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Review Article

Effects of cold storage on meat quality, oxidative stability, and organic antioxidants: A comprehensive overview

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Abstract

Food lipids are an important source of essential fatty acids and contribute to the flavor of food. During processing, heating, cooking, and storage, lipids break down into volatile components and interact with other components, leading to off-flavors. Unsaturated fatty acids can also oxidize to produce aromatic volatiles such as alcohols, ketones, and aldehydes. There are many methods to preserve meat to save it from meat deterioration. Some meat preservatives are also being used to preserve meat but cold storage is one of the storage methods of meat and nowadays is widely being used in the meat industry for storage of meat. The issue is that this technique can decrease the quality parameter of meat by several reactions that take place during storage. Cold storage of meat can affect the meat in different ways (e.g., by affecting the color, p_H, and oxidation processes) which are also explained in this review. Furthermore, this review explains the effects of cold storage on meat quality while also explaining lipid and protein oxidation along with the factors that are causing lipolysis and proteolysis. Lastly, this review also brings light to consumer preference regarding aged meat which is being preserved by using cold storage techniques.

Introduction

Lipids are essential components that affect food flavor and odor by providing energy and structure (Das et al., 2022; Shahidi & Hossain, 2022). Fats can create their flavors and aromas, act as precursors for flavor molecules, or modify the flavors and aromas of other substances (Diez-Simon et al., 2019). The fat content in food determines flavor preferences and rejections by consumers (Hamilton et al., 2000). The process of oxidation of lipids produces volatile compounds that are crucial for the reproduction of flavors (Azad et al., 2021 and 2022; Fu et al., 2022). Volatile compounds are primarily responsible for the aroma and taste of various food products (Akter et al., 2022; Ali et al., 2022; Ayseli & Ayseli, 2016). Recent research has significantly contributed to the understanding of various aspects of meat quality and animal production, including the use of probiotics (Mia et al., 2024), freezing impacts on organ meat (Mahmud et al., 2024; Sharker et al., 2024), addition of antioxidants (Shohiduzjaman et al., 2024) and meat adulteration detection using NIRS and chemometric analysis (Hashem et al., 2024a). Furthermore, studies have explored innovative technologies like machine learning and AI for improving livestock management and meat safety evaluation (Mia et al., 2025; Sharker et al., 2024). Additional reviews have addressed heat stress (Mia et al., 2023), poultry processing (Hashem et al., 2024b), and cutting-edge technology meat quality and meat preservation techniques (Alam et al., 2024; Nurul et al., 2024). These collective efforts underscore the growing reliance on interdisciplinary approaches for enhancing meat quality, food safety, and animal productivity.

Raw foods like meat tend to be odorless, while processing adds strong flavor and aroma (Diez-Simon et al., 2019). According to Rota & Schieberle, (2005), cis-1,5-octadien-3-one (as in geranium), 4-ethyloctanoic acid (as in lamb), trans-4,5-epoxy-2-du-du (iron), and trans-2,9-the 4 decades (deep-fried), all contribute to the smell of raw and cooked lamb. Additionally, cooking enhances the flavor by producing aromatic compounds such as 2-acetyl-1-pyrroline, 4-hydroxy-2, 5-dimethyl-3(2H)-furanone, and 2-aminoacetophenone. They also stated that the use of flavor enhancement (FD) further increases the intensity of these compounds.

The meat industry bears the responsibility of supplying high-quality meat to consumers worldwide (Żurek & Rudy, 2024). However, delivering meat over long distances can pose challenges to ensuring its reliability and standards (Markovic et al., 2020). To deal with this issue, the industry has widely adopted the use of freezing and cold storage systems, which have been verified to be effective in maintaining meat quality during extended storage periods (Nastasijević et al., 2017). Cold storage is a crucial technique for preserving food quality and minimizing quality loss over time (Kitinoja, 2013).

The use of frozen preservatives in meat may cause cell fragmentation and injury to muscle fibers due to the formation of ice crystals so they can't be used widely in the meat industry (El-Sayed, 2023; Khatun et al., 2022). Ice storage affects both the physical and chemical properties of meat (Lu et al., 2022). Frozen techniques affect the meat's appearance, spoilage, protein aggregation, denaturation, oxidation, color change, lipolysis, and lipid oxidation (Lu et al., 2022). Meat contains substantial amounts of oxidation catalysts such as iron and myoglobin, as well as lipids (Mostafa et al., 2025; Wang et al., 2018). These components interact with each other and are susceptible to oxidative alterations during cold storage (Wang et al., 2018).

This review highlights the impact of cold storage on the overall quality of meat. It also highlights factors affecting lipid and protein oxidation by elaborating on the reaction that takes place during

the storage of meat. The main purpose of this review is to bring light to the effects of curing meat by cold chain management on the physical and chemical properties of meat.

Factors affecting meat quality during cold storage

Here are some key points that affect the storage of meat shown in figure1. and further explained below

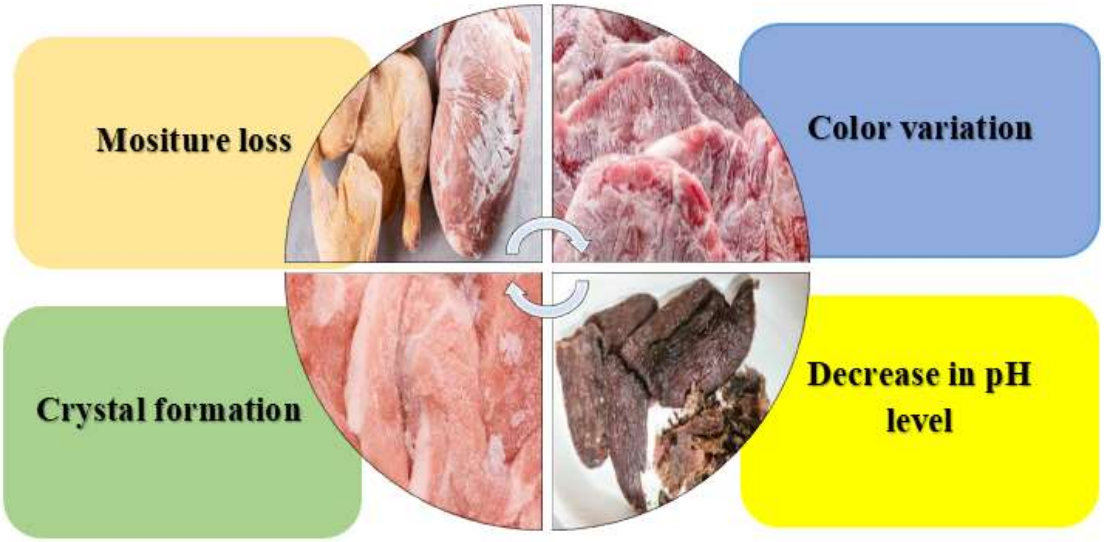

Figure 1. Factors affecting meat quality during cold storage.

Moisture Loss

Cold weather can alter the moisture content and appearance of meat (Mir et al., 2017). In meat, moisture can be measured in various ways, such as total moisture content and binding capacity (Oswell et al., 2021). According to Huff-Lonergan and Lonergan, (2005), the meat will lose moisture due to several reasons, such as a decrease in pH that brings meat closer to the pH isoelectric of proteins, loss of adenosine triphosphate (ATP), and steric effects from myofibril shrinkage, which is a conditioning stiffness and causes mortise. The other process by which moisture loss is explained in the flow chart below figure 2.

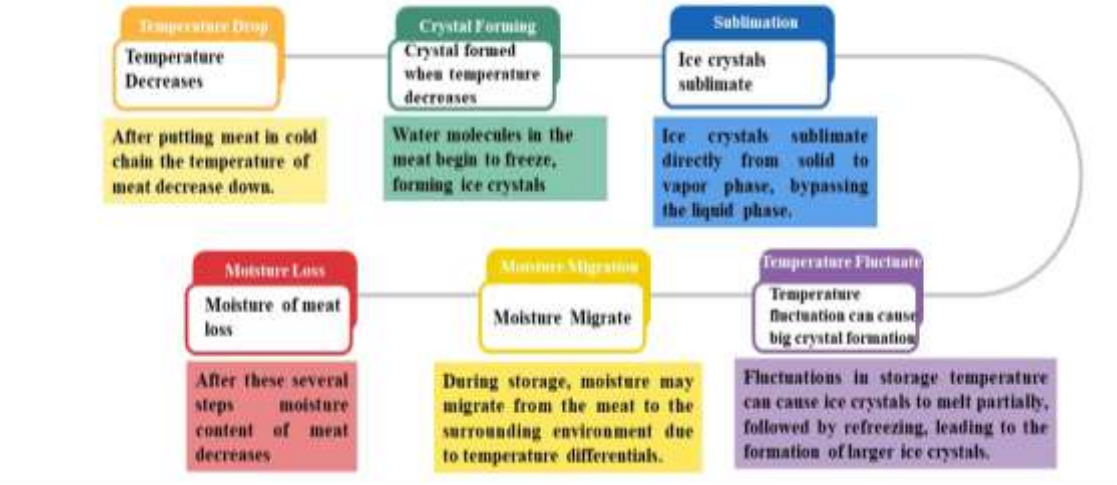

Figure 2. Flow chart diagram decrease in moisture during cold storage

Color Variation

It has been observed that during storage in cold temperatures, the myoglobin component undergoes denaturation (Adeyemi et al., 2017). Gel electrophoresis can be used to measure the color which is a technique that has been used to identify myoglobin in exudate in meat (Anon and Cavelo, 1980). The denaturation of myoglobin causes a loss of normal color visibility.

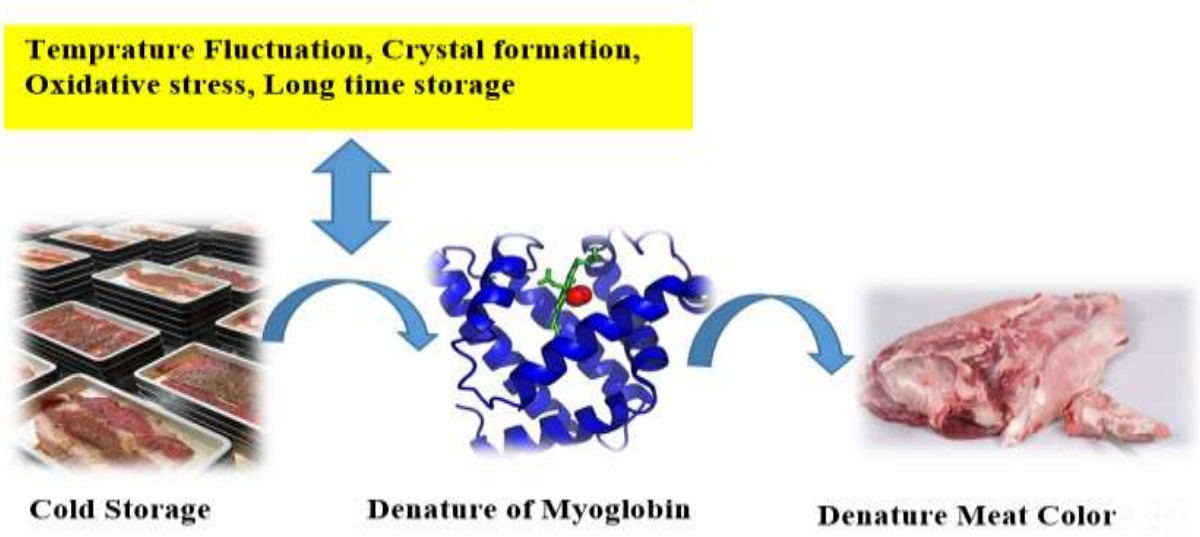

Figure 3. Effect of cold storage on meat color.

PH Level Drop

The term pH refers to the concentration of non-hydrogen ions present in a solution (Aydogdu et al., 2023). It is possible that freezing with subsequent exudate production could cause the denaturation of buffer proteins, the release of hydrogen ions, and a subsequent decrease in pH (Bomminayuni et al., 2020). During the process of coagulation and the release of effluent, buffer proteins can be degraded, and hydrogen ions can be removed or reduced from meat. Loss of moisture from meat tissues can lead to up pH levels (Leygonie et al., 2011).

Crystal Formation

The formation of ice crystals between cells creates different stresses than those caused by ice crystals within fibers (Li et al., 2022). This tension between fibers leads to the fastest fiber degradation during freezing and drying (Li et al., 2022). If pressure is applied in only one direction, only ice forms within cells, preventing significant damage (Akhtar et al., 2013). To monitor the quality of frozen meat, high-visibility wells were used (Kennedy, 2000). Investigations of frozen meat at different concentrations revealed the formation of several large pores, resulting in severe structural disruption of the muscle cells (Du et al., 2022).

Consumers highly value the quality of meat and indirectly, its tenderness and taste (Troy and Kerry, 2010). Several studies have shown that changes in meat texture after freezing can be associated with the freezing process and the rate of growth of the meat before and after freezing for two months (Akhtar et al., 2013).

Oxidation of Lipids and Protein

Due to the oxidation process, the quality of meat decreases such as its flavor, taste, color, nutritional value, and texture (Zhang et al., 2024). According to a study by Soyer, Ozalp, Dalmis, and Bilgin (2010), lipid oxidation occurs when the oxygen free compounds and lipid free radicals are generated, the lipid oxidation produce it can lead to the production of malondialdehyde and cholesterol oxidation products. These oxidative reactions can also affect proteins and stem cells.

Protein oxidation causes a range of changes in proteins, such as alterations in amino acid composition, polymer growth, solubility loss, and an increase in carbonyl groups (Zhang et al., 2013). According to this process, protein side chains bind with free radicals to form protein free radicals, which then react with oxygen to create peroxyl radicals (Davies, 2016). This process leads to the breakdown of proteins and the formation of carbonyl derivatives, causing discoloration, decreased water-binding ability, roughness, and secretion leakage (Delles, 2013).

Lipid oxidation has a significant impact during long-term freezing, and studies have shown that tenderness is greatly affected during cold storage (Al Dalali et al., 2022). Due to protein oxidation in meat, the amount of sulfhydryl groups decreases while the amount of carbonyl groups increases (Dominguez, 2021). The process of lipid oxidation primarily affects the phospholipids present in the membrane of meat (Amaral et al., 2018).

Malondialdehyde and Thiobarbituric Acid Reactive Chemicals

During the oxidation process of polyunsaturated fatty lipids, a compound called malondialdehyde is produced (Amaral et al., 2018). It is also known as 1,3-propanediol and is considered a key indicator of lipid oxidation in meat (Turkez et al., 2024). Malondialdehyde produces trace odors of rancidity that can negatively impact meat products (Dominguez et al., 2019).

To measure MDA, several methods have been established due to its highly active nature and association with other food components (Barriuso et al., 2013).

The measurement of MDA is the primary method used in the thiobarbituric acid assay (Reitznerovás et al., 2017). This is a complicated method for measuring colors that involve the use of TBA and MDA (Cheng., 2015). TBA is not limited to MDA, as it reacts with aldehydes and other oxidants (Rizzo, 2024). Therefore, this method is referred to as Thiobarbituric Acid Reactive Chemicals (TBARs). TBA can be used in the evaluation of lipid oxidation in food products and meat (Dragoev, 2024).

Consumer power of choice related to meat

Nowadays, consumers consistently prefer quality meat such as meat appearance, taste, flavor, and aroma are essential choices for buyers and sellers. They select meat that is healthy, fresh, and free of synthetic antibiotics (Haworth, 2003). Various phenolic derivatives from edible plants have been found to inhibit hydroperoxide formation, including tocopherols, rosemary extract, and many others (Frankel, 2004). Extracts from sesame, rosemary, green tea, coffee, and grapefruit catechins have also shown strong antioxidant effects on meat. (Nam and Ahn et al., 2003) (Nissen et al., 2004). These substances are very effective for reducing oxidation when applied to meat products and also protect from free radicals. Moreover, consumers are becoming more selective in their food choices, considering convenience, freshness, and quality as crucial factors (Agriculture Canada, 1990). Processed food labels provide extensive information on levels of processed fat, sodium, calories, and preservatives. Packaging dates are also an essential component of processed meat products affecting their character.

Factors influencing lipid oxidation

The cholesterol content of meat is a major determinant of cholesterol oxidation, as it is the basis of oxidation processes. Meat contains different types of fats, including triglycerides, phospholipids, cholesterol, free fatty acids, and vitamins. Triglycerides are the majority of fats in meat, accounting for 95% of meat fat (Prates, 2025), while cholesterol is present in about 500 milligrams per gram of meat (Christie, 1978). Fat content contains high-affinity phospholipids, but the concentration remains constant. This leads to increased cholesterol levels in muscle cells, causing triglycerides to exceed the limit and negatively impact muscle tissues.

Fat is a crucial component of animal tissue due to its lipolytic activity and high solubility. However, fats often react with reactive oxygen species (ROS), leading to oxidation, which is comparable to other unsaturated fatty acids (De Oliveira, 2018). The major carbon sites that are susceptible to oxidation are double bonds of 5,000 Carbon, 6, and 7 Carbon atoms, and a tertiary between Carbon atoms C20 and C25 oxidation (Domínguez et al., 2019). The concentration of the two products depends on processing or storage variables such as temperature, pH, oxygen concentration, oxidation time, buffer type, water activity, substrate size, and availability of unsaturated fats (Kim, 1993).

Organic Antioxidants

Meat can undergo prooxidant changes that are harmful to the body, but there are antioxidant molecules that can protect it against the effects of free radicals and catalysts that promote lipid oxidation. Meat can undergo prooxidant changes that create risks to the body. On the other hand, antioxidant protects the body from harmful effects of chemicals and there are some catalysts also present that promote the oxidation of lipids. There are three main groups of compounds that can be isolated and used for this purpose: enzymes, peptides, and vitamins. The primary function of antioxidants is to eliminate harmful molecules called free radicals, which can cause damage to cells and contribute to diseases.

Table 1. Organic antioxidant activity during cold storage

Antioxidants	Mechanism	Effectiveness in meat	Cold Storage impact	References
Vitamin E (α-Tocopherol)	Detoxify the lipid peroxyl radicals	Highly protective against lipid oxidation	During the cold storage, the amount of vitamin E decreases	(Coetzee & Hoffman, 2001)
Carnosine	Deactivates the ROS, and regenerates other antioxidants	Highly effective for controlling oxidative damages	Drops over time, particularly during the freeze-thaw conditions	(Chiesa et al., 2020)
Ascorbic Acid	Restore vitamin E, eliminate reactive oxygen species	Boost the other antioxidant activity	Degrades the oxidation quickly due to sensitivity in cold storage	(Yin et al., 2022)
Plant-derived Phenolics (Rosemary extract)	Scavenges the activity of ROS and neutralizes the free radicals	Increase the stability of meat color and life	Stable the antioxidants	(Gutiérrez-del-Río et al., 2021)

Factors influencing on protein oxidation

Internal Factors

Lipid oxidation and protein oxidation are closely related processes. Proteins can oxidize other proteins when reactive residues come into contact with nitrogen or sulfur centers. Additionally, proteins can also modify secondary lipids by forming covalent bonds with oxidized products, such as aldehydes or reducing sugars. Therefore, protein oxidation can be influenced by the composition of the entire food, including fats, proteins, and substances like iron, carotenoids, and phenolic compounds. (Falowo, 2014) (Ma, J.; Wang, X.; Li, Q.; Zhang, L.; Wang, Z.; Han, L.; Yu, Q, 2021) (Lund, 2011).

External factors

Processing techniques are commonly used to enhance the performance, physical properties, and stability life of fish and meat products for preservation purposes (Soladoye, 2015). Many external factors related to external such as temperature, preservation techniques, oxygen exposure, and additives can particularly react to lipid and protein oxidation (Johnson & Decker, 2015). Therefore, during processing and storage, the high temperature accelerates the oxidative processes that cause rancidity and quality degradation (Gertz et al., 2014). Oxygen availability plays a critical role in oxidative processes, as prolonged exposure can increase lipid peroxidation and alter meat color and texture (Huang & Ahn, 2019). Exposure to oxygen can be decreased by storage methods such as sealing technique, and vacuum packaging, MAP and these factors mainly degrade the reaction of oxidative activity. Additionally, preservatives like sodium nitrate, antioxidants (e.g., tocopherols, rosemary extract), and natural plant-based extracts can inhibit lipid oxidation and improve shelf life (Maheshwari, 2016). Other external influences, such as light exposure and humidity, can further impact oxidation rates, affecting the overall sensory and nutritional quality of meat and fish products.

Table 2. Storage conditions influence the activity of lipid and protein oxidation different factors

Factors	Influence on the activity of lipid oxidation	Influence on the activity of protein oxidation	References
Temperature	The rate of reaction increases due to temperature fluctuation	Accelerates the protein denaturation	(Johnson & Decker, 2015) (Zhang et al., 2023)
Exposure of Oxygen	The more reactive the lipid peroxidation	Causes the carbonyl content formation in proteins	(Domínguez et al., 2021)
pH variation	Lipids breakdown due to enzymatic activity	Changes in the protein reaction	(Yu et al., 2024) (Medina-Meza et al., 2014)
Ions activity	Catalyze more lipid oxidation processes	Enhance the protein oxidation by radical catalyst	(Domínguez et al., 2021)
Activity of water content	Rancidity	Changes in the structure of meat	(Yodkaew et al., 2017)

Relationship between protein oxidation and lipid oxidation

Dietary fats are an essential component of meat products as they contribute to flavor, texture, and overall fat content (Moloney & Teagasc, 2002). However, excessive heat can disrupt these processes by promoting lipid oxidation, which can affect the quality of meat products (Guyon et al., 2016). Although lipid oxidation in meat has been extensively studied, the simultaneous investigation of lipid and protein oxidation is necessary (Domínguez et al., 2019). The quality of meat products is closely related to lipid and protein oxidation, particularly in terms of its role as a precursor for microbial processing (Guyon et al., 2016).

Conclusion

Cold storage is the most preferable method for storing meat, however, it can cause significant differences in the meat's functional, physical, and chemical properties including lipid oxidation, protein oxidation, color deterioration, pH variation, and also water holding capacity, these changes mainly occur during the cold long storage. Therefore, these changes also break down the lipid and protein structure and their result forms volatile compounds that may easily change the flavor compounds, and ultimately affect consumer preferences. Understanding the mechanisms of lipolysis and proteolysis, along with factors influencing oxidation, is essential for maintaining meat quality. Additionally, consumer preference for aged meat highlights the need for optimizing cold storage conditions to balance preservation with quality retention. Future research should focus on improving storage techniques to minimize deterioration while maintaining desirable sensory attributes.

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