13.95 ± 0.53 bcdefg
	5 h	16.23 ± 1.29 abcd	55.67 ± 2.33 bcdef	0.46 ± 0.01 ab	0.51 ± 0.00 abc	12.15 ± 1.02 abcde
63 °C	3 h	16.83 ± 1.56 abcd	58.70 ± 4.22 defg	0.52 ± 0.01 c	0.54 ± 0.01 bcd	16.24 ± 1.22 efgh
	3.5 h	15.95 ± 1.81 abcd	67.49 ± 3.43 fg	0.49 ± 0.01 bc	0.53 ± 0.01 abcd	17.55 ± 1.07 fh
	4 h	15.92 ± 1.71 abcd	63.64 ± 2.48 efg	0.47 ± 0.01 abc	0.53 ± 0.01 abcd	15.73 ± 0.60 defgh
	4.5 h	20.20 ± 1.73 cd	73.44 ± 6.16 g	0.49 ± 0.01 bc	0.53 ± 0.01 abcd	20.26 ± 1.31 h
	5 h	17.52 ± 1.50 bcd	65.58 ± 2.88 efg	0.45 ± 0.01 ab	0.49 ± 0.01 ab	14.75 ± 0.88 cdefg
Level of significance						
Temperature		***	***	**	NS	***
Time		NS	*	***	***	***
Temperature × time interaction		***	***	***	***	***

a, b, c …—mean values in columns with different superscripts indicating significant differences at $p < 0.05$ according to the Tukey's test; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, NS—not significant.

3.9. Texture Profile Analysis

The TPA test reflects the chewing of a product sample by the human jaw. As a result of the TPA test, information is obtained on the hardness, adhesiveness, elasticity, cohesiveness, gumminess, chewiness, and cohesion of the tested product [78].

It was noted in our study that the pork loin heated at 57 °C for 3 h and 3.5 h was characterised by clearly higher values of such features as hardness and chewiness compared to the other samples (Table 4). Analysing the remaining samples, it can be observed that the use of heating temperature 59 or 60 °C had the most positive effect on those texture parameters. The most tender samples were heated at 59 °C for 4.5 h and at 60 °C for 4 and 5 h. Likewise, the values of the chewiness parameter were lower for those pork loin samples than for the remaining samples. TPA features were significantly affected by both cooking parameters as well as their interaction, except for cohesiveness which was affected only by time and interaction of temperature and time of cooking.

Other authors have also reported a reduction in the hardness and chewiness of meat heated at temperatures around 60 °C [6,68,79]. Chewiness can be considered an important texture feature in meat product perception by the consumers as its lower values indicate less mastication effort, and together with cohesiveness and springiness it was found not to be affected by the sous vide cooking time of beef while the hardness of samples was affected [40,79]. In the research of Djekic et al. [80], in which three different methods of heat treatment of pork ham (sous vide, cooking, grilling) were compared, it was shown that the sous vide-heated sample was characterised by the lowest values of texture characteristics—hardness, springiness, gumminess, and chewiness.

3.10. Sensory Evaluation

Appearance is one of the most important attributes related to consumer acceptance [79,81]. As in the samples of pork loin heated at 57 °C for 3 and 3.5 h, the protein seemed to be not adequately denatured; those samples were not subjected to sensory evaluation. Therefore, at the temperature of 57 °C, compared to the other analysed temperatures, the heating time was extended to 5.5 h while the samples cooked for 3 and 3.5 h were examined only in terms of physicochemical changes. The use of such a short heating time for meat intended for short-term storage in gastronomy gives financial benefits as a result of reduced energy costs, and the above problem can be eliminated before serving by additional heating by sous vide method or short frying, thus bringing out the taste and aroma characteristics desired by consumers.

In the present study, statistically significant differences were found between samples heated at different temperature/times combinations only in terms of colour uniformity and tenderness (Table 5). Temperature of cooking had a significant impact on all the analysed sensory properties, while time of cooking significantly affected only overall appearance ($p < 0.05$) and colour uniformity ($p < 0.01$) of samples. Nevertheless, according to the results of sensory evaluation, meat samples heated at 59 °C for 4.5 h, compared to other samples, turned out to be significantly better in terms of tenderness and, in addition, received the highest scores for juiciness, meat flavour intensity, flavour acceptability, and overall acceptability. It was also observed that with the increase in meat-heating temperature, the scores for its juiciness decreased, which would confirm the observations of other authors [23,48,82,83], while Christensen et al. [23] also reported that the juiciness of meat heated with the LTLT (low-temperature long-time) method decreased with the increased cooking time. Texture is a very important parameter of food quality and affects the acceptance of the product by the consumer [13,20]. Tornberg [39] suggested that pork loin tenderness increases when meat is heated from 50 to 65 °C as a result of the formation of a gel of aggregated sarcoplasmic proteins and reduced viscous flow between the structural meat elements. Then, the tenderness declines when meat is heated to 80 °C due to the contraction of the connective tissue above 65 °C and an increase in the elasticity of the meat.

Although no significant differences in meat flavour intensity and flavour acceptability were noted in our study, the samples heated at 59 °C received slightly higher scores for those features than other samples. In general, the flavour of cooked meat results from the Maillard reactions, thiamine degradation, and degradation of lipids [84]. As the Maillard reaction takes place noticeably at temperatures higher than 130 °C, the sous vide-cooked meats show boiled meat aroma derived mainly from volatile products of lipid degradation [2,84,85]. Roldan et al. [85] reported a higher share of lipids' volatile derivatives when lamb was sous vide cooked at milder conditions (60 °C/6 and 24 h), while at more severe conditions (80 °C/24 h), the presence of volatiles from Strecker degradation was promoted. Dominguez-Hernandez et al. [6] noted that in order to produce volatile compounds resulting from the degradation of amino acids, it is common practice to subject the sous vide-heated product to high temperature. This was confirmed by Ruiz-Carrascal et al. [19] who observed that additional, short oven-roasting before or after sous vide cooking improves the flavour of meat. Rotola-Pukkila et al. [5] pointed out a role of umami compounds in the taste of meat and meat products and reported higher levels of those compounds in pork sous vide cooked at 80 °C than 60 or 70 °C.

Table 5. Sensory quality of sous vide cooked pork loin (mean ± SEM; n = 6).

Sample		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	3 h	nd	nd	nd	nd	nd	nd	nd	nd
	3.5 h	nd	nd	nd	nd	nd	nd	nd	nd
	4 h	8.11 ± 0.38 ^{a}	8.06 ± 0.35 ^{ab}	7.44 ± 0.47 ^{a}	6.94 ± 0.48 ^{ab}	7.61 ± 0.43 ^{a}	7.00 ± 0.42 ^{a}	6.83 ± 0.53 ^{a}	7.11 ± 0.42 ^{a}
	4.5 h	7.94 ± 0.48 ^{a}	8.17 ± 0.35 ^{ab}	7.72 ± 0.44 ^{a}	6.50 ± 0.51 ^{ab}	6.83 ± 0.56 ^{a}	7.22 ± 0.36 ^{a}	6.89 ± 0.62 ^{a}	7.00 ± 0.48 ^{a}
	5 h	8.39 ± 0.29 ^{a}	8.22 ± 0.30 ^{ab}	7.17 ± 0.44 ^{a}	5.61 ± 0.66 ^{a}	6.28 ± 0.61 ^{a}	7.50 ± 0.44 ^{a}	6.89 ± 0.55 ^{a}	6.83 ± 0.47 ^{a}
	5.5 h	7.22 ± 0.38 ^{a}	6.78 ± 0.50 ^{a}	7.61 ± 0.42 ^{a}	7.44 ± 0.57 ^{ab}	7.44 ± 0.66 ^{a}	7.50 ± 0.43 ^{a}	6.78 ± 0.54 ^{a}	7.22 ± 0.48 ^{a}
59 °C	3 h	8.67 ± 0.21 ^{a}	8.89 ± 0.21 ^{b}	8.11 ± 0.35 ^{a}	7.72 ± 0.46 ^{ab}	7.61 ± 0.53 ^{a}	8.33 ± 0.24 ^{a}	8.39 ± 0.23 ^{a}	8.17 ± 0.25 ^{a}
	3.5 h	8.61 ± 0.20 ^{a}	8.78 ± 0.24 ^{b}	8.39 ± 0.24 ^{a}	7.83 ± 0.39 ^{ab}	7.83 ± 0.28 ^{a}	7.56 ± 0.30 ^{a}	7.89 ± 0.30 ^{a}	7.78 ± 0.25 ^{a}
	4 h	8.78 ± 0.19 ^{a}	8.61 ± 0.20 ^{ab}	8.17 ± 0.22 ^{a}	7.06 ± 0.60 ^{ab}	7.61 ± 0.37 ^{a}	8.28 ± 0.24 ^{a}	8.22 ± 0.42 ^{a}	7.50 ± 0.40 ^{a}
	4.5 h	8.50 ± 0.19 ^{a}	8.50 ± 0.23 ^{ab}	7.89 ± 0.21 ^{a}	9.06 ± 0.22 ^{b}	8.11 ± 0.42 ^{a}	8.39 ± 0.20 ^{a}	8.61 ± 0.26 ^{a}	8.56 ± 0.20 ^{a}
	5 h	8.56 ± 0.20 ^{a}	8.56 ± 0.27 ^{ab}	8.72 ± 0.18 ^{a}	6.94 ± 0.56 ^{ab}	7.22 ± 0.36 ^{a}	8.22 ± 0.22 ^{a}	7.61 ± 0.32 ^{a}	7.78 ± 0.25 ^{a}
60 °C	3 h	8.72 ± 0.38 ^{a}	8.28 ± 0.33 ^{ab}	7.28 ± 0.33 ^{a}	6.78 ± 0.62 ^{ab}	6.39 ± 0.59 ^{a}	7.28 ± 0.32 ^{a}	7.50 ± 0.44 ^{a}	7.39 ± 0.32 ^{a}
	3.5 h	7.69 ± 0.37 ^{a}	7.56 ± 0.40 ^{ab}	7.44 ± 0.52 ^{a}	6.81 ± 0.60 ^{ab}	6.63 ± 0.62 ^{a}	6.50 ± 0.58 ^{a}	7.19 ± 0.45 ^{a}	7.25 ± 0.44 ^{a}
	4 h	8.00 ± 0.37 ^{a}	7.94 ± 0.42 ^{ab}	7.44 ± 0.46 ^{a}	7.63 ± 0.44 ^{ab}	6.69 ± 0.61 ^{a}	7.19 ± 0.46 ^{a}	7.56 ± 0.47 ^{a}	7.38 ± 0.40 ^{a}
	4.5 h	8.75 ± 0.31 ^{a}	8.38 ± 0.26 ^{ab}	7.50 ± 0.54 ^{a}	7.06 ± 0.54 ^{ab}	6.00 ± 0.47 ^{a}	7.44 ± 0.45 ^{a}	6.81 ± 0.48 ^{a}	7.06 ± 0.32 ^{a}
	5 h	8.19 ± 0.40 ^{a}	7.88 ± 0.39 ^{ab}	7.75 ± 0.39 ^{a}	7.19 ± 0.61 ^{ab}	6.44 ± 0.54 ^{a}	7.69 ± 0.34 ^{a}	7.31 ± 0.49 ^{a}	7.31 ± 0.48 ^{a}
61 °C	3 h	8.24 ± 0.24 ^{a}	7.53 ± 0.37 ^{ab}	7.76 ± 0.33 ^{a}	5.94 ± 0.39 ^{a}	6.82 ± 0.48 ^{a}	7.47 ± 0.43 ^{a}	7.00 ± 0.41 ^{a}	6.88 ± 0.33 ^{a}
	3.5 h	8.53 ± 0.29 ^{a}	8.12 ± 0.38 ^{ab}	7.88 ± 0.26 ^{a}	6.76 ± 0.39 ^{ab}	6.59 ± 0.47 ^{a}	7.71 ± 0.35 ^{a}	7.12 ± 0.33 ^{a}	7.41 ± 0.31 ^{a}
	4 h	8.18 ± 0.31 ^{a}	7.88 ± 0.47 ^{ab}	7.59 ± 0.29 ^{a}	7.35 ± 0.61 ^{ab}	6.53 ± 0.58 ^{a}	7.76 ± 0.45 ^{a}	7.71 ± 0.45 ^{a}	7.59 ± 0.47 ^{a}
	4.5 h	8.53 ± 0.15 ^{a}	7.88 ± 0.39 ^{ab}	7.29 ± 0.35 ^{a}	6.71 ± 0.60 ^{ab}	5.35 ± 0.57 ^{a}	7.94 ± 0.28 ^{a}	7.06 ± 0.34 ^{a}	7.06 ± 0.36 ^{a}
	5 h	8.24 ± 0.30 ^{a}	8.06 ± 0.49 ^{ab}	7.71 ± 0.36 ^{a}	8.18 ± 0.38 ^{ab}	6.41 ± 0.49 ^{a}	7.53 ± 0.45 ^{a}	7.82 ± 0.27 ^{a}	7.76 ± 0.36 ^{a}
63 °C	3 h	8.19 ± 0.38 ^{a}	8.24 ± 0.34 ^{ab}	7.24 ± 0.49 ^{a}	6.95 ± 0.55 ^{ab}	6.95 ± 0.48 ^{a}	7.67 ± 0.35 ^{a}	7.52 ± 0.39 ^{a}	7.29 ± 0.43 ^{a}
	3.5 h	8.24 ± 0.39 ^{a}	8.62 ± 0.42 ^{ab}	7.95 ± 0.48 ^{a}	7.57 ± 0.62 ^{ab}	6.05 ± 0.55 ^{a}	7.86 ± 0.49 ^{a}	7.76 ± 0.53 ^{a}	7.67 ± 0.43 ^{a}
	4 h	8.05 ± 0.46 ^{a}	8.19 ± 0.52 ^{ab}	7.81 ± 0.41 ^{a}	6.95 ± 0.61 ^{ab}	5.90 ± 0.60 ^{a}	7.81 ± 0.48 ^{a}	7.76 ± 0.47 ^{a}	7.00 ± 0.45 ^{a}
	4.5 h	8.33 ± 0.36 ^{a}	8.76 ± 0.36 ^{b}	7.43 ± 0.47 ^{a}	7.43 ± 0.61 ^{ab}	5.43 ± 0.58 ^{a}	7.95 ± 0.47 ^{a}	7.90 ± 0.49 ^{a}	7.52 ± 0.40 ^{a}
	5 h	8.52 ± 0.33 ^{a}	8.76 ± 0.28 ^{b}	7.52 ± 0.36 ^{a}	7.62 ± 0.39 ^{ab}	6.24 ± 0.59 ^{a}	8.24 ± 0.41 ^{a}	8.05 ± 0.36 ^{a}	7.81 ± 0.37 ^{a}
Level of significance									
Temperature		*	***	**	*	***	***	***	**
Time		*	**	NS	NS	NS	NS	NS	NS
Temperature × time interaction		NS	NS	NS	NS	NS	NS	NS	NS

^{a}, ^{b} …—mean values in columns with different superscripts indicating significant differences at $p < 0.05$ according to the Tukey'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).

As our work used a relatively small range of meat-heating temperatures, few statistically significant differences were observed between the assessed organoleptic characteristics of the samples. Nevertheless, our study, showing that lower cooking temperature promotes better eating quality of pork loin, confirms the findings of other authors. Honegger et al. [61] reported that in terms of such characteristics as tenderness, juiciness, flavour, and overall acceptability, pork chops heat-treated with the sous vide method at 63 °C were rated higher than those heated at 71 °C and 82 °C and also higher in terms of tenderness, juiciness, and acceptability than chops prepared to the same level of doneness using a grill [63].

3.11. Analysis of the Relationships Between Selected Physicochemical and Sensory Characteristics of Cooked Pork Loin Samples

Changes in meat components upon heat treatment determine, to a greater or lesser extent, the eating quality of the meat [86]. In order to investigate the relationships between selected physicochemical and sensory properties of pork loin cooked using different temperature/time combinations of the sous vide method, the correlation coefficients were calculated and the results are presented in Table 6.

The feature that best reflects the consumer's attitude towards a food product is overall acceptability. In our study, we found high and significant correlation coefficients between overall acceptability and tenderness (r = 0.658, $p < 0.001$) as well as juiciness of meat (r = 0.657, $p < 0.001$). Meat tenderness was significantly correlated with juiciness (r = 0.499, $p < 0.0010$). Another high correlation coefficient was observed between TPA measured hardness and chewiness (r = 0.803, $p < 0.001$). Some smaller, although significant, correlation coefficients were also found between overall acceptability and cooking loss r = 0.158, $p < 0.01$), protein content (r = −0.170, $p < 0.05$), and shear force (r = −0.096, $p < 0.01$); between tenderness and cooking loss (r = 0.234, $p < 0.001$) and protein content (r = −0.254, $p < 0.01$); as well as between cooking loss and protein content (r = −0.201, $p < 0.05$) and hardness (r = −0.173, $p < 0.01$).

Table 6. Correlation coefficients between selected attributes of sous vide-cooked pork loin.

Attribute	Moisture Content	Fat Content	Protein Content	Shear Force	Hardness	Chewiness	Tenderness	Juiciness	Overall Acceptability
Cooking loss	0.110	−0.042	−0.201 *	−0.029	−0.173 **	−0.109	0.234 ***	0.026	0.158 **
Moisture content	-	0.122	0.126	0.108	0.112	0.069	0.046	0.050	0.024
Fat content	-	-	0.095	0.106	0.035	0.019	−0.024	0.009	−0.025
Protein content	-	-	-	−0.056	0.105	0.061	−0.254 **	−0.039	−0.170 *
Shear force	-	-	-	-	0.037	0.007	−0.091	−0.092	−0.096 *
Hardness	-	-	-	-	-	0.803 ***	−0.070	−0.024	0.046
Chewiness	-	-	-	-	-	-	−0.052	0.027	0.034
Tenderness	-	-	-	-	-	-	-	0.499 ***	0.658 ***
Juiciness	-	-	-	-	-	-	-	-	0.657 ***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Less cooking loss usually has a positive effect on the juiciness of the cooked meat. In the present study, we did not demonstrate such a relationship, but in previously conducted research, which also analysed the effects of heat treatment using the sous vide method on pork quality, it was found. We confirmed significant relationships between overall acceptability of pork loin and its tenderness and juiciness, between tenderness and juiciness, and between hardness and chewiness [20]. In general, fewer significant relationships were observed between the features of meat in the present study compared to the previous one, but the probable reasons for such differences in our observations were lower cooking temperatures and smaller ranges between temperatures applied in the present study, which apparently resulted in smaller differences between particular meat characteristics due to a more uniform impact of cooking temperature on the final products.

There is little literature describing the correlations between the physicochemical and sensory characteristics of meat, especially pork. Nevertheless, Pathare and Roskilly [21], in their literature review, pointed out that muscle protein changes which result from the heat treatment show an effect on meat cooking yield, moisture content, colour, and texture. Choi et al. [87] found that cooking loss and shear force were well and negatively correlated with juiciness and tenderness of beef steaks roasted in a convection oven. Jung et al. [88] reported significant, positive correlations between fat content and flavour, juiciness, tenderness, and overall palatability, and negative correlations between cooking loss and juiciness, tenderness, and overall palatability, as well as between shear force and tenderness and overall palatability of beef. Przybylski et al. [89] noted high and significant correlations between overall quality and tenderness and juiciness of sous vide-cooked poultry meat.

4. Conclusions

Due to the growing interest in the sous vide technique among both chefs and consumers, it is important to know the impact of this heat treatment on the physicochemical and organoleptic characteristics of the final product and to select such parameters of the thermal process to obtain a meat dish with the highest possible nutritional value and sensory quality.

The research showed that using lower temperatures, i.e., 57 and 59 °C, when heating pork loin using the sous vide method had more advantages than using higher temperatures, i.e., 60, 61, and 63 °C. In general, the former samples were characterised by lower cooking loss and higher moisture content, lower level of oxidative changes, and, in particular, samples cooked at 59 °C showed better tenderness and juiciness, more intense meat flavour, and better flavour acceptability and overall acceptability than samples cooked at the latter temperatures. The highest-rated meat was pork loin heated at 59 °C for 4.5 h. Since the secondary products of lipid oxidation contribute to the undesirable, rancid flavour of food, it was confirmed that it is advisable to keep the heat treatment parameters (temperature, time) at a low level, in order to minimise the oxidative changes in meat. The research results should contribute to further improvement of the quality of meat dishes and prepare the use of sous vide cooking.

Although our research is valuable, limitations of the study can be pointed out. Comparisons with other cooking methods, such as traditional roasting or grilling, would be beneficial to better understand the advantages and disadvantages of different culinary techniques. Since the sous vide method has a great potential to prepare meat in advance for delayed use, extending research with a storage study would provide an additional insight into such meat storage stability. Consumer acceptance is a key factor in a restaurant's success; therefore, including representatives of general public in the assessment of consumer preferences would obtain more diverse and representative results related to the meat dish quality.

Since meat cooking with the use of the sous vide method is increasingly used in gastronomy, it seems reasonable to continue research on this method of heat treatment but in combination with other culinary procedures used in gastronomy, such as searing meat before or after sous vide cooking, marinating meat before heat treatment, and storage of cooked meat. It is worth remembering that due to differences in the muscles structure, other meat cuts will require different sous vide heat treatment parameters, which may also be the subject of further research on the optimisation of the sous vide process in gastronomy.

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References

1. Gómez, I.; Janardhanan, R.; Ibañez, F.C.; Beriain, M.J. The Effects of Processing and Preservation Technologies on Meat Quality: Sensory and Nutritional Aspects. *Foods* **2020**, *9*, 1416. [CrossRef] [PubMed]
2. Baldwin, D.E. Sous vide cooking: A review. *Int. J. Gastron. Food Sci.* **2012**, *1*, 15–30. [CrossRef]
3. Richa, R.; Shahi, N.C.; Singh, A.; Lohani, U.C.; Omre, P.K.; Kumar, A.; Bhattacharya, T.K. Ohmic heating technology and its application in meaty food: A review. *Adv. Res.* **2017**, *10*, 1–10. [CrossRef]
4. Cui, Z.K.; Yan, H.; Manoli, T.; Mo, H.Z.; Bi, J.C.; Zhang, H. Advantages and challenges of sous vide cooking. *Food Sci. Technol. Res.* **2021**, *27*, 25–34. [CrossRef]
5. Rotola-Pukkila, M.K.; Pihlajaviita, S.T.; Kaimainen, M.T.; Hopia, A.I. Concentration of umami compound in pork meat and cooking juice with different cooking times and temperatures. *J. Food Sci.* **2015**, *80*, 2711–2716. [CrossRef]
6. Dominguez-Hernandez, E.; Salaseviciene, A.; Ertbjerg, P. Low-temperature long-time cooking of meat: Eating quality and underlying mechanisms. *Meat Sci.* **2018**, *143*, 104–113. [CrossRef]
7. Thatsarani, A.P.K.; Alahakoon, A.U.; Liyanage, R. Current status and future trends of sous vide processing in meat industry; A review. *Trends Food Sci. Tech.* **2022**, *129*, 353–363. [CrossRef]
8. Głuchowski, A.; Czarniecka-Skubina, E.; Buła, M. The use of the sous-vide method in the preparation of poultry at home and in catering—Protection of nutrition value whether high energy consumption. *Sustainability* **2020**, *12*, 7606. [CrossRef]
9. Karpińska-Tymoszczyk, M.; Draszanowska, A.; Danowska-Oziewicz, M.; Kurp, L. The effect of low-temperature thermal processing on the quality of chicken breast fillets. *Food Sci. Technol. Int.* **2020**, *26*, 563–573. [CrossRef]
10. Uttaro, B.; Zawadski, S.; McLeod, B. Efficacy of multi-stage sous-vide cooking on tenderness of low value beef muscles. *Meat Sci.* **2019**, *149*, 40–46. [CrossRef]
11. Haghighi, H.; Belmonte, A.M.; Masino, F.; Minelli, G.; Lo Fiego, D.P.; Pulvirenti, A. Effect of time and temperature on physicochemical and microbiological properties of sous vide chicken breast fillets. *Appl. Sci.* **2021**, *11*, 3189. [CrossRef]

12. Akoğlu, I.; Bıyıklı, M.; Akoglu, A.; Kurhan, S.; Biyikli, M. Determination of the Quality and Shelf Life of Sous Vide Cooked Turkey Cutlet Stored at 4 and 12 C. *Braz. J. Poult. Sci.* **2018**, *20*, 1–8. [CrossRef]
13. Gómez, I.; Ibanez, F.C.; Beriain, M.J. Physicochemical and sensory properties of sous vide meat and meat analog products marinated and cooked at different temperature-time combinations. *Int. J. Food Prop.* **2019**, *22*, 1693–1708. [CrossRef]
14. da Silva, F.L.F.; de Lima, J.P.S.; Melo, L.S.; da Silva, Y.S.M.; Gouveia, S.T.; Lopes, G.S.; Matos, W.O. Comparison between boiling and vacuum cooking (sous-vide) in the bioaccessibility of minerals in bovine liver samples. *Food Res. Int.* **2017**, *100*, 566–571. [CrossRef]
15. Roascio-Albistur, A.; Gámbaro, A. Consumer perception of a non-traditional market on sous-vide dishes. *Int. J. Gastron. Food Sci.* **2018**, *11*, 20–24. [CrossRef]
16. Schilling, W.; Campbell, Y. Cooking up Quality, Convenience via Sous Vide. *Food Technol. Mag.* **2021**, *75*, 75. Available online: https://www.ift.org/news-and-publications/food-technology-magazine/issues/2021/june/columns/processing-sous-vide (accessed on 16 August 2024).
17. Lafarga, T.; Viñas, I.; Bobo, G.; Simó, J.; Aguiló-Aguayo, I. Effect of steaming and sous vide processing on the total phenolic content, vitamin C and antioxidant potential of the genus Brassica. *Innov. Food Sci. Emerg. Technol.* **2018**, *47*, 412–420. [CrossRef]
18. Beretta, C.; Hellweg, S. Potential environmental benefits from food waste prevention in the food service sector. *Resour. Conserv. Recycl.* **2019**, *147*, 169–178. [CrossRef]
19. Ruiz-Carrascal, J.; Roldan, M.; Refolio, F.; Perez-Palacios, T.; Antequera, T. Sous-vide cooking of meat: A Maillarized approach. *Int. J. Gastron. Food Sci.* **2019**, *16*, 100138. [CrossRef]
20. Kurp, L.; Danowska-Oziewicz, M.; Kłębukowska, L. Sous Vide Cooking Effects on Physicochemical, Microbiological and Sensory Characteristics of Pork Loin. *Appl. Sci.* **2022**, *12*, 2365. [CrossRef]
21. Pathare, P.B.; Roskilly, A.P. Quality and energy evaluation in meat cooking. *Food Eng. Rev.* **2016**, *8*, 435–447. [CrossRef]
22. Jeong, K.O.H.; Shin, S.Y.; Kim, Y.S. Effects of sous-vide method at different temperatures, times and vacuum degrees the quality, structural, and microbiological properties of pork ham. *Meat Sci.* **2018**, *143*, 1–7. [CrossRef] [PubMed]
23. Christensen, L.; Gunvig, A.; Tørngren, M.A.; Aaslyng, M.D.; Knøchel, S.; Christensen, M. Sensory characteristics of meat cooked for prolonged times at low temperature. *Meat Sci.* **2012**, *90*, 485–489. [CrossRef] [PubMed]
24. AOAC International. Official methods of analysis 950.46. In *Moisture in Meat*, 18th ed.; AOAC International: Gaithersburg, MD, USA, 2005.
25. AOAC. Official method of analysis method 991.36. In *Fat (Crude) in Meat and Meat Products*, 18th ed.; Association of Analytical Communities: Gaithersburg, MD, USA, 2006.
26. AOAC. Official methods of analysis method 992.15. In *Crude Protein in Meat and Meat Products Including Pet Foods*, 17th ed.; Association of Analytical Communities: Gaithersburg, MD, USA, 2006.
27. Salih, A.M.; Smith, D.M.; Price, J.F.; Dawson, L.E. Modified extraction 2-thiobarbituric acid method for measuring lipid oxidation in poultry. *Poultry Sci.* **1987**, *66*, 1483–1488. [CrossRef]
28. Pikul, J. *Chemical Evaluation of Poultry Meat Lipids Quality*; Technological evaluation of raw material and products of poultry industry; Wydawnictwo Akademii Rolniczej w Poznaniu: Poznań, Poland, 1993; pp. 116–117. (In Polish)
29. *PN-EN ISO 8586:2014-03*; Sensory Analysis. General Guidance for Selection, Training and Monitoring of Selected Assessors and Experts. Polish Committee for Standardization: Warsaw, Poland, 2014.
30. *ISO 4121:2003*; Sensory Analysis—Guidelines for the Use of Quantitative Response Scales. ISO: Geneva, Switzerland, 2003.
31. Hwang, S.I.; Lee, E.J.; Hong, G.P. Effects of temperaturęand time on the cookery properties of sous-vide processed pork loin. *Food Sci. Anim. Resour.* **2019**, *39*, 65–72. [CrossRef]
32. Macharáčková, B.; Bogdanovičová, K.; Ježek, F.B.; Haruštiaková, D.; Kameník, J. Cooking loss in retail beef cuts: The effect of muscle type, sex, ageing, pH, salt and cooking method. *Meat Sci.* **2021**, *171*, 108270. [CrossRef]
33. Supaphon, P.; Astruc, T.; Kerdpiboon, S. Physical Characteristics and Surface-Physical Properties Relationship of Thai Local Beef during Sous-Vide Processing. *Agric. Nat. Resour.* **2020**, *54*, 25–32. Available online: https://li01.tci-thaijo.org/index.php/anres/article/view/240256 (accessed on 16 August 2024).
34. Kovaleva, O.A.; Zdrabova, E.M.; Kireeva, O.S. Influence of heat-induced changes in meat proteins on the quality characteristics of the finished product. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *848*, 012050. [CrossRef]
35. Lawrie, R.A.; Ledward, D.A. *Lawrie's Meat Science*; Woodhead Publishing Limited: Cambridge, UK, 2006; pp. 279–341.
36. James, B.J.; Yang, S.W. Effect of cooking method on the toughness of bovine *M. semitendinosus*. *Int. J. Food Eng.* **2012**, *8*. [CrossRef]
37. Purslov, P.P.; Oiseth, S.; Hughes, J.; Warner, R.D. The structural basis of cooking loss in beef: Variations with temperature and ageing. *Food Res. Int.* **2016**, *89*, 739–748. [CrossRef]
38. Roldán, M.; Antequera, T.; Martín, A.; Mayoral, A.I.; Ruiz, J. Effect of different temperature—Time combinations on physicochemical, microbiological, textural and structural features of sous-vide cooked lamb loins. *Meat Sci.* **2013**, *93*, 572–578. [CrossRef]
39. Tornberg, E. Effect of heat on meat proteins—Implications on structure and quality of meat products. *Meat Sci.* **2005**, *70*, 493–508. [CrossRef] [PubMed]
40. Botinestean, C.; Hossain, M.; Mullen, A.M.; Kerry, J.P.; Hamill, R.M. The influence of the interaction of sous-vide cooking time and papain concentration on tenderness and technological characteristics of meat products. *Meat Sci.* **2021**, *177*, 108491. [CrossRef] [PubMed]

41. Zielbauer, B.I.; Franz, J.; Viezens, B.; Vilgis, T.A. Physical aspects of meat cooking: Time dependent thermal protein denaturation and water loss. *Food Biophys.* **2016**, *11*, 34–42. [CrossRef]
42. Ismail, I.; Hwang, Y.-H.; Joo, S.-T. Interventions of two-stage thermal sous-vide cooking on the toughness of beef semitendinosus. *Meat Sci.* **2019**, *157*, 107882. [CrossRef] [PubMed]
43. Aaslyng, D.M.; Bejerholm, C.; Ertbjerg, P.; Bertram, H.C.; Andersen, H.J. Cooking loss and juiciness of pork in relations to raw meat quality and cooking procedure. *Food Qual. Prefer.* **2003**, *14*, 277–288. [CrossRef]
44. Jiang, S.; Xue, D.; Zhang, Z.; Shan, K.; Ke, W.; Zhang, M.; Zhao, D.; Nian, Y.; Xu, X.; Li, C. Effect of Sous-vide cooking on the quality and digestion characteristics of braised pork. *Food Chem.* **2022**, *375*, 131683. [CrossRef]
45. Rezler, R.; Krzywdzińska-Bartkowiak, M.; Piatek, M. The Influence of the Sous Vide Cooking Time on Selected Characteristics of Pork Loin. *Molecules* **2023**, *28*, 6102. [CrossRef]
46. Jung, Y.; Kim, H.-J.; Kim, D.; Joo, B.; Jhoo, J.-W.; Jang, A. Physicochemical Properties and Volatile Organic Compounds of Dairy Beef Round Subjected to Various Cooking Methods. *Food Sci. Anim. Resour.* **2023**, *43*, 767–791. [CrossRef]
47. Vasanthi, C.; Venkataramanujam, V.; Dushyanthan, K. Effect of cooking temperature and time on the physico-chemical, histological and sensory properties of female carabeef (buffalo) meat. *Meat Sci.* **2007**, *76*, 274–280. [CrossRef]
48. Becker, A.; Boulaaba, A.; Pingen, S.; Krischek, C.; Klein, G. Low temperature cooking of pork meat—Physicochemical and sensory aspects. *Meat Sci.* **2016**, *118*, 82–88. [CrossRef] [PubMed]
49. Oz, F.; Aksu, M.; Turan, M. The effects of different cooking methods on some quality criteria and mineral composition of beef steaks. *J. Food Process. Pres.* **2017**, *41*, 3008. [CrossRef]
50. Abdel-Naeem, H.H.S.; Sallam, K.I.; Zaki, H.M.B.A. Effect of different cooking methods of rabbit meat on topographical changes, physicochemical characteristics, fatty acids profile, microbial quality and sensory attributes. *Meat Sci.* **2021**, *181*, 108612. [CrossRef] [PubMed]
51. Xu, B.; Zhang, Q.; Zhang, Y.; Yang, X.; Mao, Y.; Luo, X.; Hopkins, D.L.; Niu, L.; Liang, R. Sous vide cooking improved the physicochemical parameters of hot-boned bovine semimembranosus muscles. *Meat Sci.* **2023**, *206*, 109326. [CrossRef] [PubMed]
52. Bıyıklı, M.; Akoğlu, A.; Kurhan, Ş.; Akoğlu, İ.T. Effect of different sous vide cooking temperature-time combinations on the physicochemical, microbiological, and sensory properties of turkey cutlet. *Int. J. Gastron. Food Sci.* **2020**, *20*, 100204. [CrossRef]
53. Díaz, P.; Nieto, G.; Garrido, M.D.; Bañón, S. Microbial, physical—Chemical and sensory spoilage during the refrigerated storage of cooked pork loin processed by the sous-vide method. *Meat Sci.* **2008**, *80*, 287–292. [CrossRef] [PubMed]
54. ul Haq, I.; Asghar, B.; Manzoor, A.; Ali, S.; Nauman, K.; Ahmad, S.; Hopkins, D.L.; Nasir, J. Investigating the impact of sous vide cooking on the eating quality of spent buffalo (*Bubalus bubalis*) meat. *Meat Sci.* **2024**, *209*, 109417. [CrossRef]
55. Kaliniak-Dziura, A.; Domaradzki, P.; Kowalczyk, M.; Florek, M.; Skałecki, P.; Kędzierska-Matysek, M.; Stanek, P.; Dmoch, M.; Grenda, T.; Kowalczuk-Vasilev, E. Effect of heat treatments on the physicochemical and sensory properties of the longissimus thoracis muscle in unweaned Limousin calves. *Meat Sci.* **2022**, *192*, 108881. [CrossRef]
56. Odeyemi, O.A.; Alegbeleye, O.O.; Strateva, M.; Stratev, D. Understanding spoilage microbial community and spoilage mechanisms in foods of animal origin. *Compr. Rev. Food Sci. Food Saf.* **2020**, *19*, 311–331. [CrossRef]
57. Rahman, M.S.; Labuza, T.P. Water Activity and Food Preservation. In *Handbook of Food Preservation*; Rahman, M.S., Ed.; CRC Press: Boca Raton, FL, USA, 2020; pp. 487–502.
58. Campo, M.M.; Nute, G.R.; Hughes, S.I.; Enser, M.; Wood, J.D.; Richardson, R.I. Flavour perception of oxidation in beef. *Meat Sci.* **2006**, *72*, 303–311. [CrossRef]
59. Kitpot, T.; Sriwattana, S.; Angeli, S.; Thakeow, P. Evaluation of Quality Parameters and Shelf Life of Thai Pork Scratching "Kaeb Moo". *J. Food Quality* **2019**, *2019*, 2421708. [CrossRef]
60. Hughes, J.M.; McPhail, N.G.; Kearney, G.; Clarke, F.; Warner, R.D. Beef longissimus eating quality increases up to 20 weeks of storage and is unrelated to meat colour at carcass grading. *Anim. Prod. Sci.* **2015**, *55*, 174–179. [CrossRef]
61. Honegger, L.T.; Richardson, E.; Schunke, E.D.; Dilger, A.C.; Boler, D.D. Final internal cooking temperature of pork chops influenced consumer eating experience more than visual color and marbling or ultimate pH. *J. Anim. Sci.* **2019**, *97*, 2460–2467. [CrossRef] [PubMed]
62. Suman, S.P.; Nair, M.N.; Joseph, P.; Hunt, M.C. Factors influencing internal color of cooked meats. *Meat Sci.* **2016**, *120*, 133–144. [CrossRef]
63. Honegger, L.T.; Bryan, E.E.; Price, H.E.; Ruth, T.K.; Boler, D.D.; Dilger, A.C. The effect of cooking method and cooked color on consumer acceptability of boneless pork chops. *Foods* **2022**, *11*, 106. [CrossRef]
64. Sánchez del Pulgar, J.; Gázquaz, A.; Ruiz-Carrascal, J. Physico-chemical, textural and structural characteristics of sous-vide cooked pork cheeks as affected by vacuum, cooking temperature, and cooking time. *Meat Sci.* **2012**, *9*, 828–835. [CrossRef]
65. Bojarska, U.; Batura, J.; Cierach, M. The Effect of Measurement Site on the Evaluation of Tom Breast Muscle Color. *Pol. J. Food Nutr. Sci.* **2003**, *53*, 45–49. Available online: https://journal.pan.olsztyn.pl/THE-EFFECT-OF-MEASUREMENT-SITE-ON-THE-EVALUATION-OF-TOM-BREAST-MUSCLE-COLOUR-,97757,0,2.html (accessed on 16 August 2024).
66. Christensen, L.; Ertbjerg, P.; Aaslyng, M.D.; Christensen, M. Effect of prolonged heat treatment from 48 degrees C to 63 degrees C on toughness, cooking loss and color of pork. *Meat Sci.* **2011**, *88*, 280–285. [CrossRef]
67. García-Segovia, P.; Andrés-Bello, A.; Martínez-Monzó, J. Effect of Cooking Method on Mechanical Properties, Color and Structure of Beef Muscle (*M. pectoralis*). *J. Food Eng.* **2007**, *80*, 813–821. [CrossRef]

68. Park, C.H.; Lee, B.; Oh, E.; Kim, Y.S.; Choi, Y.M. Combined effects of sous- vide cooking conditions on meat and sensory quality characteristics of chicken breast meat. *Poultry Sci.* **2020**, *99*, 3286–3291. [CrossRef]
69. Naveena, B.M.; Khansole, P.S.; Kumar, M.S.; Krishnaiah, N.; Kulkarni, V.V.; Deepak, S.J. Effect of sous vide processing on physicochemical, ultrastructural, microbial and sensory changes in vacuum packaged chicken sausages. *Food Sci. Technol. Int.* **2017**, *23*, 75–85. [CrossRef]
70. Latoch, A.; Libera, J.; Stasiak, D.M. Physicochemical Properties of Pork Loin Marinated in Kefir, Yoghurt or Buttermilk and Cooked Sous Vide. *Acta Sci. Pol. Technol. Aliment.* **2019**, *18*, 163–171. [CrossRef] [PubMed]
71. Rój, A.; Przybyłowski, P. Color Measurement of Energy Drink (In Polish: Ocena Barwy Napojów Energetyzujących). *Bromat. Chem. Toksykol.* **2012**, *3*, 817–821. Available online: https://www.ptfarm.pl/pub/File/Bromatologia/2012/3/817-821.pdf (accessed on 16 August 2024).
72. Naqvi, Z.B.; Thomson, P.C.; Ha, M.; Campbell, M.A.; McGill, D.M.; Friend, M.A.; Warner, R.D. Effect of sous vide cooking and ageing on tenderness and water-holding capacity of low-value beef muscles from young and older animals. *Meat Sci.* **2021**, *175*, 108435. [CrossRef] [PubMed]
73. Destefanis, G.; Brugiapaglia, A.; Barge, M.T.; Dal Molin, E. Relationship between beef consumer tenderness perception and Warner-Bratzler shear force. *Meat Sci.* **2008**, *78*, 153–156. [CrossRef] [PubMed]
74. Ayub, H.; Ahmad, A. Physiochemical changes in sous-vide and conventionally cooked meat. *Int. J. Gastron. Food Sci.* **2019**, *17*, 100145. [CrossRef]
75. Christensen, L.; Ertbjerg, P.; Løje, H.; Risbo, J.; van den Berg, F.W.J.; Christensen, M. Relationship between meat toughness and properties of connective tissue from cows and young bulls heat treated at low temperatures for prolonged times. *Meat Sci.* **2013**, *93*, 787–795. [CrossRef]
76. Dominguez-Hernandez, E.; Ertbjerg, P. Effect of LTLT heat treatment on cathepsin B and L activities and denaturation of myofibrillar proteins of pork. *Meat Sci.* **2021**, *175*, 108454. [CrossRef]
77. Kathuria, D.; Dhiman, A.K.; Attri, S. Sous vide, a culinary technique for improving quality of food products: A review. *Trends Food Sci. Technol.* **2022**, *119*, 57–68. [CrossRef]
78. Bourne, M.C. *Food Texture and Viscosity: Concept and Measurement*; Academic Press: Cambridge, MA, USA, 2002.
79. Botinestean, C.; Keenan, D.F.; Kerry, J.P.; Hamill, R.M. The effect of thermal treatments including sous-vide, blast freezing and their combinations on beef tenderness of M. Semitendinosus steaks targeted at elderly consumers. *LWT Food Sci. Technol.* **2016**, *74*, 154–159. [CrossRef]
80. Djekic, I.; Ilic, J.; Lorenzo, J.M.; Tomasevic, I. How do culinary method affect quality and oral processing characteristics of pork ham? *J. Texture Stud.* **2020**, *52*, 36–44. [CrossRef] [PubMed]
81. Armstrong, G.A.; McIlveen, H. Effects of prolonged storage on the sensory quality and consumer acceptance of sous vide meat-based recipe dishes. *Food Qual. Prefer.* **2000**, *11*, 377–385. [CrossRef]
82. Mortensen, L.M.; Frøst, M.B.; Skibsted, L.H.; Risbo, J. Effect of time and temperature on sensory properties in low temperature long-time sous-vide cooking of beef. *J. Cul. Sci. Techn.* **2012**, *10*, 75–90. [CrossRef]
83. Vaudagna, S.; Sanchez, G.; Neira, M.S.; Insani, E.M.; Picallo, A.B.; Gallinger, M.M.; Lasta, J.A. Sous vide cooked beef muscles: Effects of low temperature-long time (LT-LT) treatments on their quality characteristics and storage stability. *Int. J. Food Sci. Technol.* **2002**, *37*, 425–441. [CrossRef]
84. Resconi, V.C.; Escudero, A.; Campo, M.M. The development of aromas in ruminant meat. *Molecules* **2013**, *18*, 6748–6781. [CrossRef]
85. Roldán, M.; Ruiz, J.; Sánchez del Pulgar, J.; Pérez-Palacios, T.; Antequera, T. Volatile compound profile of sous-vide cooked lamb loins at different temperature-time combinations. *Meat Sci.* **2015**, *100*, 52–57. [CrossRef]
86. Schwartz, M.; Marais, J.; Strydom, P.E.; Hoffmann, L.C. Effects of increasing internal end-point temperatures on physicochemical and sensory properties of meat: A review. *Compr. Rev. Food Sci. Food Saf.* **2022**, *21*, 2843–2872. [CrossRef]
87. Choi, Y.M.; Garcia, L.G.; Lee, K. Correlations of sensory quality characteristics with intramuscular fat content and bundle characteristics in bovine *longissimus thoracis* muscle. *Food Sci. Anim. Resour.* **2019**, *39*, 197–208. [CrossRef]
88. Jung, E.-Y.; Hwang, Y.-H.; Joo, S.-T. The relationship between chemical compositions, meat quality, and palatability of the 10 primal cuts from Hanwoo steer. *Korean J. Food Sci. Anim. Resour.* **2016**, *36*, 145–151. [CrossRef]
89. Przybylski, W.; Jaworska, D.; Kajak-Siemaszko, K.; Sałek, P.; Pakuła, K. Effect of heat treatment by the sous-vide method on the quality of poultry meat. *Foods* **2021**, *10*, 1610. [CrossRef]