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Effect of refrigeration and frozen storage of raw chicken breast and pork on the quality of sous-vide cooked products

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ABSTRACT

This study investigated the effects of two storage conditions on the quality characteristics of sous-vide cooked chicken breast and pork loin. Refrigeration (for 2 and 10 days at 3 °C) and freezing (for 10 days and 6 months at −25 °C) were used as pretreatments in the experiment, and then the samples were cooked sous-vide for 45 min at 60 °C. Pork showed a higher post-cooking loss (8.06–26.88%) than chicken, which showed a substantial increase in weight loss from 0.2% (2 days refrigerated) to 3.90% (6 months frozen) prior to cooking and from 5.43 to 7.09% following sous-vide. Sous-vide processing raised the pH values of pork from 5.70 to 6.06 and pre-cooked, 6-month frozen chicken from 5.87 to 6.21. Following sous-vide, lightness (L^*) increased significantly, reaching 75.96 for pork (long-term frozen) and 79.99 for chicken (short-term refrigerated). Lipid oxidation, measured by thiobarbituric acid reactive substances (TBARS), increased with storage and cooking, with the highest values in sous-vide samples stored refrigerated long-term (3.27 mg MDA/kg chicken, 3.53 mg MDA/kg pork). Sensory evaluation showed the highest overall acceptance (4.67/5) in chicken stored refrigerated short-term, while frozen long-term samples retained acceptable quality (4.17/5). These findings demonstrate that storage duration and conditions significantly influence weight loss, texture, lipid oxidation, color, and sensory attributes in sous-vide cooked meat,

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emphasizing the importance of optimal storage for quality preservation. It should be noted that the thickness of the two samples (chicken breast and pork loin) is different, and both cross-species comparisons and differences among storage conditions should be interpreted with caution.

KEYWORDS

chicken breast, lipid oxidation, pork, sous-vide cooking, storage condition

1. INTRODUCTION

The increment of the human population worldwide leads to an increased demand for food, including food of livestock origin (Herrero and Thornton, 2013). Over the past two decades, poultry consumption has significantly increased globally, alongside a rise in pork consumption. Pork is the second most widely consumed meat worldwide, representing approximately 34% of total global meat production. Between 1990 and 2022, global pork consumption demonstrated a 77% increase, growing from 63.5 to 113 million tonnes (Kim et al., 2024). Chicken meat is highly regarded for its multitude of health benefits stemming from its rich nutritional composition, characterized by high protein content and low cholesterol, calorie, and fat levels. The price of chicken meat is relatively affordable and represents a cost-effective alternative compared to other types of meat (Sujiwo et al., 2025).

Inconsistency in tenderness and palatability is a major concern for the meat industry. Nowadays, growing consumer demand for desirable sensory qualities has compelled the food industry to adopt minimal processing technologies. Such technologies are intended to maintain bioactive compounds and prolong the shelf life of processed foods. Minimal food processing technologies are gaining traction within the global food industry due to increasing demand for fresh, nutritious, and minimally altered food products (Berdejo et al., 2023). Minimally processed foods are preserved using partial or mild treatments that ensure safety while maintaining their natural quality. This approach minimizes alterations to sensory and nutritional attributes such as flavor, texture, and nutrient content. By applying gentle preservation methods, these foods retain their fresh-like qualities, meeting consumer demands for convenience without compromising on quality (Zhang et al., 2023). Sous-vide mild heat treatment is a contemporary minimal processing technology that effectively preserves meat quality by enhancing tenderness and juiciness while maintaining nutritional value (Kenesei et al., 2024).

The freshness and quality of raw materials are key factors for the end product in sous-vide cooking and other minimally processed products. Before applying sous-vide cooking, meat can undergo several pretreatments to enhance flavor, texture, and safety. Common pretreatment methods include marinating, vacuum sealing, pre-searing, and freezing. Freezing is the most common method used to preserve meat before sous-vide cooking; meat can be seasoned, vacuum-sealed, and frozen for later use, ensuring convenience and extended shelf life (Yadav et al., 2025).

However, there is considerable evidence that incorporating freezing has both beneficial and detrimental effects on meat quality, particularly texture. Studies have shown that prolonged frozen storage increases drip loss, protein oxidation, and textural degradation due to ice crystal formation and structural damage in muscle tissue. Additionally, thawing methods and duration can influence the extent of quality loss, affecting water-holding capacity, tenderness, and organoleptic characteristics of cooked meat (Leygonie et al., 2012). Various studies have also demonstrated that applying refrigeration and freezing in sous-vide cooking affects lipid oxidation and sensory attributes, resulting in variability in the final product's quality (Hasani et al., 2023). The role of storage conditions in preserving or compromising quality parameters such as texture, flavor, and oxidative stability is thus critical for optimizing meat processing outcomes (Gil et al., 2022). However, there is no research that has been conducted on the effects of refrigeration and freezing prior to sous-vide cooking of meat, particularly chicken breast and pork.

The evaluation of cooked meat quality, particularly weight loss, color, and oxidative stability, is essential for predicting the shelf life of food products. Based on this, the present study aimed to evaluate how pretreatments, particularly refrigeration and frozen storage of raw chicken breast and pork, influence key quality parameters of sous-vide cooked meat.

2. MATERIALS AND METHODS

2.1. Sample preparation

Fresh chicken breast *(Pectoralis major)* and pork loin *(Longissimus dorsi)* meat samples 24 h post-mortem were obtained from the same supplier at a wholesale market to ensure uniformity of raw materials. The biological characteristics, age and breeds of meat were unknown, as the study mainly focuses on the effect of storage condition and sous-vide cooking rather than the effect of those characteristics. Then the samples were transported to the Livestock Products and Food Preservation Technology Department, Hungarian University of Agriculture and Life Sciences, Budapest, Hungary using an ice-filled thermos cool box. Visible fat and connective tissue were removed, and small and uniform pieces were prepared from chicken breast with an average weight of 182 ± 11 g and a thickness of 5.5 ± 0.5 cm. In contrast, the pork loin samples had an average weight of 157 ± 8 g and a thickness of 3.2 ± 0.4 cm. Meat pieces (4 × 5 pcs) were put in PA/PE pouches (200 × 250 mm) and vacuum packed using a vacuum machine (Multivac C100, MULTIVAC Sepp Haggenmüller SE & Co. KG, Wolfertschwenden, Germany) and the treatments were assigned randomly.

2.2. Experimental design

This study performed experiments to explore how pretreatment refrigeration and frozen storage influence the quality characteristics of sous-vide-cooked chicken breast and pork. Prior to cooking, chicken breast and pork loin samples were subjected to refrigerated storage at 3 °C for 2 or 10 days, or frozen storage at −25 °C for durations of 10 days or 6 months. After each storage period, the samples were cooked sous-vide for 45 min at 60 °C. The experimental design included two main factors: (1) pre-treatment (raw) and (2) post-treatment (after sous-vide cooking), each with four levels: refrigerated short, refrigerated long, frozen short, and frozen long. The cooked meat samples were then cooled to 10 °C in iced water. In this study, the raw sample refers to meat that was subjected to the designated storage conditions (refrigerated or frozen) but had not yet undergone sous-vide cooking, and sous-vide sample was the sample after storage which was cooked sous-vide at 60 °C for 45 min. Measurements were carried out both before treatment and immediately after the sous-vide treatment. The detailed experimental treatments are summarized in Table 1.

2.3. Analysis methods

2.3.1. Weight loss. The weight loss was determined at two stages, namely during storage (drip loss) and after sous-vide cooking (cooking loss). The weight loss was expressed as a percentage of the initial sample weight. It was determined by calculating the ratio of the difference between the pre- and post-treatment weights to the initial weight of the meat samples, which were measured using a Kern PLJ 3500-2NM balance (Kern & Sohn, Ebingen, Germany).

2.3.2. pH value. Measurement of the pH for chicken breast and pork samples was performed following AOAC (2006) guidelines. A pH meter (Testo AG, Germany) was used for the measurements. The pH was recorded at approximately the same temperature between 12 and 14 °C for the raw samples and around 10–12 °C for the heat-treated samples.

2.3.3. Color. The meat color of each sample was assessed based on the CIELAB system (CIE, 1977). A CR-400 colorimeter (Konica Minolta Sensing Inc., Osaka, Japan) was used to determine the L^* (lightness), a^* (redness), and b^* (yellowness) parameters following white calibration of the device. Each sample was measured in five replicates to confirm that results are consistent.

2.3.4. Texture measurement. The texture was measured using a Stable Micro System TA XT Plus instrument (Stable Micro Systems Ltd.). The measurement was done by the method of Kenesei et al. (2024) with slight modification. A needle probe with a 2 mm diameter was used for puncture tests. The probe penetrated perpendicularly to the muscle fibers to a depth of 30 mm. A trigger force of 0.049 N was set. Throughout the measurement, force (N) was continuously recorded relative to the probe's penetration distance. The pre-test and test speeds were set to 2 mm s^{-1} prior to the texture measurements. To determine sample hardness, the maximum force ($F_{max,}$ N) was used as the texture parameter. The work (N·mm) was also calculated as the multiplication of force and distance to get the total mechanical energy needed to penetrate the meat over the measured distance.

2.3.5. Lipid oxidation. The thiobarbituric acid reactive substances (TBARS) test is widely used as an objective indicator of secondary oxidation products in meat, specifically related to the

Table 1. Experimental design summary, including storage conditions, duration, and sous-vide cooking applied to chicken breast and pork loin samples

Storage condition	Storage duration	Sous-vide cooking
Refrigerated short	2 days at 3 °C	60 °C for 45 min
Refrigerated long	10 days at 3 °C	60 °C for 45 min
Frozen short	10 days at −25 °C	60 °C for 45 min
Frozen long	6 months at −25 °C	60 °C for 45 min

formation of malondialdehyde (MDA) during lipid peroxidation. The levels of TBARS in the samples were analyzed following the procedure outlined by Dias et al. (2013), with certain adjustments. Five grams of meat were homogenized for 2 min in 20 mL of 5% trichloroacetic acid (TCA) and 0.5 mL of the synthetic antioxidant 0.15% butylated hydroxytoluene (BHT; Sigma-Aldrich, Munich, Germany) using a Digital Ultra-Turrax homogenizer (Staufen, Germany). The homogenates were then centrifuged for 10 min at 5,000×*g*. The supernatants were diluted to a final volume of 25 mL with 5% TCA after filtration through Whatman No. 1 filter paper into 25 mL volumetric flasks. Glass tubes containing 2 mL of the filtrate and 2 mL of 0.08% thiobarbituric acid (TBA) solution were heated at 95 °C for 30 min in a water bath. After cooling to room temperature and vortexing, the solutions' absorbance was measured at 532 nm using a U-2900 UV-visible spectrophotometer (Hitachi Ltd., Tokyo, Japan) against a blank (a mixture of 2 mL of 5% TCA and 2 mL of 0.08% TBA). TBARS results, which were calculated as mg malondialdehyde/kg of meat sample, were the average of three measurements for each sample.

2.3.6. Sensory characteristics of the chicken breast. Sensory evaluation was conducted only on chicken breast samples because it was difficult to obtain panelists for pork sensory testing due to religious and ethical limitations. The sensory characteristics of chicken breast samples were assessed to evaluate the impact of refrigeration as well as freezing on the final organoleptic property of sous-vide-cooked meat. During the storage experiment, on each sampling day, after sous-vide cooking, the pouches were aseptically opened, and the samples were evaluated for various sensory attributes. Chicken breast sample was assessed with respect to color, smell, texture, taste, as well as overall acceptability. Sensory evaluation was conducted using a 5-point hedonic scale (1 = dislike very much, 5 = like very much) to assess color, smell, texture, taste, and overall acceptability. Sensory evaluation was conducted by a panel of 24 trained panelists. Each sample was labeled with a three-digit random code, and the order of sample presentation to the panelists was randomized.

2.4. Statistical analysis

Each treatment was performed in triplicate ($n = 3$), and the data are presented as the mean ± the standard deviation (SD). IBM SPSS Statistics with version 29.0 for Windows was used to do the statistical analysis. Data were analyzed using Analysis of Variance (ANOVA) and the General Linear Model (GLM). The normality of residuals was assessed using the Kolmogorov–Smirnov test ($P > 0.05$), and the homogeneity of error variances was verified using Levene's test ($P > 0.05$). Finally, Tukey's post hoc test was performed because the homogeneity assumption was satisfied in order to detect significant differences between groups.

3. RESULTS AND DISCUSSION

3.1. Weight loss

In this study, the effects of pre-treatment (raw) and post-treatment (after sous-vide) on the weight loss of chicken breast and pork were analyzed and are presented in Fig. 1. The storage conditions applied prior to sous-vide cooking significantly affected the weight loss of both

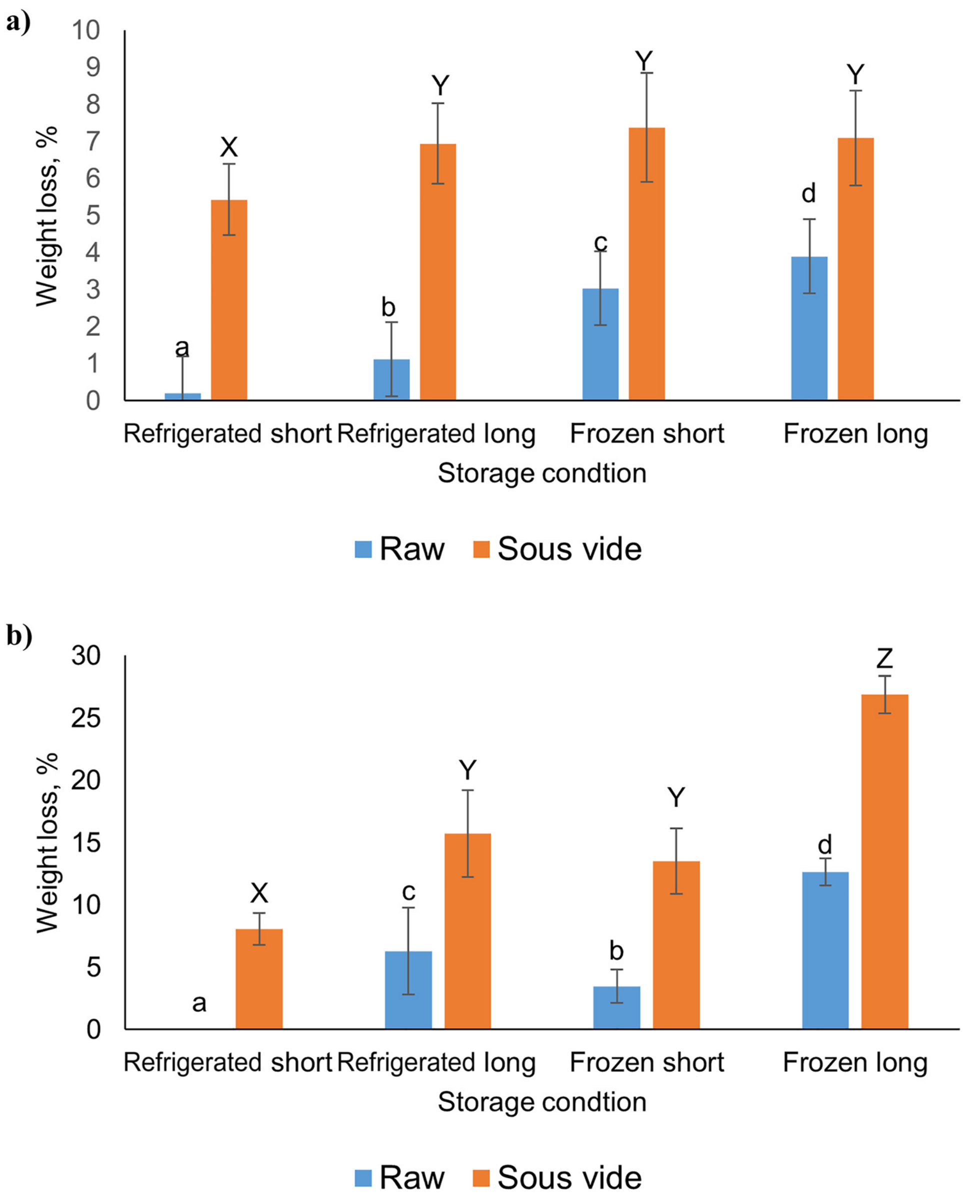

Fig. 1. a) Weight loss values before and after Sous-vide cooking of chicken breast; b) Weight loss values before and after Sous-vide cooking of pork meat samples. [a–d, X–Z]: Values sharing the same letter do not differ significantly, while those with different letters indicate significant differences ($P < 0.05$) among samples

chicken breast and pork meat samples ($P < 0.05$). During storage of chicken breast (before treatment), weight loss increased from 0.2% (2 days at 3 °C) to 3.90% (6 months frozen). Weight loss further increased significantly after sous-vide cooking (post-treatment) in both chicken breast and pork samples. Weight loss after sous-vide ranged from 5.43% (2 days at 3 °C) to 7.09% (6 months frozen) for chicken breast, and from 8.06% (2 days at 3 °C) to 26.88% (6 months frozen) for pork samples. The increase in weight loss with prolonged frozen storage observed in this study is consistent with previous research, where extended cold storage led to higher cooking losses in sous-vide cooked meat (Gil et al., 2022). While our study focuses on the impacts of pre-treatment storage time on weight loss in sous-vide cooked chicken breast, Hasani et al. (2021) similarly demonstrate that processing conditions, specifically double-step sous-vide treatments, can reduce weight loss and improve moisture retention compared to single-step methods. Together, these findings highlight that both pre-treatment and cooking parameters strongly influence final cooking yields.

Based on the measured data, it is also noticeable that there is a greater difference between products stored for a short and a long time in refrigeration compared to products frozen for a short versus a long time. In chicken breast only a slight difference was observed between 10th day and six-month freezing. The ten days frozen sample released slightly more juice during heat treatment. This may be due to significant moisture loss that had already occurred during the six-month storage, so less remained to be lost during heat treatment (Leygonie et al., 2012).

The results clearly show that meat loses weight already during storage due to water being released; the longer it is stored, the more liquid it releases. It is clearly visible that frozen meat loses the most weight during heat treatment. In this study, the application of freezing triggers the weight loss of the meat samples. The increase in weight loss due to storage is primarily associated with the natural drip loss of the fresh meat while the formation of ice crystals and subsequent cellular damage depend on the rate of freezing. The sous-vide treatment modifies the protein structure (denaturation) and thus the modified water-holding capacity explains the weight loss. Chang et al. (2022) demonstrated how freezing rate impacts ice crystal formation and plays a role in tissue damage during the freezing of meat. Generally, weight loss during storage and sous-vide cooking is closely associated with biochemical and microstructural alterations in muscle tissue. In the case of refrigerated and frozen storage, myofibrillar proteins gradually undergo denaturation, resulting in a reduced water-holding capacity (WHC) of muscle fibres. As a consequence, intracellular water migrates into the extracellular space, where it is subsequently lost as drip (Lund et al., 2011). Freezing exacerbates these effects due to the formation of large extracellular ice crystals, which compromise cell membrane integrity and cause irreversible structural damage. This damage further diminishes the ability of muscle tissue to retain moisture after thawing (Leygonie et al., 2012).

Sous-vide cooking introduces additional moisture losses. The application of heat triggers protein aggregation and myofibrillar shrinkage, mechanically forcing water out of the protein matrix, which contributes to cooking loss (Roldán et al., 2013). Furthermore, prolonged storage can accelerate protein oxidation, reducing the availability of functional groups involved in water binding and thereby intensifying both purge and cooking losses (Estévez, 2011).

Moreover, the extent of weight loss has significant implications for the texture and overall quality of meat products. Excessive moisture loss not only reduces yield but can also negatively affect tenderness, juiciness, and consumer acceptance. Particularly in sous-vide cooking, where precise control over texture and juiciness is essential, minimizing pre-cooking weight loss is crucial to maintaining product quality. Therefore, optimizing storage conditions, such as controlling freezing rates and storage duration, remains vital for preserving the technological and sensory attributes of meat. The differences in sample thickness between pork and chicken may be one of the limitations and this thickness influenced heat transfer and moisture migration during sous-vide cooking as well as during storage, leading to variations in weight loss between species. Thicker cuts generally require longer heating times, resulting in greater fluid loss due to prolonged protein denaturation (Roldán et al., 2013).

3.2. pH

Storage conditions and sous-vide cooking significantly affected the pH values of chicken breast samples ($P < 0.05$), as shown in Fig. 2. In pork meat, storage condition had a limited effect on pH in raw samples, and no significant differences were observed among storage groups after sous-vide cooking.

pH is one of the most important characteristics of meat. For chicken breast, the lowest pH value (5.87 ± 0.11) was recorded in samples pretreated by freezing for six months. Conversely, the highest pH (6.21 ± 0.08) was observed in the sample that had been frozen for six months and subsequently cooked sous-vide. In pork meat, the lowest pH value (5.70 ± 0.20) was recorded in samples pretreated by long-term freezing, while the highest pH (6.06 ± 0.15) was observed in samples frozen for six months and subsequently cooked sous-vide. These results suggest that values change proportionally before and after heat treatment. During storage, the pH slightly decreases, which is also evident from the fact that the maximum pH value was recorded in the raw and sous-vide cooked chicken breast samples stored for a short time under refrigeration. However, in pork meat, refrigerated short storage did not consistently result in the highest pH, particularly after sous-vide cooking, where no significant differences were observed among storage groups.

Sujiwo et al. (2025) likewise observed a decrease in pH during storage, supporting the present findings. It also decreases to a similar extent in heat-treated products, confirming that the quality of the raw material indeed affects the properties of the heat-treated product. In the case of six months of freezing, a slightly higher pH value was observed compared to 10 days of frozen storage, but due to data variation, this difference is not considered significant. A low pH reduces the distance between the filaments that make up the myofibrils and induces the denaturation of myosin. This is associated with reduced protein solubility and increased drip loss, which in turn causes the meat color to lighten. Liu et al. (2016) reported that sarcoplasmic proteins undergo denaturation during storage, leading to decreased solubility and altered water-holding capacity in meat. Their study highlighted that lower pH levels accelerate protein denaturation, resulting in increased exudation of meat juices.

3.3. Color

The effects of different storage methods and sous-vide treatment on the color attributes (L^*, a^*, and b^*) of pork and chicken were clearly observed in this study (Table 2). The L^* values of both chicken breast and pork meat samples were significantly influenced by storage conditions and sous-vide cooking ($P < 0.05$). The raw pork stored frozen for a short period meat had lowest L^* value (42.27 ± 2.03). On the other hand, the highest L^* value was recorded in chicken sous-vide samples stored frozen for a long period (81.17 ± 0.80). This trend supports previous

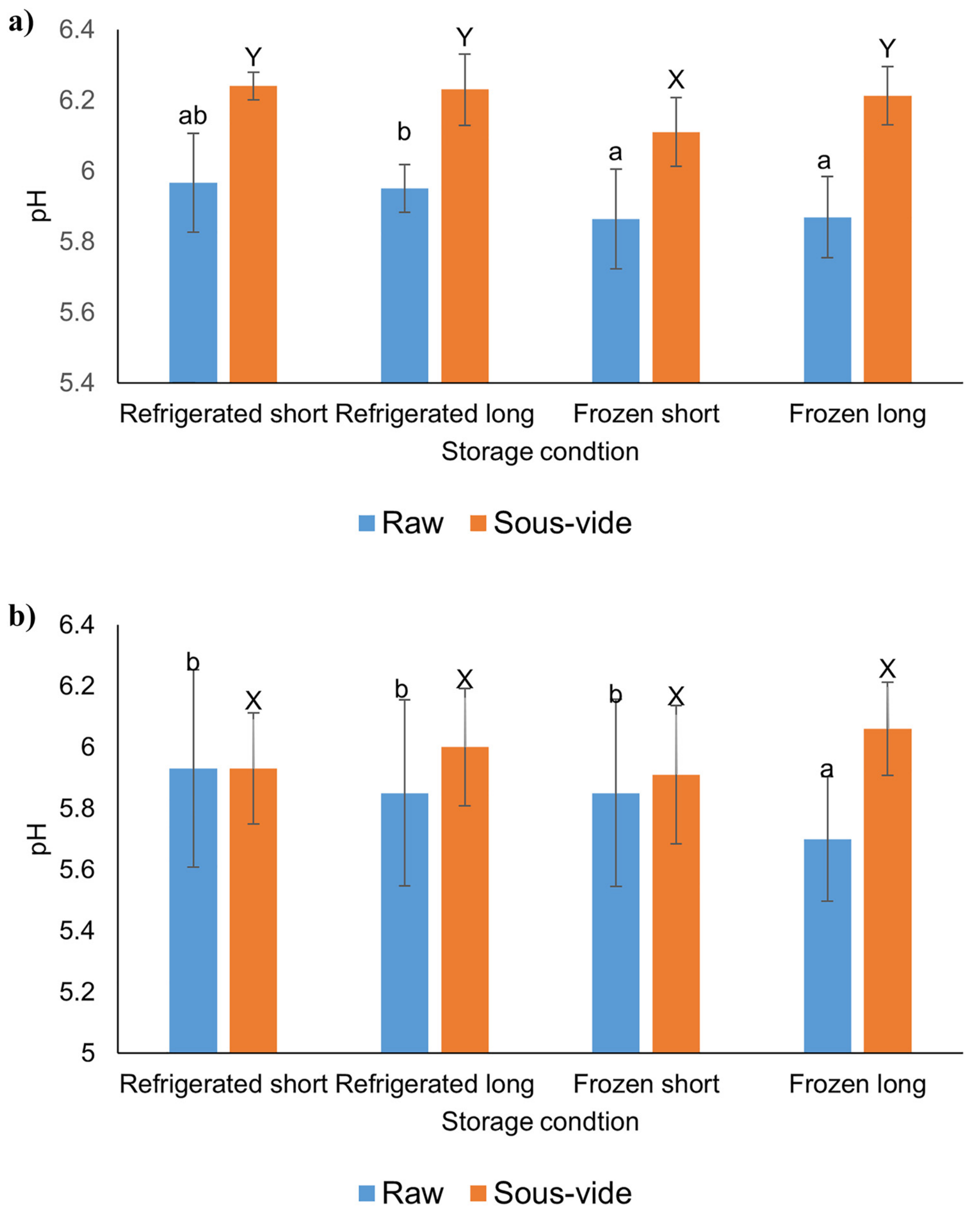

Fig. 2. a) pH of chicken breast pre and post sous-vide cooking; b) pH of pork meat pre and post sous-vide cooking. $^{a–b,\ X\_Y}$: Values sharing the same letter do not differ significantly, while those with different letters indicate significant differences ($P < 0.05$) among samples

findings that sous-vide cooking enhances lightness by promoting protein denaturation and moisture retention (Baldwin, 2012). Storage duration and conditions further influenced the

Table 2. Means ± standard deviations of color attributes of chicken breast and pork meat samples

Samples	Chicken			Pork		
Raw	L^*	a^*	b^*	L^*	a^*	b^*
Refrigerated short	48.29 ± 5.48^{a}	3.73 ± 0.91^{c}	2.70 ± 2.13^{a}	45.54 ± 3.96^{b}	5.63 ± 1.80^{b}	5.77 ± 1.92^{c}
Refrigerated long	51.52 ± 2.85^{b}	3.10 ± 0.79^{b}	2.70 ± 1.61^{a}	43.06 ± 3.67^{a}	4.99 ± 0.97^{a}	3.41 ± 1.08^{b}
Frozen short	48.22 ± 3.01^{a}	3.70 ± 1.01^{c}	2.84 ± 1.48^{a}	42.27 ± 2.03^{a}	5.32 ± 1.21^{b}	3.37 ± 0.71^{b}
Frozen long	50.07 ± 7.13^{b}	2.67 ± 1.00^{a}	2.71 ± 1.59^{a}	46.75 ± 4.17^{b}	8.51 ± 1.19^{c}	1.01 ± 1.14^{a}
Sous-vide						
Refrigerated short	79.99 ± 1.30^{X}	3.99 ± 0.96^{Y}	8.94 ± 0.59^{X}	72.08 ± 2.40^{Y}	7.86 ± 1.73^{Y}	12.72 ± 0.53^{Z}
Refrigerated long	81.17 ± 0.80^{X}	3.66 ± 0.38^{X}	9.10 ± 1.11^{X}	67.70 ± 4.15^{X}	7.26 ± 1.21^{Y}	9.43 ± 0.78^{YZ}
Frozen short	80.02 ± 1.11^{X}	3.86 ± 0.89^{XY}	10.03 ± 1.17^{XY}	72.72 ± 8.66^{YZ}	8.01 ± 1.32^{Y}	8.95 ± 0.70^{Y}
Frozen long	80.07 ± 1.93^{X}	3.51 ± 0.92^{X}	11.24 ± 0.94^{Y}	75.96 ± 1.33^{Z}	6.93 ± 0.73^{X}	7.28 ± 0.29^{X}

$^{a–c,\ X\_Z}$: Values sharing the same letter do not differ significantly, while those with different letters indicate significant differences ($P < 0.05$) among samples.

lightness values. In both meats, long-term frozen storage resulted in higher L^* values compared to short-term storage. This could be attributed to the effects of freezing, such as ice crystal formation and increased drip loss, which alter the meat surface structure (Leygonie et al., 2012).

The a^* values, which indicate redness, were also significantly affected by storage and cooking, particularly in chicken samples ($P < 0.05$). In raw chicken breast, a^* values decreased with extended storage, especially under frozen conditions. Refrigerated short and frozen short samples showed higher a^* values, while frozen long storage led to a significant reduction in redness (2.67 ± 1.00). Sous-vide-treated chicken exhibited minor variations in a^* across storage conditions, with no statistically significant differences in most cases, indicating that sous-vide cooking reduced the variability in redness caused by storage. Although sous-vide-treated chicken showed increased a^* values, the differences among storage groups were less pronounced, suggesting that sous-vide cooking stabilizes redness to some extent, possibly by limiting oxygen exposure and preserving pigment integrity (Baldwin, 2012). On the other hand, the a^* values raw pork samples showed significant differences depending on storage conditions, with the highest redness observed in refrigerated short meat (5.63 ± 1.80), and an increment of a^* noted in frozen long samples (8.51 ± 1.19). After sous-vide cooking, pork samples showed increased a^* values overall, ranging from 6.93 ± 0.73 to 8.01 ± 1.32, suggesting that both the storage condition and cooking had a significant effect on redness. The decrease in a^* values for chicken suggests oxidative degradation of myoglobin over storage (Mancini and Hunt, 2005; Suman and Joseph, 2013).

Regarding b^* values (yellowness), both chicken and pork generally showed lower values across all storage conditions, with slight declines over time. The lowest b^* value was observed in pork raw frozen long-term samples (1.01 ± 1.14), while the highest was found in pork sous-vide samples refrigerated short-term (12.72 ± 0.53). These variations in b^* values can be associated with lipid oxidation, which alters the surface color by breaking down pigments and fats (Faustman et al., 2010). In general, pork, in particular, showed greater stability in color characteristics under sous-vide treatment. These results align with previous studies highlighting sous-vide's protective effect against color degradation through limited oxygen exposure and gentle thermal treatment (Baldwin, 2012; Roldán et al., 2013).

3.4. Texture

Texture of pork and chicken under varying storage conditions revealed significant alterations in mechanical properties, notably in maximum force (F_{max}) and work done during deformation (Fig. 3). These changes are indicative of the structural modifications occurring within muscle tissues due to different storage methods and durations. Short-term frozen storage resulted in the highest F_{max} values for both pork (8.16 N) and chicken (3.82 N), suggesting an increase in muscle toughness. According to Leygonie et al. (2012), this phenomenon results from solidification of water into ice during freezing, which may induce structural damage to muscle fibres and consequently increase tissue rigidity.

Conversely, long-term frozen storage led to a decrease in F_{max} for pork (5.37 N) but an increase in work for chicken (79.41 N·mm). The reduction in pork's F_{max} may be due to proteolytic degradation and partial denaturation of myofibrillar proteins over extended freezing periods, resulting in softer tissue (Leygonie et al., 2012). The increased work in chicken suggests a higher energy requirement for deformation, potentially due to changes in muscle cohesiveness or water distribution within the tissue (Zhang et al., 2020). Under refrigerated storage, both

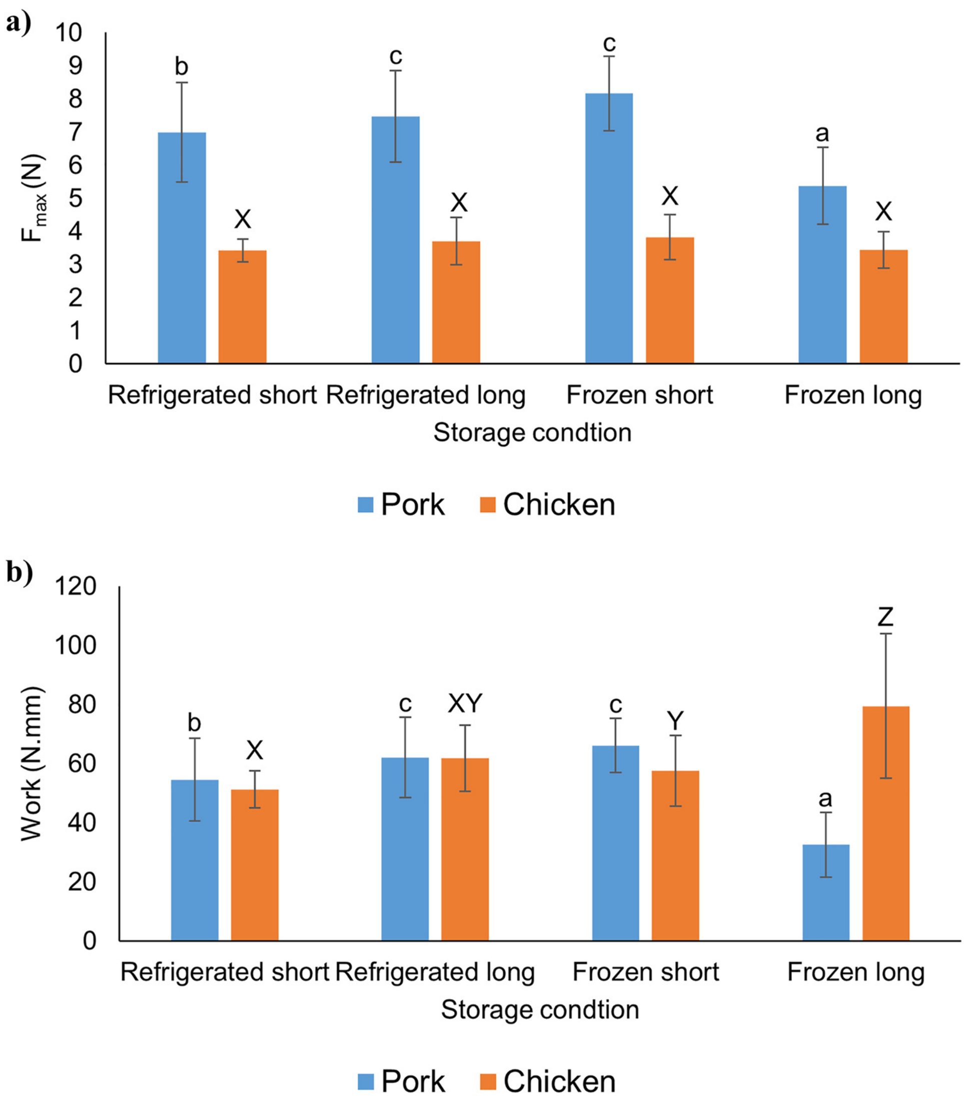

Fig. 3. Texture profile of pork and chicken breast sous-vide cooked meat: (a), F_{max} value and (b), work value. [a–c, X_Z]: Values sharing the same letter do not differ significantly, while those with different letters indicate significant differences ($P < 0.05$) among samples

meats exhibited slight increases in F_{max} and work over time. Pork's F_{max} rose from 6.99 to 7.47 N, and work from 54.51 to 62.01 N·mm. Chicken showed increases from 3.42 to 3.70 N in F_{max} and from 51.16 to 61.76 N·mm in work. These changes may be attributed to moisture loss and minor protein crosslinking during refrigeration, leading to firmer textures (Karlović et al., 2009). Overall, the results indicate that storage conditions significantly impact meat texture, with freezing and refrigeration affecting pork and chicken differently, and this texture change is driven by a combination of physical (ice crystallization, water migration) and biochemical (protein denaturation, oxidation, proteolysis) factors. Understanding these effects is crucial for optimizing storage practices to maintain desirable textural properties in meat products.

3.5. Lipid oxidation

The results clearly demonstrate that both storage condition and sous-vide cooking significantly influence lipid oxidation or TBARS (mg MDA/kg) values ($P < 0.05$) in chicken and pork (Fig. 4). Among all conditions, the highest TBARS values were observed in sous-vide samples stored for a long period under refrigeration: 3.27 mg MDA/kg in chicken and 3.53 mg MDA/kg in pork. This suggests that prolonged refrigerated storage, combined with sous-vide processing, promotes oxidative degradation of lipids. The combination of extended storage time and heat exposure, even at the relatively low temperatures used in sous-vide, appears to accelerate oxidation, possibly due to cumulative thermal and enzymatic effects. Sous-vide leads to higher TBARS values compared to raw samples in long-refrigerated and short-frozen meat, especially pork. This suggests that sous-vide cooking promotes lipid oxidation, even though it is considered a gentle cooking method. Comparable results were reported by Kenesei et al. (2024), indicating that sous-vide-treated pork exhibited measurable TBARS values, though lower than those resulting from combined high-pressure treatments, confirming that even mild thermal processes can initiate oxidative reactions in meat. In contrast, the lowest TBARS values were found in raw samples stored under frozen short-term conditions, 1.15 mg MDA/kg for chicken and 1.286 mg MDA/kg for pork—indicating that freezing effectively limits oxidative reactions, at least in the short term. Even when frozen for a long duration, raw samples still exhibited lower TBARS values compared to their sous-vide counterparts, showing that freezing helps preserve lipid stability better than refrigeration.

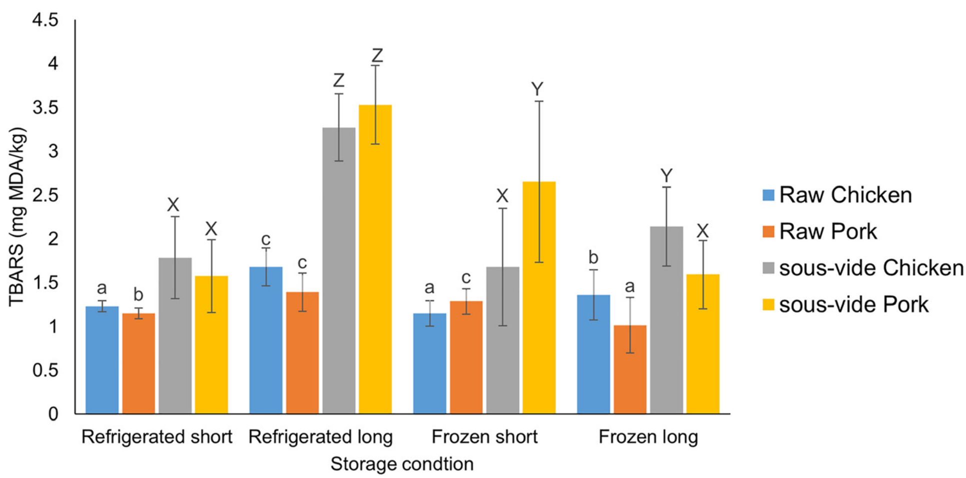

Fig. 4. TBARS values of chicken breast and pork before and after sous-vide cooking. $^{a–c,\ X–Z}$: Values sharing the same letter do not differ significantly, while those with different letters indicate significant differences ($P < 0.05$) among samples

The result of this study showed that sous-vide cooking led to higher TBARS values than raw samples under all storage conditions, highlighting its potential to enhance lipid oxidation despite being a gentle cooking method. Another study, Roldan et al. (2014) support this idea and they showed that maintaining the minimal temperature of sous-vide cooking is mandatory to keep the meat product more oxidatively stable. Overall, the results suggest that both storage method and cooking treatment significantly affect lipid oxidation in meat. In addition to lipid oxidation, it is likely that protein oxidation and structural alterations contributed to the observed increases in TBARS values. Oxidative reactions can also target amino acid side chains and sulfhydryl groups, leading to the formation of protein carbonyls and cross-links that affect texture and water-holding capacity (Lund et al., 2011).

In general, in this study chicken samples generally exhibited higher TBARS values than pork under similar conditions, particularly in sous-vide treatments following long-term storage. This might be because chicken contains more polyunsaturated fatty acids, which are more prone to oxidation. However, pork also showed considerable increases in TBARS values under adverse storage and processing conditions, especially with sous-vide cooking following long-term refrigeration.

3.6. Sensory evaluation

The sensory characteristics of sous-vide cooked chicken were evaluated after different storage conditions (refrigerated short-term, refrigerated long-term, frozen short-term, and frozen long-term). The mean scores for color, smell, texture, taste, and overall acceptance varied depending on the storage duration and method (Fig. 5).

Overall, refrigerated short-term storage resulted in the highest sensory scores across almost all attributes. Specifically, the color (4.58), smell (4.42), texture (4.75), taste (4.67), and overall acceptance (4.67) were rated the highest among all groups. These results suggest that shorter refrigerated storage prior to sous-vide cooking preserved the chicken's sensory quality most effectively. This finding is in agreement with Baldwin (2012), who reported that maintaining fresh quality before sous-vide processing is critical for optimizing the final sensory properties.

In contrast, refrigerated long-term storage yielded the lowest sensory ratings, particularly for smell (3.00), texture (3.50), taste (3.33), and overall acceptance (3.29). Extended refrigeration likely allowed greater microbial activity and oxidative changes, negatively affecting odor and flavor (Roldán et al., 2013). The color score after refrigerated long-term storage (3.58) was also

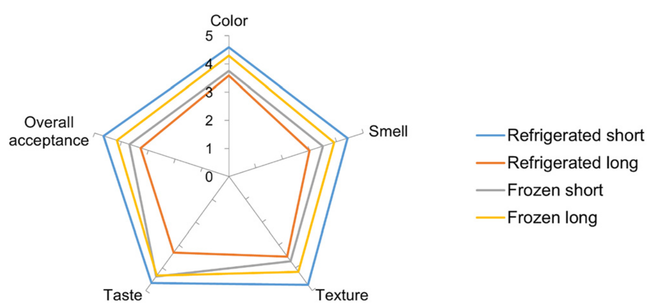

Fig. 5. Sensory characteristics of sous-vide chicken breast

the lowest among all groups, which aligns with previous findings that discoloration is a major quality degradation factor during extended chilled storage (Mancini and Hunt, 2005).

For frozen samples, short-term freezing showed moderate sensory scores with overall acceptance of 3.71, while long-term frozen storage showed improved ratings, especially in texture (4.17) and taste (4.33). Interestingly, the overall acceptance for frozen long-term (4.17) was higher than that for frozen short-term (3.71), indicating that controlled long-term freezing, followed by sous-vide cooking, might mitigate some of the negative sensory impacts typically associated with freezing, possibly by reducing protein denaturation and moisture loss during cooking (Leygonie et al., 2012). Taste scores were highest for refrigerated short-term samples and remained relatively high even in frozen long-term samples. This suggests that sous-vide processing helps retain flavor components despite prior frozen storage, consistent with previous studies showing that sous-vide minimizes volatile loss during cooking (Roldán et al., 2013). In general, the sensory evaluation demonstrated that refrigerated short-term storage prior to sous-vide cooking produced the best overall sensory quality. However, frozen long-term storage also maintained acceptable sensory properties, highlighting the effectiveness of sous-vide cooking in preserving meat quality under varying pretreatment conditions.

4. CONCLUSIONS

In conclusion, this study's findings indicate that pretreatment storage parameters, particularly time and temperature, significantly influence the quality attributes of chicken breast and pork prepared using sous-vide cooking. The longer storage time, particularly in freezing circumstances, affected texture, color, and lipid oxidation and increased weight loss (up to 7.09% in chicken and 26.88% in pork). After prolonged refrigeration, the highest TBARS levels (3.27 mg MDA/kg in chicken and 3.53 mg MDA/kg in pork) were noted, indicating that sous-vide cooking increased lipid oxidation while also elevating pH and lightness. The best sensory qualities were obtained from short-term chilled storage before sous-vide, according to sensory research, although long-term frozen storage also preserved respectable quality. Overall, maximizing the sensory and physicochemical quality of sous-vide cooked meats requires preserving raw material freshness through shorter storage periods, especially under refrigeration. These results offer insightful information for industrial and culinary applications that seek to strike a balance between product quality, shelf life, and convenience.

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