Effect of Storage on the Physicochemical and Textural Quality of Pork Chops and Chicken Breast

by

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ABSTRACT

Meat is an essential source of amino acids and micronutrients in the human diet, and its consumption is increasing worldwide. Chicken and pork meat currently dominate the global market due to their affordability and availability. Nevertheless, meat is a highly perishable food with a short shelf life; due to its greater water activity and can be prone to the growth of microorganisms leading to accelerated deterioration. For the meat industry, extending the shelf life of products while maintaining wholesome quality is essential. Therefore, cold storage methods such as refrigeration and freezing, along with vacuum packaging, can help extend the shelf life of meat. To understand the impact of storage on physical, chemical and textural characteristics, two studies were conducted under cold storage conditions.

In the first study, the impact of 120 days of frozen storage on the characteristics of vacuum-packed chicken breasts was evaluated. Chicken breasts (N = 25 per sampling day) were analyzed on days 0, 30, 60, 90 and 120 of storage, for cooked color, cooking loss, Warner-Bratzler shear force, and texture profile. Chicken breast fillets were darker ($p < 0.0001$) after 30 days, as well the surface was more yellow ($p < 0.0005$) and also further from the red axis and greater vividness on day 120. Cooking losses increased with increased storage time ($p < 0.0074$) and Warner-Bratzler shear force decreased ($p < 0.0002$) during storage. Texture profile analysis decreased until day 60 and then an increase in hardness ($p < 0.0003$) and chewiness ($p < 0.0001$) occurred through day 120 of storage. Frozen storage at -20°C effectively preserved the quality of the chicken breast in the short term, but after 2 months there was a noticeable deterioration in chicken characteristics.

A second study analyzed the impact of 60-day refrigerated (Treatment 1) and frozen (Treatment 2) storage on the quality characteristics of pork chops. Pork chops were analyzed every 10 days during storage (as described) and evaluated for cooking loss, Warner- Bratzler shear force,

texture profile, internal cooked color, and pH values. Cooking loss increased ($p < 0.0001$) while shear force decreased ($p < 0.0001$) throughout storage and treatment 2 resulted in greater shear force ($p < 0.0001$) compared to treatment 1. For texture profile analysis, both treatments decreased in hardness, but Treatment 2 was harder ($p < 0.0001$) than Treatment 1. Similarly, chewability and resilience decreased over time ($p < 0.0001$). Cooked internal color decreased ($p < 0.0001$) for L*, a*, b* values, and the red-to-brown color transition during storage for both treatments. Finally, pH values decreased ($p < 0.0001$) over the days of refrigerated storage. These findings from study two demonstrate that preservation methods are essential to extending shelf life and maintain the quality of a retail pork product. Regardless of the storage treatment, prolonged storage had the greatest impact on pork quality causing gradual changes, while storage temperature only modulates the speed at which these changes occur.

Artificial Intelligence (AI) Use Disclosure Statement

In the preparation of this thesis, no Artificial Intelligence (AI) tools were used.

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"Commit to the Lord whatever you do, and he will establish your plans."- Proverbs 16:3.

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LITERATURE REVIEW

1. INTRODUCTION

In the food industry, meat plays an important role as it is presented an essential source of protein, amino acids and essential micronutrients essential amino acids and micronutrients (Sheffield et al., 2024). Over the last three decades, the level of consumption in different parts of the world has increased exponentially, even in countries where purchasing power is moderately low, reaching per capita consumption levels equal to a high-income country. Regarding the types of meat, poultry and pork consumption volumes are increasing and are currently dominating the consumer market (Parlasca & Qaim, 2022). Chicken meat is consumed globally in large quantities as a source of accessible protein, especially in underdeveloped and developed countries, providing them with essential fats, vitamins and various minerals (Farrell, 2013). As in chicken, pork is frequently consumed as an important source of protein, iron, zinc and vitamins (Penkert et al., 2021).

As reflected in the United States where chicken meat was the most consumed during 2022, reaching 98.9 pounds per capita, and is projected to grow to 107.5 pounds per capita in 10 years, while pork consumption was 51.1 pounds per capita (USDA, 2024).

Extending the shelf life of a food is crucial for it to be marketable and reach the consumer with the best possible quality. Storing fresh and frozen meat products for longer periods can reduce financial losses caused by spoilage, enhances market reach, and improves supply chain efficiency while creating new opportunities for trade and innovation. Preservation techniques not only mitigate and reduce food safety risks, but also maintain meat quality over a long storage period, considering that consumers are guided by intrinsic and extrinsic quality signals for their purchasing decisions (Aboah & Lees, 2020; Espinoza et al., 2022).

Meat products are a food that is prone to deterioration, since it can have a proliferation of bacteria that will make this product perishable (Aymerich et al., 2008). For this reason, the meat industry has evaluated methods of preservation so that it can mitigate processes of changes in the quality of the meat throughout the time preventing a series of factors that affect to the shelf life of the meat (Zhou et al., 2010). Non thermal packaging method is one of the most widely used in the industry. Freezing preservation, which is considered one of the best preservation methods for all types of meats, helping to slow down enzymatic reactions and microbial growth, preserving the desired characteristics of the food. Another typical method is refrigeration which keeps the food below the range for microbial growth at a temperature of 0ºC to 8ºC (Chellaiah et al., 2020).

Despite this, prolonged storage in different segments of the marketing chain has an impact on meat properties. Considering their significant importance, the objective of this review is to evaluate the impact of refrigeration and freezing on the physical and chemical attributes of pork and poultry meat throughout storage.

2. MEAT PRESERVATION

Meat shelf life can be described as the period during which meat remains safe and acceptable for consumption, primarily by resisting spoilage from bacteria and chemical changes. Once the shelf life ends, the meat can become unsafe due to pathogenic bacteria or develop unpleasant odors, flavors, and textures from spoilage bacteria. It was described as the time that elapses before the desirable organoleptic characteristics of the product are lost–(Lorenzo & Gómez, 2012). In the meat industry, large economic losses occur due to product deterioration

(Wu et al., 2021). Specifically, in the United States, the meat industry accounts for approximately 38% of the total value of food losses, equivalent to a monetary loss of $31 million annually (Buzby & Hyman, 2012). For producers and consumers this can represent a loss of 40% of raw meat from production (Lorenzo et al., 2014).

Processing and preservation technologies have been of interest in recent years in which the development of a more resistant meat value chain is sought to satisfy the client (Troy et al., 2016). Meat quality is demanded by the client, encouraging processors and distributors to guarantee these qualities, with the main objective of inhibiting microbial growth, minimizing oxidation and enzymatic deterioration (Addis, 2015). As a commodity that is highly perishable, the meat industry has applied some processing and preservation techniques to maintain the quality and nutritional status during storage (Rahman et al., 2018).

3. TECHNIQUES OF MEAT PRESERVATION

The preservation techniques or methods used can be based on the final demand of the product, taking into account that there will be a final impact on the quality of the meat, which can cause different sensory and nutritional changes (Dave & Ghaly, 2011). Currently there are several methods used in the meat industry, generally divided into three main groups, temperature control, use of preservatives, and water activity control (Gomez et al., 2020). Packaging also plays a very important role in conservation techniques since it ensures the safety and quality of the food, and also protects the product and reduces losses (Soro et al., 2021). These techniques often manage to combine with each other to achieve maximum help in preventing spoilage and maintaining the quality of raw and processed meat (Rahman et al., 2023).

4. FREEZING

Freezing offers an advantage in the preservation of raw materials by indorsing very minimal changes in natural properties (Ishevskiy & Davydov, 2017), promoting the possibility of prolonged storage, handling in transport and trade (Mao et al., 2024). The freezing temperature of -20 °C in the muscle is one of the most reliable methods used during meat storage (Lisitsyn et al., 2019). Prolonged storage of meat at freezing temperature of −20°C, offers an advantage in maintaining freshness compared to other techniques such as chemical preservation, drying, smoking or canning (Augustyńska-Prejsnar et al., 2019). At the moment of freezing the meat, water is eliminated from the matrix through the formation of ice crystals and the activity of water is reduced promoting the microorganisms to stop being active, in spite of this, meat is considered a delicate structure that can suffer cellular damage due to the formation of ice crystals causing mechanical damage, when there are more ice crystals they expand and compress the matrix, cross-linking of proteins and limited reabsorption, however this process can occur due to the rhythms or speed of freezing, if the food is frozen slowly there will be larger crystals occupying the extracellular spaces causing dehydration of the cells (Nesvadba, 2008), on the contrary if it freezes fast the cellular water will not have time to leave by osmosis but will group together freezing in small uniform crystals in the tissues, causing less damage. (Rinwi et al., 2023).

Freezing temperature fluctuations and the type of meat will influence the shelf life of the product, causing protein denaturation, fat oxidation and even loss of sensory and nutritional qualities. Nevertheless, it is known that chicken meat stored in freezing between -18 °C and -24 °C can be stored for 18 to 24 months, and pork meat stored at these same temperatures can be stored for 10 to 15 months (James, 2008; Zhu et al., 2025).

5. REFRIGERATION

One of the best-known traditional methods of meat preservation is refrigeration. Refrigeration has a main function to preserve and maintain food quality by keeping it fresh while maintaining a temperature of around 4°C. Although refrigeration also helps slow bacterial growth, microorganisms are not completely eliminated, and the food remains sensitive to changes in conditions (Tuan, 2014). Refrigeration retains the product's organoleptic characteristics and nutritional content if the humidity and temperature factors are carefully controlled (Aste, Del Pero, & Leonforte, 2017).

Throughout the food industry refrigeration technology is used at all stages, from storage of raw materials to distribution and consumption by customers (Popa et al., 2019). Currently refrigeration is used after slaughter or in primary pieces after boning, helping to preserve the meat at low temperatures and allowing to maintain quality (Coombs et al., 2017). Storing meat and foods above the freezing point, physical damage by ice crystals is not generated within the structure of the meat (Lee et al., 2023).

Despite these conditions for storing meat products, the chemical nature of meat has a progressive deterioration over time (Bida, 2019), which can cause the shelf life of meat in refrigerated storage to decrease due to microbial growth that begins to be present after the first week of storage, apart from additional changes in organoleptic characteristics that can be affected over time (Cao et al., 2023).

6. PACKAGING

Packaging is a key point in the production and storage of meat products, to help preserve and prolong shelf life, and facilitate handling and storage (Wang et al., 2018). The type of packaging and the technology used are also important. Meat packaging includes vacuum packaging (VP) and modified atmosphere packaging (MAP) in trays, which allows for gas exchange, influencing product stability by changing the entire environment within the packaging. Most meat and food packages containing an atmosphere consisting of nitrogen, followed by oxygen in smaller quantities and carbon dioxide. There are also brown paper wrappers and simple foam trays with plastic film (overwrap), all designed to preserve freshness and extend shelf life by displacing oxygen to prevent oxidative reactions within the packaging. The meat is then marketed and reaches the consumer without any microbiological problems and with a fresh appearance (Zouharová et al., 2022). Poor packaging can promote bacterial proliferation, oxidation of lipids and proteins, obtaining a high leading to meat deterioration (Yan et al., 2024). Packaging techniques also help to keep the product intact without being exposed to the outside conditions, preventing contamination and damage from atmospheric gas exchange, and allowing the food to maintain its fresh appearance. Packaging materials selected for storing food and meat are often identified by the final objective of the food production system. Packaging materials will depend on the type of food and the degree of oxygen barrier, PVC (polyvinyl chloride), PVA (polyvinyl acetate), EVOH (ethylene vinyl alcohol), PET (polyethylene terephthalate), are usually used (Patil et al., 2020).

Vacuum packaging is a very common technology used in the meat industry to help extend the shelf life of food. Since vacuum packaging allows the food to remain in storage for longer periods of time, reducing product weight losses due to evaporation, helping to preserve color and helping to prevent microbiological growth. This technology is based on putting the primary or sub primal cuts of meat inside bags and extracting the air inside the bag by means of a vacuum machine (Seideman & Durland, 1983), thus removing the air from the packaging and hermetically sealing it, creating a physical protection of the contents for display.

Meat industry commonly uses vacuum packaging in combination with thermoforming, a process in which a polymer sheet is heated inside a machine, molding it and fitting it into the planned cavity. This forms the base of the package, which is then filled with meat, followed by a film over the top for heat sealing. (Bernardez-Morales et al., 2023).

This packaging process, which uses a thermoformed package and vacuum application, can reduce losses at the retail counter by maintaining a stable color on the meat's surface and preventing spoilage, thus contributing to the meat's shelf-life. (Nichols et al., 2024).

7. IMPACT OF STORAGE ON META QUALITY

7.1 COLOR

The color of meat plays an important role in the consumer's perception at the time of consumption, since it can be associated with the freshness of the food. The protein called myoglobin is primarily responsible for the color of meat, along with others such as heme, hemoglobin, and cytochrome C (Mancini & Hunt, 2005).

Heme iron, which is part of the myoglobin protein, has the ability to form bonds and is capable of reversibly binding with oxygen, carbon dioxide and nitric oxide, which causes 4 possible chemical forms of myoglobin, which are deoxymyoglobin, oxymyoglobin, carboxymyoglobin, and metmyoglobin (Mancini, 2013).

Oxymyoglobin occurs when the surface of the meat is oxygenated, causing the characteristic bright red or cherry color known as meat. Metmyoglobin is produced when there is a loss of an electron from myoglobin and oxymyoglobin resulting in a brown to purple color, however these pigments will only be the result of the type of storage and packaging (Boles & Pegg, 2010).

During storage it is important that the meat has the presence of oxymyoglobin so that it has the appearance of fresh meat since it maintains the red pigment. When it is vacuum packed the formation of metmyoglobin begins and after opening the sealed package the reddish color of the meat can return due to the presence of oxygen again. If during prolonged storage a brown color can be seen, it can be said that there has been a formation of metmyoglobin due to the passage of oxygen from the packaging during storage (Šuput et al., 2023).

The temperature during storage is also a factor that will affect the color of the meat. Generally, with a longer time under frozen storage, the luminosity, red color and intensity values tend to lower, showing a reduction in its color more quickly than fresh meat. Also observe the formation of brown color during storage due to enzymatic activity and lipid oxidation (Vieira et al., 2009). A similar pattern would be shown if kept refrigerated, except that the changes would be in a short time between 10 and 14 days, causing the color intensity to decrease. All these changes will also depend on the type of meat that is evaluated, since if it is chicken meat it contains less myoglobin content than beef, therefore the instrumental color values may vary (Katiyo et al., 2020).

7.2 ***TEXTURE***

Meat texture refers to its firmness, cohesiveness, tenderness, and juiciness, determined by factors like muscle fiber size, connective tissue, fat marbling, and moisture content. More active muscles produce tougher meat due to longer fibers, while less-used muscles are more tender (Listrat et al., 2016). Texture is an important quality in meat quality, since apart from the objective tests that are carried out, its most important evaluation will be subjective by the consumer at the time of consumption. It is important to consider what part of the animal that meat comes from, since the cuts that come from the hind limbs and the dorsal area can be considered more tender, which is understood by studying the structure of the muscle, which is composed of 75% water, then 15% to 20% will be protein and the rest will be fat, carbohydrates, and salts.

Meat has a complex mixture of proteins which through their arrangement will determine the tenderness of the meat (Bailey, 1972). This structure is composed of muscle fibers and connective tissues, the fibers are composed of myofibrils proteins, the integrity of these myofibrils are those that undergo changes during storage (Nishimura, 2010).

This change in structure can be measured by mechanical methods to obtain quantitative values, through compression, shear, and traction. There are several methods but the Warner-Bratzler shear force is used to measure the maximum shear force through a blade, a texture profile analysis can also be performed, in which values of hardness, chewiness, elasticity, gumminess and resilience of the food can be observed (Schreuders et al., 2021).

During storage the texture of the meat will depend on the period it remains and the temperature approximately at 4°C reflects a progressive softening over time, due to the enzymatic degradation of muscle tissues such as calpain and proteases (Olivera et al., 2013), however at freezing temperature it will influence the formation of crystals in the matrix these depending on their size can break the fibrillar structures causing less resistance to chewing. Maintaining at that temperature the enzymatic activity of calpain stops and continues when it is thawed, despite this the quality of the meat will be negatively affected if it is kept in storage for long periods (Coll Cárdenas & Olivera, 2016).

7.3 ***COOKING LOSS***

Cooking loss in meat is the reduction in weight from raw to cooked, primarily due to moisture and fat expulsion caused by muscle fiber contraction and protein denaturation during heating. This change is an attribute affected by the temperature and method of cooking, also internally it can be affected by the lengths of the muscle fibers, the shorter the length of the muscle fiber the greater the cooking loss can be, and when longer fibers are present these can help to greater water retention since the sarcomeres are longer, the sarcolemma is also a barrier to the lateral movement of water and the thermal contraction of collagen.

Temperature also plays an important role in affecting this characteristic due to longer cooking times (Bouton, Harris, & Shorthose, 1976), since the weight loss of the meat increases with the cooking temperature, leading to the contraction of the myofibrillar proteins since after 65 °C the fibers shrink causing a greater loss of water, which would occur during cooking in a convection oven in which it would be considerably greater due to the time and temperature to which the meat will be exposed (Ježek et al., 2019).

It was shown that in chicken meat the cooking loss values are high since a high heat treatment time has always been maintained for its cooking for longer (Barbanti & Pasquini, 2005), this causes greater evaporation of water and dripping of water and fat (Küçüközet & Uslu, 2018). Pork which loses moisture, which is why it reflects less cooking loss at a lower temperature 63 °C than at a higher one such as 71 °C (Gaffield et al., 2020).

The temperature at which the meat is maintained before being cooked will also have an impact on the cooking loss, since if it is frozen there will be more losses as the storage time progresses, because the matrix has been damaged by the formation of ice crystals causing greater denaturation of proteins resulting in low water retention capacity, compared to meat kept at a cold temperature, the values show a lower cooking loss (Muela et al., 2010).

*7.4 **pH VALUES***

The pH in meat is a product of the energy metabolism of the animal's muscle. The normal pH of fresh meat typically ranges from 5.5 to 6.2, but can vary by animal and condition, with live animal muscle starting around 7.1 and dropping post-slaughter due to lactic acid accumulation (Young et al., 2004).

After slaughter, glycolysis generates ATP and glycogen is depleted, which generates lactate, which reduces pH levels (Hamoen et al., 2013). Therefore, it can be said that the final pH of the meat will be defined by the amount of glycogen present. When there is a high pH in the muscle, other characteristics can also be affected, such as the color, which may become a little darker, or water retention, since there is protein degradation (Allen et al., 1997).

The pH directly affects the solubility of sarcoplasmic and myofibrillar proteins in meat; this is because there may be a precipitation of these proteins (Zhang et al., 2005). Similarly, the pH will be impacted by the form and duration of storage, since if it is kept frozen it has been proven that it causes an increase in the solubility of sarcoplasmic proteins, even causing a pale color in the meat (Chan et al., 2011).

8. CONCLUSION

Throughout this review, the impact on the characteristics of meat during storage has been pointed out, taking into consideration the type of packaging and temperature of preservation, whether frozen or refrigerated. It was identified that when different preservation methods are used in the meat industry, the union of some of them can achieve stability and lengthen the shelf life of the product during storage, without losing the organoleptic characteristics of the food, i.e., the aid of a thermoformed vacuum package that is stored frozen can maintain similar characteristics or be stable over time compared to a portion stored fresh. However, there is insufficient information on the interaction of freezing rate on the color and stability of meat using different types of packaging. Also, there are several elements to consider in meat science when studying these impacts, since the reactions will be different if one considers the type of meat (pork, chicken, beef), the part of the animal from which the meat portion comes and above all the conditions to which it will be subjected. In conclusion, the preservation of meat without having a major impact on quality during storage continues to be a subject of interest for science, industry and consumer satisfaction.

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CHAPTER II

Impact of Frozen Storage on Cooked Chicken Stored Frozen using Vacuum Packaging

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Abstract:

Worldwide consumption of chicken meat is popular due to its nutritional value and affordability. Despite the rise in popularity, chicken has a disadvantage to other meat proteins such as a much shorter storage life. Therefore, a combination of antimicrobials, antioxidants, or packaging may be considered, but frozen storage maybe the best option for increasing storage life of chicken. However, frozen storage may alter meat quality. Therefore, the objective of this study was to evaluate the effect of frozen storage (-20°C) on the characteristics of cooked chicken breast fillets when stored in vacuum packaging for 120 days. Chicken breasts (N = 25 per sampling day) were analyzed on day 0, 30, 60, 60, 60, 90, and 120 of storage. Instrumental cooked color lightness (L*), redness (a*) and yellowness(b*), cooking loss, Warner Bratzler shear force (WBSF), and texture profile analysis (TPA) was evaluated. Cooked chicken breast fillets were darkest ($p < 0.0001$) after 30 days of frozen storage, and became lighter as storage duration increased. Cooked surface color was more yellow, further from the true red axis, and most vivid ($p < 0.0005$) at the conclusion of the frozen storage on day 120. Cooking loss tended to increase with increased storage duration and was greatest ($p < 0.0074$) on day 90 of the storage duration. Objective texture (WBSF) decreased ($p < 0.0002$) with increasing storage duration. Texture profile analysis (TPA) increased for hardness ($p < 0.0003$) and chewiness ($p < 0.0001$) as storage time increased. Results indicate that frozen storage of chicken breast fillets can preserve meat attributes for a long time, however after 60 days in frozen storage, the physicochemical characteristics become affected, resulting in reduced quality upon cooking.

Keywords: chicken breast; cooked color; freezing; shear force; texture analysis

1. Introduction

Fresh meats are a group of global commodities stored using a variety of packaging systems for retail display in supermarkets [1]. Consumers select meat products based on characteristics such as surface color, price, flavor, and consumer convenience. Selection criteria suggests that the color of meat is also a primary indicator of quality and freshness. Consumers perceive meat to be fresher and of greater quality in contrast to discolored cuts that are commonly considered to be of poor quality [2]. High quality animal protein from the poultry industry has made it the main supplier to meet the growing demand by consumers [1]. Nutritional values, lower prices, and adaptability to consumer menus are the main characteristics that have made poultry meat a more attractive product for consumers. Poultry consumption will continue to lead global meat demand through 2030, representing 52% of all meat consumed [2].

Chicken meat is considered by U.S. consumers to be a healthier food because of its lower percentages of fat compared to other animal sources where macronutrient content (proteins) is limited [3]. Although the nutritional characteristics of poultry products such as chicken breast are very good for consumption. This product faces a grave problem of limitations to storage life as a result of greater water activity causing accelerated deterioration and growth of microorganisms. According to previous studies of fresh poultry meat without any antimicrobial treatments stored in refrigeration (4°C) can only be kept for up to 8 days due to the growth in bacteria from 1.53 log CFU/g at to 4 log CFU/g, which would end its useful life [4,5,6].

To help prolong the shelf life of this product, industries are increasingly developing new methods to maintain quality attributes over time, as the application of preservatives, packaging (vacuum packaging or modified atmosphere packaging), and frozen storage of meat [7]. Oxygen is the cause of many reactions that affect the product throughout the shelf life, so the deprivation of oxygen inside the product is promoted by packaging technologies such as thermoforming packaging [8].

Packaging is used to maintain the properties of the product for as long as possible, preserving the freshness, structure, and quality of the food. Previous research has concluded that the use of vacuum packaging and modified atmosphere in chicken breasts for 12 days at 4 °C reported a significant influence in preserving the flavor, consumer acceptability, and decreased chemical spoilage and microbial growth, compared to untreated packaging [9,10].

Fresh chicken is very susceptible to deterioration, so the commercial industry uses freezing at -18°C during storage as a preservation method that helps extend the shelf life of the product while maintaining quality [11]. During the freezing process, most fresh meat reactions slow down so it is necessary to freeze meat products at colder temperatures (-20°C) and faster speeds to obtain better results.

Freezing temperatures such as -18 °C, reduce the activity of lipid and protein oxidation, especially during the first 3 months of storage, thus preserving protein structures for a longer time. Freezing poultry meat is the most effective way to maintain product quality for long-term storage. [12,13,]. This present study aimed to assess the impact of storing chicken breast fillets for 120 days of frozen storage and the subsequent influence of temperature on the physicochemical parameters of vacuum packaged chicken.

2. Materials and Methods

2.1 Raw materials

Fresh, boneless, skinless chicken breast fillets (N = 125) were purchased from a commercial poultry processing facility (Wayne Farms, Union Springs, AL, USA) and transported on dry ice to the Lambert-Powell Meat Laboratory at Auburn University (Auburn, AL, USA) within 12 hours of slaughter. Breast fillets were stored under refrigerated conditions at 2°C ±

1.5°C (Model LEH0630, Larkin, Stone Mountain, GA, USA) in the absence of light for 24 hours prior to packaging and frozen storage.

2.2 Sample Preparation

Chicken breast fillets were individually packaged using a Variovac Optimus system (Model OL0924, Variovac, Zarrentin am Schaalsee, Germany). Vacuum packages were created using a forming film consisting of a 175-micron containing co-extruded nylon, EVOH, and enhanced polyethylene. Forming film had an oxygen transmission rate of 0.4 cc/m²/24 hours, and a moisture vapor transmission rate of 3.3 g/m² /24 hours. A standardized non-forming film was used composed of a 75-micron coextrusion of nylon, EVOH, and polyolefin plastomer, with an oxygen transmission rate of 1.0 cc/m²/24 hours and a moisture vapor transmission rate of 4.0 g/m²/24 hours.

2.3 Cooked Surface Color

Throughout the 120-day storage period, chicken breasts (n = 25) were evaluated for instrumental cooked surface color using a HunterLab MiniScan EZ colorimeter (Hunter Associates Laboratory Inc., Reston, VA, USA) and a D65 illuminant. Color measurements were recorded every 30 days on days 0, 30, 60, 90, and 120. After cooking, chicken breasts were allowed to cool to room temperature (23°C), three surface color readings were captured for each chicken breast. Prior to instrumental color readings, the colorimeter was standardized using black and white tiles. Chicken breasts were evaluated for surface color lightness (L*), redness (a*), and yellowness (b*). Hue angle (HA) and Chroma (CHMA) were calculated from the L*, a*, and b* values using the equations √a*2 + b*2 and tan-1(b*/a*), respectively. Hue angle represents the color shift from red to yellow, with a greater value indicating a greater shift, while chroma is indicative of a more vivid color and a greater value indicates a more vivid color [14].

2.4 Cook Loss and Warner-Bratzler Shear Force

Chicken breasts (n = 25) were removed from their packaging, and excess moisture blotted dry using a paper towel. Raw weight of each breast was recorded using an analytical balance (PB3002-S, Mettler Toledo, Greifensee, Switzerland). Chicken breasts were cooked in a convection oven (Vulcan, Baltimore, MD, USA) preheated to 177°C until the internal temperature reached 74°C, as monitored by a data-logging thermometer (Therma K-Plus, American Fork, UT, USA). After cooking, breast fillets were cooled to room temperature (23°C) prior to recording cooked weights. The percentage of cooking loss was calculated using the following formula [(weight of raw meat samples−post-cook weight of samples) ÷ weight of raw meat samples ×100].

Tenderness was measured using Warner-Bratzler shear force (WBSF) with a texture analyzer (Model TA-XT Icon, Texture Technologies Corp., New York, NY, USA). A load cell of 294 N and a crosshead speed of 50 mm/min sheared each core once. Six cores of 1.27 cm were removed parallel to the muscle fiber from each steak and each core was sheared perpendicular to the fiber direction [15]. The maximum peak force recorded during analysis was reported as Newton (N) of shear force.

2.5 Texture Profile Analysis

Texture profile analysis (TPA) was performed cooked chicken breast fillets (n = 25). Chicken breasts were cooked using the same procedures as described for WBSF. After cooking breast fillets were cooled to reach room temperature (23°C), 2 samples of 1 x 1 cm^2 were extracted from each chicken breast and analyzed in a two-cycle compression test configured with a 30 kg load cell, compressed to 50% of its height, using a cylindrical probe (TA-25A) at a speed of 5.00 mm/sec. The following parameters were obtained: hardness (kg) is the force exerted in the first compression cycle, springiness is the elastic capacity of a food, cohesiveness is the degree to which the sample cracks or breaks, chewiness is the force exerted in chewing and swallowing the sample, resilience is the ability of the food to recover its position after deformation [16,17].

2.6 Statistical Analysis

Data were analyzed with SAS software (version 9.2; SAS Inst., Cary, NC, USA) using SAS GLIMMIX procedures (version 9.2; SAS Inst., Cary, NC, USA). Least-squares means were calculated for all dependent variables (surface color, cooking loss, Warner-Bratzler shear strength, and texture profile analysis) with storage time as the independent variable. Significant means ($p \leq 0.05$) were separated by pairwise t-tests (PDIFF option).

3. Results and Discussion

3.1 Cooked Surface Color

Surface color of cooked chicken breast fillets were darkest ($p < 0.0001$) after 30 days of storage in frozen (-20°C) temperatures (Table 1). Variation in surface colors of meat after extended storage can be associated with several factors such as pH, moisture loss, ice crystal formation, and even oxidation. Previous studies have reported a decrease in surface lightness (L*) values can occur during frozen storage and these color changes will alter the surface color of cooked meat due to protein denaturation [18,19]. Current results obtained for the values of (a*) indicate significant differences ($p < 0.0001$), where redness was greatest on day 30 and the values began to decrease and but were stable between days 60, 90 and 120. A decrease in redness is presumed to be the result of the oxidative process of the meat due to the passage of oxygen through the packaging film during the days of storage [18,20]. It is plausible that the current decrease of redness in chicken breast fillets was observed due to the appearance of metmyoglobin [21]. These studies agree with our current results since warmer storage temperatures can lead to the oxidation of myoglobin to metmyoglobin. A statistical difference occurred for yellowness values (b*) which increased ($p < 0.0001$) on the cooked surface of the chicken breast fillets as storage duration increased. Increasing yellowness is the result of the Maillard reaction generated by the interaction among amino acids and reducing sugars, causing a more intense surface color throughout the storage days [22].

Calculated relative values for Hue Angle (HA) and Chroma (CHMA) differed statically across the days of storage, with HA values increasing from day 30 to 90 ($p < 0.0005$) whereas, chroma values also increased from day 0 to 120 (Table 2). Chroma showed values that followed a significant increasing pattern ($p < 0.0001$) starting with the lowest value at day 0 and reaching its maximum on day 120. These values are linked to the results of (a*) and (b*) as they change over time in cooked chicken breasts, the color tones can be shifted towards more yellow and saturated tones.

3.2 Cook Loss and Warner-Bratzler Shear Force

Cooking losses of chicken breast fillets increased ($p < 0.0074$) as the storage period increased, reaching the greatest among of loss on day 90 (Table 2). These results agree with previous studies reporting that chicken stored at -18°C can cause a significant increase of more than 21% of moisture loss during cooking after the fourth month of storage causing structural changes in sarcoplasmic proteins decreasing the water holding capacity [13, 23].

In the current study greater cooking loss was observed on day 90 of storage, this moisture loss may be attributed to changes in structural proteins such as actin and myosin as a result of the contraction associated with freezing and thawing. In addition, cooking temperatures above 65°C can intensify protein denaturation process, causing lateral and longitudinal contractions of muscle fibers to occur, and resulting in greater expulsion of water from the matrix and its evaporation during cooking. [24,25].

Shear force values (WBSF) decreased from day 0 to day 60 ($p < 0.0002$), causing an increase in tenderness. A similar trend was observed in previous studies, in which WBSF scores decreased with the aging period [24]. In the current study, the greatest tenderness value was observed on day 90 and may be associated with the greater cooking losses that occurred suggesting that water lost during cooking can result in less tender meat [26,27]. Maximum tenderness was achieved on day 120 of storage, and is in agreement with previous studies concluding that by day 90 of frozen storage, muscle fibers are likely weaker due to proteolytic degradation caused by aging, resulting in increased tenderness of chicken meat attributed to structural breakdown caused by freezing. [7, 24].

In addition, it is important to consider that the storage temperature and the speed at which the chicken is frozen may play an important role in avoiding the formation of ice crystals during the freezing process, weakening the matrix and affecting juiciness and texture. Studies have concluded that the use of low freezing temperatures(-7°C) will cause greater structural damage due as the creation of large ice crystals within the intracellular spaces further accelerating oxidative reactions, and exposing the quality of meat during storage [12].

3.3 Texture Profile Analysis

A significant difference ($p < 0.0003$) was recorded for hardness values during frozen storage of chicken breast fillets (Table 3). From day 0 to day 30, there was a slight increase, followed by a decrease until day 90 due to proteolysis. Results from the current study agree previous studies reporting that during meat aging, endogenous proteases such as calpain and cathepsin can degrade myofibrillar proteins and reduce the structural hardness causing softening during as storage time increases [29].

Surprisingly, on day 120 an increase in objective tenderness was recorded likely due to prolonged storage in frozen conditions caused by protein oxidation and the creation of disulfide bridges. Previous studies have concluded that over time and with excessive oxidation, proteolysis can be inhibited, making it more difficult to break down fibers and soften the meat. Additionally, cooking can contribute to these structural changes because protein contractions and water loss during cooking can result in a firmer meat structure [25,30].

Springiness values showed a significant upward trend ($p < 0.0408$), as did chewiness, which also increased over time ($p < 0.0001$). This increase in values is due to water loss in the meat, increasing its hardness and in turn requiring greater chewing force. Previous studies obtained similar results when observing chicken meatballs stored for 4 months in freezing conditions, where TBARS (Thiobarbituric Acid Reactive Substance) values were high due to protein oxidation, reflecting this increase in chewability values. [31]. Resilience indicated a significant difference ($p < 0.0115$) with a reduction from day 0 to 30 of storage likely caused by the changes of internal structural organization of the proteins.

4. Conclusions

Storage time had an impact on the physicochemical properties of frozen chicken breasts. In the color attributes, redness decreased due to the time since myoglobin was oxidized resulting in decreasing values, while yellowness presented an increase, due to the presence of chemical reactions such as maillard during cooking. Cooking loss and shear force were related to a progressive increase over time, due to protein denaturation and water retention capacity, reflected in the texture profile analysis in which hardness, chewiness, and resilience increased. Frozen storage of chicken breasts is a great way to preserve them for a certain period, but, after 2 months, a decrease in the quality attributes of the chicken breasts begins to become noticeable due to time degradation. Based on the results obtained in this study, it is necessary to carry out future research that considers evaluating different cooking temperatures, other types of packaging and also microbiological tests that allow us to have a complete scenario to understand the different reactions that occur over time.

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TABLES

Table 1. Instrumental surface color of cooked chicken breast during frozen storage.

			DAY				
	0	30	60	90	120	SEM*	p-value
L*[1]	75.27^{a}	72.41^{b}	77.35^{a}	76.66^{a}	75.40^{a}	0.728	<0.0001
a*[2]	5.01^{b}	6.03^{a}	5.51^{ab}	5.34^{ab}	5.47^{ab}	0.244	<0.0001
b*[3]	24.32^{c}	26.37^{bc}	26.96^{b}	26.52^{b}	29.14^{a}	0.603	<0.0001
HA[4]	78.43^{ab}	77.22^{b}	78.49^{ab}	78.67^{a}	79.46^{a}	0.376	0.0005
CHMA[5]	24.85^{c}	27.06^{bc}	27.53^{ab}	27.08^{b}	29.66^{a}	0.626	<0.0001

L*[1] – Lightness (0-100, largest values indicate lighter color). a*[2] – Redness (largest values indicate redder color). b*[3] – Yellowness (largest values indicate a more yellow color). HA[4] - Hue Angle (largest values indicate a greater shift from red to yellow). CHMA[5] – Chroma (largest values indicate a more vivid color). [a-c] Mean values within a row lacking common superscripts are significantly different ($p < 0.05$). *SEM – standard error of the mean.

Table 2. Cooking loss and shear force values of cooked chicken breast during frozen storage.

	DAY						
	0	30	60	90	120	SEM*	p-value
Cooking Loss (%)[1]	27.63^{b}	27.61^{b}	28.95^{ab}	30.57^{a}	29.53^{ab}	0.832	< 0.0074
WBSF (N)[2]	14.46^{a}	11.01^{bc}	10.50^{bc}	13.23^{ab}	9.55^{c}	0.836	0.0002

[1]Cooking Loss was calculated using the following formula [(weight of raw meat samples−post-cook weight of samples) ÷weight of raw meat samples ×100]. WBSF (N)[2] Warner-Bratzler shear force was reported as a newton. $^{a-c}$ Mean values within a row lacking common superscripts are significantly different ($p < 0.05$). *SEM – standard error of the mean.

Table 3. Texture profile analysis values of cooked chicken breast during frozen storage.

	DAY						
	0	30	60	90	120	SEM*	p-value
Hardness (kg)[1]	8.06^{b}	8.53^{b}	7.84^{b}	7.83^{b}	10.68^{a}	0.576	0.0003
Springiness[2]	0.50^{b}	0.53^{ab}	0.55^{ab}	0.53^{ab}	0.56^{ab}	0.019	0.0408
Cohesiveness[3]	0.40^{a}	0.42^{a}	0.42^{a}	0.43^{a}	0.44^{a}	0.017	0.5692
Chewiness[4]	1.66^{b}	1.91^{b}	1.85^{b}	1.77^{b}	2.73^{a}	0.185	<0.0001
Resilience[5]	0.18^{ab}	0.17^{b}	0.16^{b}	0.20^{a}	0.17^{ab}	0.010	0.0115

[1]Hardness (kg) force of the first compression. [2]Springiness ratio of the force exerted during the first compression to the second compression. [3]Cohesiveness strength of the area during the second compression to the first compression. [4]Chewiness = hardness x cohesiveness (Area 2/Area 1). [5]Resilience ratio of the time duration of force input during the first compression. $^{a\text{-}b}$ Mean values within a row lacking common superscripts are significantly different ($p < 0.05$). * SEM* standard error of the mean.

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CHAPTER III

Impact on The Quality of Fresh and Frozen Storage Pork Chops

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Abstract:

Pork remains one of the main sources of protein consumed worldwide, reflected in its constant growth in terms of production and economic importance. As demand for more affordable protein increases, the meat industry faces a major challenge in meeting customer needs by offering a quality product. Therefore, this study aimed to analyze the impact of storage conditions (fresh vs. frozen) on the quality characteristics of pork chops throughout a 60 days storage period. Treatment 1 (Fresh chops) were stored at 4.4°C and then cooked, while treatment 2 (frozen chops) were stored at −20°C and thawed for 24 h before cooking. Samples were analyzed every 10 days during the storage period from day 0 to 60, to obtain cooking loss, Warner Bratzler Shear Force (WBSF), texture profile, internal cooked color, and pH values. Cooking loss showed an increase ($p < 0.0001$) with the passage of storage time, contrary to what was observed in the shear force that decreased with time ($p < 0.0001$). In addition, treatment 2 was the one with the highest shear force value ($p < 0.0001$). The texture profile showed that hardness and chewiness had a decreasing pattern during the days of storage ($p < 0.0001$), and treatment 2 was the one that presented the highest values ($p < 0.0001$) during the first 30 days. The internal cooked color values had differences ($p < 0.0001$) for L * showed an increase at the end of the days, a * was reduced moving away from red and b * ended with an increase in its values, over time in both treatments the transition from red to brown was marked ($p < 0.0001$), which was reflected in the impact of the forms of myoglobin ($p < 0.0001$) since metmyoglobin increased while deoxymyoglobin decreased. Finally, the pH was affected ($p < 0.0001$) decreasing its values until the last day of storage. The storage method influenced the quality of the pork: Treatment 1 maintained a more consistent color, while treatment 2 preserved tenderness but experienced greater oxidative changes and greater firmness at later stages.

Keywords: Cooked color, cooking loss, pork chop, shear force, texture analysis

1. Introduction

Pork has been a fundamental food for mankind for thousands of years. Throughout history, it has been observed that as agricultural production increased, so did the consumption of pork [1]. This type of meat is one of the most widely consumed worldwide thanks to the quality of protein it offers and essential micronutrients [2]. Approximately 37% of the meat consumed in the world is pork, equivalent to 110 million tons annually [3]. In the United States, with a population of 275 million people, the domestic market for pork is considerable. Per capita pork consumption is 31.6 kg, a figure that has remained constant since 1955. The U.S. population is projected to increase by about 1% per year. Although it is difficult to forecast consumption trends with certainty, pork demand is expected to grow by about 1.5% per year [4].

Pork quality includes fundamental characteristics that determine its suitability for processing and storage, as well as for sale to the public. Among the main attributes are water retention capacity, color, fat quantity and composition, stability against oxidation, uniformity, as well as flavor, tenderness and juiciness of the cooked meat, which are evaluated by means of a subjective score [5-6].

One of the key objectives in the meat industry is producing safe, high-quality, and nutritious meat products efficiently and profitably, while increasingly focusing on environmental sustainability, ethical animal welfare, and meeting growing global consumer demand. [7]. To guarantee the consumption of safe and wholesome meat products, it is necessary to employ appropriate processing and preservation methods that ensure the microbiological safety, quantity, and nutritional value of meat products, thus prolonging their shelf life [8].

Currently, vacuum packaging is the most commonly employed method to extend the shelf life of fresh meat, as it helps preserve refrigerated meats by creating a low-oxygen environment inside the package [9]. This preserving effect of vacuum packaging is due to the reduction of oxygen, which significantly inhibits or even eliminates microorganisms that could cause meat spoilage. The vacuum packaging process involves placing large pieces in flexible plastic bags, which prevents moisture loss from the meat samples [10].

Freezing is another common procedure for extending the shelf life of meat, as it significantly minimizes microbial growth and biochemical reactions responsible for spoilage [11]. This process can extend the usefulness of pork for several months, allowing producers to store large quantities without compromising its quality. This technique is especially useful in the global distribution of meat, as it facilitates the storage and transportation of cardoon meat over long distances without spoilage [12]. In addition, the combination of freezing and vacuum packaging further enhances protection against oxidation and moisture loss, ensuring that the product remains fresh and attractive to consumers [13].

Given the crucial role that preservation methods play in extending the shelf life of pork while maintaining its quality, the aimed of this study were to evaluate the effects of refrigerated and frozen storage for 60 days on the quality characteristics of pork chops.

2. Materials and Methods

2.1 Raw materials

Boneless pork loins (N = 30) were obtained from the Lambert-Powell Meat Laboratory at Auburn University. Paired loins were fabricated by hand from pork carcasses 48 hours after slaughter and identified. Loins were stored refrigerated at 2°C (Model LEH0630, Larkin, Stone Mountain, GA, USA). Using a band saw (Model 334, Biro Manufacturing Co., Marblehead, OH, USA) loins were cut into individual chops (n = 420) 2.54 cm thick, individually identified and packaged by treatment.

2.2 Packaging Treatments

Fabricated chops were identified, and each chop was vacuum packed using 20.32 cm × 25.40 cm pouches (3 mil, nylon/polyethylene, O_2 transmission rate = 7.5cc/100 in^2/24h/atm, Prime Source, St Louis, MO, USA). Packaged chops from Treatment 1 were stored at refrigerated temperature (4.4°C) in a refrigeration unit (Model LEH0630, Larkin, Stone Mountain, GA, USA). Treatment 2 were stored at freezing temperature (-20°C) in a blast freezer (Model LHE6950, Larkin, Stone Mountain, GA, USA). For the laboratory analysis, 60 chops were analyzed each day of the study (0,10,20,30,40,50,60). Packaged chops within each treatment were assigned for the analysis of cook loss, Warner-Bratzler Shear Force (WBSF) Texture Profile Analysis (TPA), internal cooked color and postmortem pH.

2.3 Cook Loss and Warner-Bratzler Shear Force

Prior to analysis, chops from treatment 2 were thawed for 24 hours 4.4°C in a glass door (Model, Manufacturer, City, State, Country). Pork chops for both treatments (n = 15/treatment) were removed, and excess moisture was blotted with a paper towel. Raw weight of each chop was recorded with an analytical balance (Model PB3002/S, Mettler Toledo, Columbus, OH, USA). Chops were cooked in a convection oven (Model VC3ED, Vulcan, Baltimore, MD, USA) preheated to 177°C until the internal temperature reached 70°C and monitored by a data logging thermometer (Therma K-Plus, American Fork, UT, USA).

After cooking, chops were cooled to room temperature (23°C) and cooked weights of each chop were recorded using the analytic balance. Percentage of cooking loss was calculated using the following formula [(raw chop weight - cooked chop weight) ÷ raw chop weight ×100].

Objective tenderness was measured on each chop using Warner-Bratzler shear force (WBSF). Six 1.27 cm cores were extracted from each chop parallel to the muscle fiber and sheared perpendicular to the direction of the fiber [14]. A texture analyzer (Model TA-XT Icon, Texture Technologies Corp., New York, NY, USA) was used with a load cell of 294 N and a crosshead speed of 50 mm/min sheared each core once.

2.4 Texture Profile Analysis

For the TPA analysis, the remaining 15 chops from each treatment were used. A 1 × 1 cm^2 sample was extracted from each chop and was analyzed using a cylindrical probe (TA-25A) attached to a texture analyzer (Model, Manufacturer, City, State, Country), a two-cycle compression test, with a 30 kg load cell compressed to 50% at a speed of 5.00 mm/sec. TPA analysis recorded the parameters of hardness (kg) as the force exerted during the first cycle, elasticity which is the elastic capacity of a food, cohesiveness the point at which the sample cracks, chewability as the force exerted when chewing, and resilience represented as the ability of the food to recover its position after deformation [15,16].

2.5 Internal Cooked Color

Internal cooked color was evaluated (n = 15/treatment) using a HunterLab MiniScan EZ colorimeter (Hunter Associates Laboratory Inc., Reston, VA, USA) and D65 illuminant. Prior to color measurement the colorimeter was standardized using black and white tiles, and 3 readings of the internal color of each chop were recorded. Cooked color tests were performed every 10 days from day 0 to day 60 after cooking chops. Pork chops were cooked in a convection oven at 177°C until the internal temperature reached 70°C. Chops cooled to room temperature (23°C) then sliced through the geometric center. Lightness (L*), redness (a*) and yellowness (b*) were evaluated. The hue angle (HA) represents the shift from the true red axis and chroma (CHMA) is an indication that the color is more vivid. Color measurements were calculated from the L*, a* and b* values using the equations of √a*2 + b*2 and tan-1(b*/a*), respectively. A reflectance ratio of 630 nm:580 nm was used for recording the changes internal of pork chops from red to brown (RTB).

2.6 Postmortem pH

Postmortem pH was measured during each day of analysis (0,10,20,30,40,50,60). Briefly, 2 g of each chop cut by hand and placed into a plastic centrifuge tube with 20 ml of deionized water then homogenized for 45 s using a homogenizer (Kinematica CH-6010, Brinkmann Instruments, Inc., Westbury, NY, USA). Prior to pH readings, the pH meter (Model-HI99163, Hanna Instruments, Woonsocket, RI, USA) was calibrated (pH 4.0 and pH 7.0) using 2-point standard samples (Thermo FisherScientific, Chelmsford, MA, USA).

2.7 Statistical Analysis

Data were analyzed with SAS software (version 9.2; SAS Inst., Cary, NC, USA) using SAS GLIMMIX procedures (version 9.2; SAS Inst., Cary, NC, USA). Least-squares means were calculated for all dependent variables (internal cooked color, cooking loss, Warner-Bratzler shear force, texture profile analysis and pH) with storage time and treatment as the independent variables. Significant means ($p < 0.05$) were separated by pairwise t-tests (PDIFF option).

3. Results and Discussion

3.1 Cook Loss and Warner-Bratzler Shear Force

There was no interaction ($p = 0.5807$) of treatment and storage day for the pork loin chops. However, an increase in cooking loss occurred as storage duration increased ($p < 0.0001$) for the pork chops (Table 1). Cooking losses were greatest after day 20 ($p < 0.0001$) of storage regardless of packaging treatment (Table 1). This change in cooking loss is likely due to altered structural changes within the muscle that occur during storage specifically, causing water to be lost easily. Previous studies concluded that the space between myofibrils is reduced after extended storage and following cooking making it difficult for the muscle to retain water [19].

Additionally, a main effect for objective tenderness occurred throughout 60 days of storage (Table 1). WBSF data were recorded in the shear force that the highest value was obtained on day 0 (31.09) and then a significant decrease was recorded, as the days of storage increased on reaching day 60 the lowest value was obtained (20.56 N), these results agree with another study that shows a progressive decrease in WBSF values over the study time, produced by structural alterations and changes in the myofibrillar proteins in the muscle tissue causing them to weaken, also taking into account that another factor involved in the tenderness of meat is enzymatic degradation [20].

Regarding the WBSF values of each treatment, (Table 2). Showed a significant difference in WBSF ($p < 0.0001$), treatment 2 (frozen) showed the highest value (26.48) and treatment 1 (fresh) with the lowest value (22.82). This indicates that due to having been kept frozen for a time and then thawed prior to cooking, a study mentions that structural changes occur creating ice crystals that caused greater hardness in the meat, due to a greater quantity of fibers per area attributing more values to the cutting force [21,22]. Meanwhile, the cooking loss values for each treatment did not show any statistical difference during the study, which is consistent with previous studies that mention that cooking loss is usually lower when the thawing process is refrigerated for 24 hours [23].

3.2 Texture Profile Analysis

An interaction of packaging treatment × storage day was recorded for texture profile analysis (Table 3). Pork loin chops were hardest ($p < 0.0001$) on day 0 and the softest on day 30 when stored at -20°C. It is likely that the differences in hardness were greater for loin chops stored frozen (-20°C) because of the variation in meat traits that occurs after freezing and thawing prior to cooking. It is likely that the formation of ice crystals intracellularly caused disorganization in the meat fiber matrix, exposing the myofibrillar proteins, causing greater water loss resulting in greater hardness [21]. Additionally, increasing storage duration allowed hardness values to decline regardless of storage temperature and likely caused by the proteolysis that occurs over time. Changes in proteolysis over timer can alter the hardness values become increasingly lower with increasing storage time, these results agree with previous studies where increasing storage time results in a lower hardness and decrease in the cutting force since the activity of calpain can decrease [24].

Chewiness showed an interaction of treatments x storage days (Table 3). Treatment 2 showed higher values than Treatment 1. The highest value was observed on day 0 ($p < 0.0001$), and the lowest value was observed on day 40 for both treatments. Chewiness values decreased over time, showing a downward trend in both treatments with a slight recovery on day 60.

Pork loin chops stored at -20°C exhibit higher chewiness values because freezing and thawing can cause greater release of intracellular water and create a firm structure, resulting in greater resistance to chewing [21]. The reduction in these values during the storage period is due to the disintegration of the protein structure, as the myofibrils break down during storage, losing structural integrity [20]

Resilience values (Table 3) showed an interaction between treatment and storage days ($p < 0.0001$). Both treatments started with equal values on day 0. Pork chops from Treatment 1 showed less resilience compared to chops from Treatment 2; however, throughout the storage period, both treatments showed a clear decrease by day 60. In general, during prolonged storage, structural changes such as myofibrillar fragmentation occur, leading to a reduction in meat resilience values over time [19].

Springiness changed significantly over storage time ($p < 0.0001$), Figure 1 shows that from day 0 to 10 there was an increase in the springiness value, but a reduction in the values was observed until day 30 and then it increased until stabilizing from day 50 onwards. Overall, the results agree with other studies where springiness is affected by storage time and its central tendency is to decrease [25].

Springiness differed between treatments ($p < 0.0001$) was observed in Figure 2. Pork loin chops stored at -20°C showed higher values because they were subjected to freezing during storage, which allowed for the retention of certain structural characteristics that preserve meat integrity. Previous studies report that enzymatic activity decreases during frozen storage (-20°C) and continues upon thawing, maintaining matrix integrity and thus achieving these elasticity values over the extended storage period [22,23].

Cohesiveness was not affected ($p = 0.6711$) by the treatments, nevertheless, storage time did show a significant difference ($p < 0.0001$). Figure 3 shows a decrease in values from day 0 to 20, followed by a recovery on day 30. Subsequently, it remained relatively stable; however, after day 30, the trend was downward, reaching a low point by day 60. The factors responsible for this change in cohesion are related to the changes in the muscle matrix mentioned above. A previous study highlighted that water loss increases over time, and that protein interaction and degradation can decrease meat cohesion [19].

3.3 Internal Cooked Color

An interaction for treatment × storage day occurred on pork loin chops for cooked color (Table 4). Internal cooked color of pork chops was darkest ($p < 0.0001$) on day 20 when stored at -20°C and lightest ($p < 0.0001$) on day 50 in -20°C temperatures. Pork loin chops contain less myoglobin compared to meat proteins like beef and lamb. However, it is likely that the frozen storage resulted in greater moisture losses during thawing and prior to cooking causing quantity of the water-soluble color protein myoglobin to decrease. A previous study showed that freeze-thaw cycles increase lightness values [26]. A brighter cooked color was attributed to greater water loss from the meat matrix, subsequently caused by greater denaturation of the muscle protein during the cooking process [21].

Redness (a*) was also affected by the treatments and storage time. The internal color of the chops was redder ($p < 0.0001$) on day 0 in chops kept at refrigeration temperature (4°C) and less red on day 30 ($p < 0.0001$) at the same temperature. Both treatments showed a trend of decreasing redness values over time. Other studies also indicate that myoglobin denaturation during the frozen storage period caused a decrease in redness values [25,26].

The internal cooked color yellowness values of the pork chops were higher ($p < 0.0001$) on day 60 when stored at -20 °C. Although the chops stored at 4 °C remained constant, both showed increases in their values over time, attributing this to the fact that lipid oxidation leads to the formation of hydroperoxides during storage, which induces more noticeable changes towards the yellowness of the meat [24].

Table 5 shows the interaction between treatment and storage days. For hue angle (HA) values, chops stored at -20 °C showed the highest values on day 40 ($p < 0.0001$), and the lowest value was on day 10 ($p < 0.0001$) for those stored at 4°C. However, the trend over time for both treatments was increasing, causing the color to change from reddish to brown tones. since myoglobin oxidation contributes to the increase in hue values, resulting in a reddish-brown color [27].

The Chroma (CHMA) values of the chops stored frozen at -20 °C showed the highest color saturation on day 60 ($p < 0.0001$), and the lowest on day 10 ($p < 0.0001$) in those stored at

4 °C. Although both treatments remained constant, treatment 2, by keeping the chops at -20 °C, allowed them to preserve color saturation. The internal color of the cooked pork chops exhibited a greater transition from red to brown (RTB) in those stored at 4°C on day 60, and in both treatments the values decreased as the storage time increased, which meant the color change from red to brown.

3.4 pH Values

pH values (Figure 4) showed a significant difference ($p < 0.0001$), throughout the days of storage, they had a behavior with a tendency to decrease over time, which from day 0 was more than 5.7 and the last day was almost 5.5, this reduction is due to the aforementioned that the denaturation of proteins occurs causing the release of hydrogen ions, also a concentration of solutes, marking a decrease in pH values [21]. These results agree with other studies where it is indicated that the pH has a tendency to decrease either in fresh or frozen storage [24,27].

4. Conclusions

Results of the current study conclude that the type of storage temperature of pork loin chops in vacuum packaging can change the quality characteristics of cooked pork chops. Storage temperature treatments had a significant effect on shear force values, texture profile analysis, cooked color, and pH. Overall, these results provide greater insight into how storage conditions affect the key characteristics of pork loin chops. These results pave the way for future research that evaluates product quality within a shorter storage window, providing data from a scenario more focused on biochemical changes and identifying the most efficient preservation strategies.

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TABLES

Table 1. Main effect of storage day on cook loss and warner-bratzler shear force of pork loin chops during storage.

	DAY								
	0	**10**	**20**	**30**	**40**	**50**	**60**	**SEM***	**p Value**
Cook Loss (%)[1]	28.74^{bc}	26.40^{c}	33.01^{a}	29.02^{b}	29.20^{b}	30.71^{ab}	29.25^{b}	0.901	<0.0001
WBSF(N)[2]	31.09^{a}	26.77^{b}	24.85^{bc}	23.76^{cd}	22.23^{de}	23.24^{cd}	20.56^{e}	0.705	<0.0001

[1]Cooking Loss was calculated using the following [(raw chop weight - cooked chop weight) ÷ raw chop weight ×100]. [2]WBSF (N) Warner-Bratzler shear force was reported as a newton. $^{a-e}$Mean values within a row lacking common superscripts differ ($p < 0.05$). *SEM – standard error of the mean.

Table 2. Main effect of packaging treatment for cook loss and warner-bratzler shear force values of pork loin chops.

	Treatments			
	TRT 1	**TRT 2**	**SEM***	**p Value**
Cook Loss (%)[1]	29.58	29.38	0.481	0.775
WBSF(N)[2]	22.82[b]	26.48[a]	0.452	<0.0001

[1]Cooking Loss was calculated using the following formula [(raw chop weight - cooked chop weight) ÷ raw chop weight ×100]. WBSF (N)[2] Warner-Bratzler shear force was reported as a newton. [a-b]Mean values within a row lacking common superscripts are significantly different ($p < 0.05$). TRT 1. Fresh pork chop stored at (4.4°C). TRT 2. Pork chop was kept frozen (-20°C) and was defrosted 24 hours before cooking. *SEM – standard error of the mean.

Table 3. Texture profile analysis values of cooked pork chops during storage of both treatments.

	0	10	20	30	40	50	60	SEM*	p Value
Hardness (kg)[1]									
TRT 1	5.96^{cd}	7.07^{bc}	5.93^{cd}	4.36^{ef}	4.09^{ef}	4.34^{ef}	7.64^{ab}	0.490	<0.0001
TRT 2	8.67^{a}	6.99^{bc}	6.25^{cd}	6.82^{bc}	3.50^{ef}	5.37^{de}	6.63^{bcd}	0.490	<0.0001
Chewiness[2]									
TRT 1	1.96^{cde}	2.41^{ab}	1.66^{def}	1.17^{fg}	0.98^{g}	0.99^{g}	2.17^{bcd}	0.199	<0.0001
TRT 2	3.32^{a}	2.58^{b}	1.57^{ef}	1.96^{cde}	0.90^{g}	1.22^{fg}	1.80^{de}	0.199	<0.0001
Resilience[3]									
TRT 1	0.25^{a}	0.21^{cde}	0.21^{cde}	0.22^{bcd}	0.20^{de}	0.21^{cde}	0.19^{ef}	0.007	<0.0001
TRT 2	0.25^{a}	0.24^{ab}	0.18^{ef}	0.23^{abc}	0.22^{bcd}	0.20^{ef}	0.19^{f}	0.007	<0.0001

[1]Hardness (kg) force of the first compression. [2]Chewiness = hardness x cohesiveness (Area 2/Area 1). [3]Resilience ratio of the time duration of force input during the first compression.

[a-g] Mean values within a row lacking common superscripts are significantly different ($p < 0.05$). TRT 1. Fresh pork chop stored at (-4.4°C). TRT 2. Pork chop was kept frozen (-20°C) and was defrosted 24 hours before cooking. *SEM – standard error of the mean.

Table 4. Interaction between TRT x Storage of Instrumental Internal Cooked Color (L*, a*, b*).

	0	10	20	30	40	50	60	SEM*	p Value
				Lightness (L*)[1]					
TRT 1	75.09^{abcd}	74.64^{bcd}	75.04^{bcd}	75.16^{abcd}	75.41^{abcd}	75.89^{abc}	75.21^{abcd}	0.562	<0.0001
TRT 2	76.19^{ab}	73.99^{d}	71.37^{e}	74.94^{bcd}	76.15^{ab}	76.63^{a}	74.54^{cd}	0.562	<0.0001
				Redness (a*)[2]					
TRT 1	4.07^{a}	3.91^{ab}	3.73^{abc}	2.83^{e}	3.44^{bcd}	3.31^{cde}	3.15^{de}	0.199	<0.0001
TRT 2	3.56^{abcd}	3.59^{abcd}	4.09^{a}	3.58^{abcd}	2.87^{e}	3.31^{cde}	3.94^{ab}	0.199	<0.0001
				Yellowness (b*)[3]					
TRT 1	15.51^{cde}	13.67^{g}	14.81^{f}	14.96^{ef}	15.07^{ef}	15.65^{cd}	15.08^{def}	0.208	<0.0001
TRT 2	15.12^{def}	14.74^{f}	15.46^{cde}	15.81^{bc}	15.52^{cde}	16.31^{ab}	16.66^{a}	0.208	<0.0001

L*[1] – Lightness. a*[2] – Redness. b*[3] – Yellowness. $^{a-g}$ Mean values within a row lacking common superscripts are significantly different ($p < 0.05$). TRT 1. Fresh pork chop stored at (-4.4°C). TRT 2. Pork chop was kept frozen (-20°C) and was defrosted 24 hours before cooking. *SEM – standard error of the mean.

Table 5. Interaction between packaging treatment × storage day for instrument cooked color of pork loin chops.

	0	10	20	30	40	50	60	SEM*	p Value
Hue Angle (HA)[1]									
TRT 1	75.48^{efg}	74.17^{g}	75.86^{def}	79.29^{a}	77.15^{bcd}	78.09^{abc}	78.24^{abc}	0.548	<0.0001
TRT 2	76.77^{cde}	76.34^{def}	75.23^{fg}	77.36^{bcd}	79.61^{a}	78.51^{ab}	76.94^{cde}	0.548	<0.0001
Chroma (CHRMA)[2]									
TRT 1	16.05^{bcd}	14.24^{f}	15.28^{e}	15.23^{e}	15.46^{de}	16.01^{bcd}	15.41^{de}	0.241	<0.0001
TRT 2	15.56^{cde}	15.18^{e}	16.03^{bcd}	16.22^{bc}	15.79^{cde}	16.63^{ab}	17.16^{a}	0.241	<0.0001
Red to Brown (RTB)[3]									
TRT 1	1.47^{a}	1.33^{bcd}	1.33^{bcd}	1.28^{d}	1.41^{abc}	1.35^{bcd}	1.31^{cd}	0.035	<0.0001
TRT 2	1.42^{ab}	1.38^{abcd}	1.33^{bcd}	1.34^{bcd}	1.28^{d}	1.32^{cd}	1.41^{abc}	0.035	<0.0001

[1]HA - Hue Angle. [2]CHMA[2] – Chroma. [3]RTB – Red to Brown. [a-g]Mean values within a row lacking common superscripts are significantly different ($p < 0.05$). TRT 1. Fresh pork chop stored at (-4.4°C). TRT 2. Pork chop was kept frozen (-20°C) and was defrosted 24 hours before cooking. *SEM – standard error of the mean.

FIGURES

Figure 1 Springiness values of cooked pork chops during storage.

[1]Springiness ratio of the force exerted during the first compression to the second compression. a-d Mean values within a row lacking common superscripts are significantly different ($p < 0.05$).

*SEM – standard error of the mean.

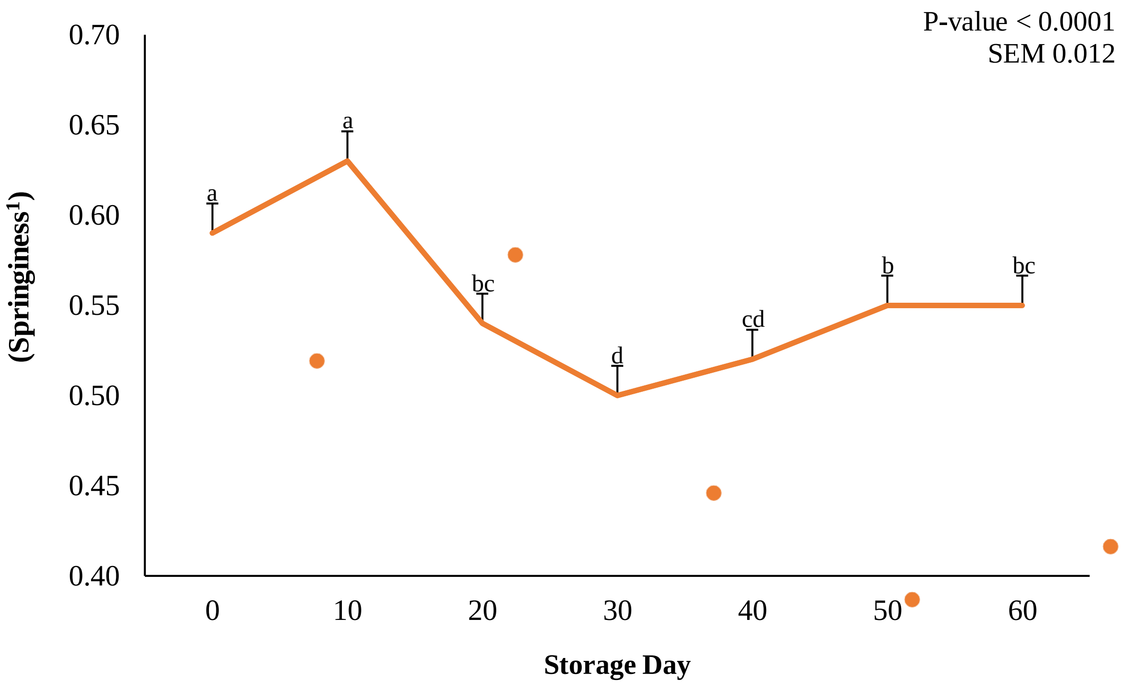

Figure 2. Springiness values of cooked pork chops from each treatment.

[1]Springiness ratio of the force exerted during the first compression to the second compression. [a-b] Mean values with different superscripts differ significantly ($p < 0.05$). *SEM – standard error of the mean.

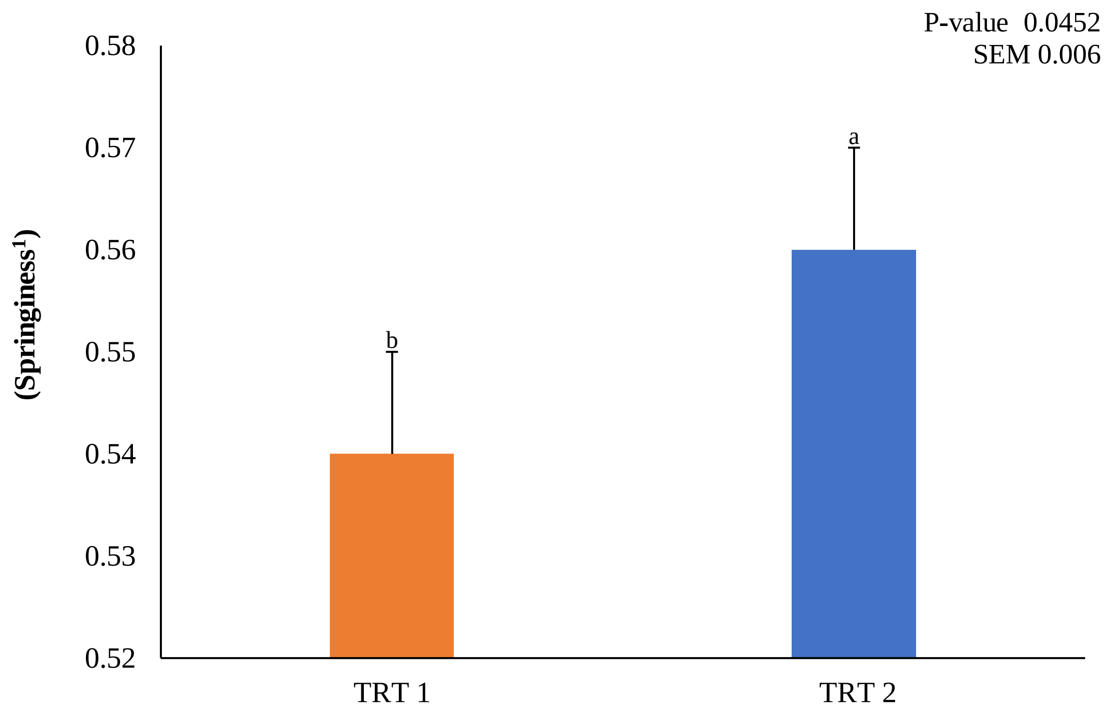

Figure 3. Cohesiveness values of cooked pork chops during storage.

[a-d] Mean values with different superscripts differ significantly ($p < 0.05$). *SEM – standard error of the mean.

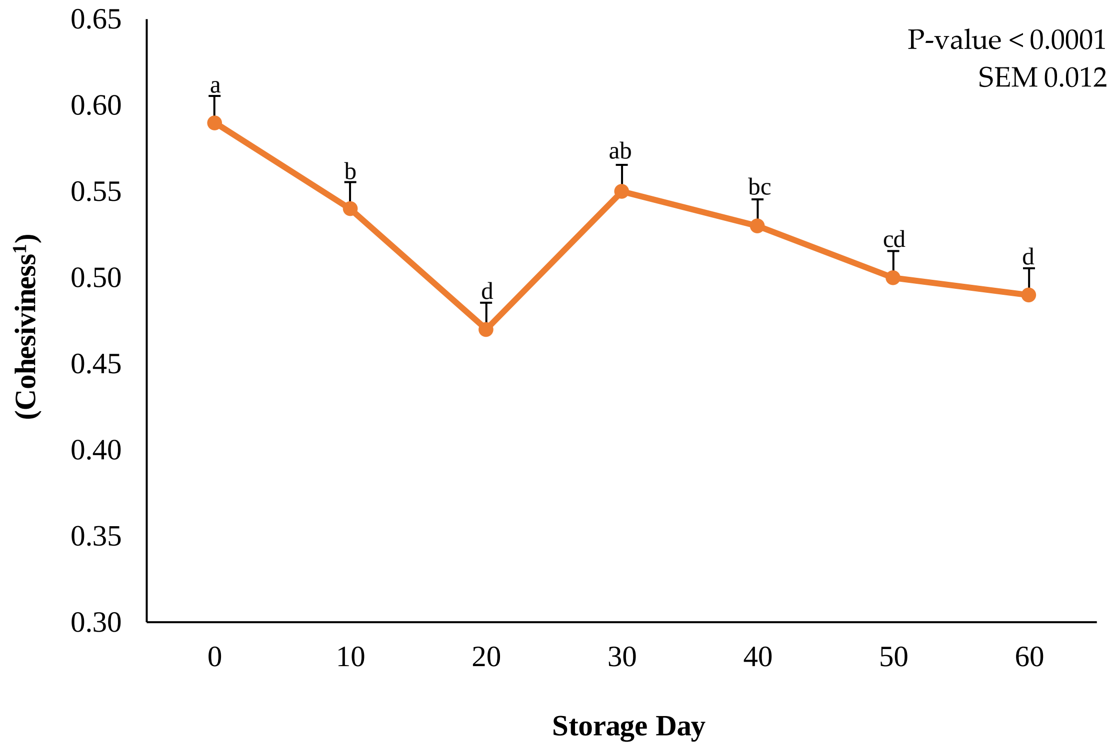

Figure 4. Effect of storage time on the pH values of cooked pork chops

[a-d] Mean values with different superscripts differ significantly ($p < 0.05$). *SEM – standard error of the mean