

The cold chain question: Effect of beef trim cold chain management on ground beef quality,
shelf life, and palatability

by

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Abstract

Ground beef is one of the most widely consumed and economically important beef products in the United States and plays a critical role in carcass utilization by providing an outlet for lean and fat trimmings generated during fabrication. Because domestic lean trim supplies are limited, frozen trim remains an important component of the beef supply chain for storage, transport, and import applications. Although freezing improves logistical flexibility, it may also alter the functional properties of meat and influence the resulting ground beef. Therefore, the objective of this study was to evaluate the impact of varying combinations of fresh, frozen, and thawed beef trim on the shelf life, quality characteristics, and palatability of ground beef. Beef trim of varying lean percentages (50%, 80%, and 90%) and cold chain states (fresh, thawed, and frozen) was ground and combined to create 10 unique treatments of 80% lean ground beef. Product was formed into 151 g patties, overwrapped, and subjected to 5 days of simulated retail display. Trained visual panel redness and discoloration scores and objective color measurements were collected daily throughout display. Consumer visual panels evaluated packages on day 3 of display and consumer taste panels, trained taste panels, shear force, texture profile analysis, and TBARS were conducted on patties after 3 days of display. The cold chain state of trim has substantial effects on both visual acceptability and eating quality. Patties containing fresh trim or fresh combined with frozen or thawed trim were rated highest ($P < 0.05$) for appearance and purchase intent, whereas exclusively frozen treatments were least preferred ($P < 0.05$). Trained panelists detected treatment differences in redness during early and mid-display, with treatments containing frozen lean trim declining the most rapidly, although discoloration scores did not differ among treatments. Frozen-only treatments declined the most rapidly (23.1% by day 1) in a^* values, and treatments containing frozen lean trim accumulated greater metmyoglobin

percentages during later display. In contrast, thawed trim treatments generally behaved similarly to fresh treatments, maintaining redness and a^* value across display, without a sharp decline. Trained panelists reported greater ($P < 0.05$) oxidized off-flavor in frozen only treatments and consumer beef-flavor liking scores generally favored treatments containing fresh or thawed trim. Lipid oxidation measured by TBARS closely matched these sensory responses, as treatments produced from frozen lean trim had greater ($P < 0.05$) oxidation, and treatments from entirely fresh trim had the least ($P < 0.05$). Frozen-only treatments were rated as more tender but lower ($P < 0.05$) in texture liking and produced the lowest shear force and cohesiveness values, indicating a softer, less cohesive product. The most severe quality losses occurred when trim was ground directly from the frozen state, particularly when the lean component remained frozen. Treatments produced from fresh or thawed trim maintained greater color stability, lower oxidation, more desirable flavor, and better structural integrity. These results indicate that frozen trim can remain part of the beef supply chain without necessarily compromising final product quality, provided it is thawed prior to grinding rather than ground while still frozen.

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Dedication

This thesis is dedicated to my family. To my parents, Jim and Lori, who never said no to me pursuing opportunities to better myself and who have supported me along the way. To my brother Jimmy, who was always someone I could look up to and pushed me to be better.

Chapter 1 - A Review of Literature

Introduction

Ground beef is one of the most widely consumed and economically important beef products in the United States. Its affordability, versatility, and broad use across foodservice, institutional settings, and home meal preparation make it a central component of the domestic beef market. In addition to serving as a major source of consumer beef intake, ground beef also plays an essential role in carcass utilization because it provides a practical outlet for trimmings generated during fabrication of whole-muscle cuts. As a result, maintaining the quality and consistency of ground beef is important not only for consumer satisfaction, but also for preventing economic losses to the beef industry.

Despite its importance, ground beef is a highly perishable product. During refrigerated storage and retail display, microbial growth, myoglobin and lipid oxidation continue to occur, reducing product quality (Mancini & Hunt, 2005). These changes influence appearance and flavor, but of these attributes, visual color is especially important because consumers associate a bright cherry-red color with freshness (Frink et al., 2026; Lybarger et al., 2023). As meat discolours from bright cherry-red to brown, consumers interpret this change as an indication of spoilage, even while the product remains safe for consumption (Frink et al., 2026). Consequently, the shelf life of ground beef is determined by consumer perception rather than safety alone, leading to product discounts, product discard, and substantial economic losses within the beef industry.

Ground beef quality is further influenced by the raw materials used in its manufacture. Formulations are often produced by blending trimmings of different lean points to achieve target lean to fat ratios, and the availability of these raw materials has become increasingly more

important as domestic supplies of lean trim have tightened (Anderson, 2025). U.S. beef production generates relatively large quantities of higher-fat trim, and as a result, lean trimmings are frequently imported as frozen product to support storage, transport, and manufacturing flexibility (Anderson, 2025; NCBA, 2025a). Freezing is therefore an important tool in the beef supply chain, but it also introduces structural and biochemical changes to the product. Ice crystal formation, moisture loss during thawing, lipid oxidation, and myoglobin oxidation may all influence the resulting quality characteristics of ground beef produced from frozen or previously frozen raw materials (Dang et al., 2021; Leygonie et al., 2012).

Although the effect on freezing whole muscle beef cuts has been studied previously (Beyer et al., 2024; Decker et al., 2024; Thompson et al., 2023), less attention has been given to how the fresh, frozen, or thawed state of beef trim influences the quality of ground beef products. This is an important gap because changes in raw material condition may alter color stability, oxidative stability, and palatability traits that ultimately influence consumer acceptance and shelf life of the final product. Therefore, the objective of this review is to examine the factors that influence ground beef quality, with emphasis on shelf life, consumer perception of beef color, and the effects of fresh, frozen, and thawed beef trim on the resulting quality characteristics of ground beef.

Shelf Life

Shelf life of meat products is ultimately defined by consumer opinion rather than solely by safety or microbial counts (Frink et al., 2026; Lybarger et al., 2023). Independent of microbial counts and safety, consumer rejection based on sensory attributes still results in product discard (Frink et al., 2026; Lybarger et al., 2023; Ramanathan et al., 2022). In fresh meat products, shelf

life represents the point at which product quality declines beyond the threshold of consumer acceptability rather than the point at which the product becomes unsafe to consume.

Several factors contribute to the deterioration of meat quality during storage and display. Microbial growth gradually increases during refrigerated storage and ultimately leads to spoilage characteristics such as off-odors, slime formation, and texture changes (Frink et al., 2026; Rogers et al., 2014). However, microbial spoilage is often not the primary determinant of marketable shelf life for fresh beef products (Frink et al., 2026; Lybarger et al., 2023). Instead, biochemical and oxidative processes frequently limit product acceptability earlier in the display period (Frink et al., 2026). These processes include lipid and myoglobin oxidation, which alter flavor, odor, and visual appearance of meat products (Faustman et al., 2010; Frink et al., 2026; Mancini & Hunt, 2005). Among these sensory attributes, visual appearance is one of the most influential factors affecting consumer purchasing decisions for fresh beef products (Frink et al., 2026; Lybarger et al., 2023; Mancini & Hunt, 2005). Oxidative changes in myoglobin result in the gradual conversion of oxymyoglobin to metmyoglobin during retail display, resulting in brown discoloration commonly associated with spoilage (Frink et al., 2026; Mancini & Hunt, 2005). Consumers frequently use visual color as a proxy for spoilage when evaluating fresh meat products. As a result, a product may remain microbiologically safe for consumption while still being rejected by consumers (Frink et al., 2026). Consequently, discoloration often determines the point at which meat products are discounted or removed from retail display (Ramanathan et al., 2022). For this reason, understanding the relationship between meat color, discoloration, and consumer perception has become an important focus of shelf life research in beef products.

Ground Beef Market

Ground beef is one of the most widely consumed beef products in the United States and plays a central role in the American diet. It is widely utilized across foodservice establishments, institutional food systems, and at-home meal preparation. Fast-food chains, restaurants, schools, hospitals, and consumers preparing meals at home rely on ground beef as an affordable and versatile protein source. Its adaptability across a wide variety of cuisines and cooking methods has contributed to its continued popularity among consumers.

Ground beef is defined by the Code of Federal Regulations as “Chopped fresh and/or frozen beef with or without seasoning, with beef fat addition of not more than 30%, with no added water, binders, phosphates, or extenders” (Miscellaneous Beef Products, 2005). As beef carcasses are processed into subprimal and retail cuts, trimmings are generated that cannot be marketed as whole muscle products. These trimmings are incorporated into ground beef formulations, allowing processors to maximize carcass utilization and reduce waste within the beef supply chain. Trimmings are sorted based on general lean to fat ratio, the portion of the carcass from which they were obtained (chuck, round, etc.), and whether they meet any breed or branded program standards (North American Meat Institute, 2015). The manufacturing process typically occurs through a continuous process of grinding, blending, and forming. The grinding process reduces particle size and creates a uniform mixture. Following grinding, trimmings from different lean points are blended to achieve target fat levels. The blended product may then be packaged as bulk ground beef or formed into patties or loaves for foodservice or retail applications.

Lean to fat ratios in ground beef vary widely to meet different consumer preferences and cooking applications. The maximum amount of fat permitted in ground beef products is 30%

(USDA FSIS, 2025). Common retail lean to fat ratios include 90/10, 85/15, 80/20, and 73/27. These varying fat levels allow processors and retailers to target specific consumer preferences related to flavor, juiciness, cooking performance, and nutritional considerations.

Ground beef represents a substantial portion of total beef consumption in the United States. National Cattlemen's Beef Association (2025b) reports ground beef products account for 47% of beef sales by volume (lbs.) and 36% of sales by value (\$) in the United States, which is more than any other beef category. Additionally, 62% of consumers reported consuming ground beef in the past week (National Cattlemen's Beef Association, 2025b). The widespread consumption of ground beef highlights its importance within both the beef industry and the broader food system.

Economics

Ground beef plays a critical economic role in the U.S. beef industry due to its high consumption rate and its ability to utilize trimmings generated during fabrication of beef carcasses. Retail ground beef prices have increased over time. From 2020 to 2024, the average price of ground beef has risen from \$4.15 to \$5.16, approximately a 24% increase (National Cattlemen's Beef Association, 2025b). However, the consumer willingness to pay has only risen 9% over the same time period (National Cattlemen's Beef Association, 2025b). Despite this, ground beef remains one of the most affordable beef options available to consumers, compared to premium whole muscle cuts such as steaks and roasts. The affordability of ground beef, combined with its versatility in cooking, has helped sustain strong consumer demand.

The U.S. ground beef market is also influenced by international trade. Domestic cattle production tends to generate higher fat trimmings, commonly referred to as "50s," indicating approximately 50% lean and 50% fat. This is due to grain finishing practices that are typical of

U.S. beef production systems (Gerdt, 2023). In contrast, imported beef trimmings are typically leaner, referred to as “90s” or 90% lean trim. These imported “90s” are often combined with domestic “50s” to produce ground beef formulations of varying lean to fat ratios (Gerdt, 2023). To accomplish this, the U.S. imports substantial quantities of lean beef trimmings, commonly sourced from countries with large grass-fed cattle populations such as Australia, New Zealand, Argentina, and Brazil, where cattle generally contain lower fat levels compared to U.S. fed cattle (USDA Agricultural Marketing Service, 2026).

Food Safety

Ground beef is considered a higher-risk beef product because the grinding process distributes microorganisms throughout the product. Bacteria that are normally confined to the surface of whole-muscle cuts may become incorporated into the interior during grinding, meaning the product must be thoroughly cooked to ensure safety. Several pathogenic microorganisms are associated with ground beef, Shiga-toxin producing *Escherichia coli* (STEC), specifically *E. coli* 0157:H7, is of greatest concern (USDA FSIS, 2025). Additional pathogens of concern include *Salmonella spp.* and *Listeria monocytogenes*, which can contaminate beef during processing or handling (USDA FSIS, 2025). Because these organisms may be present throughout the product, consuming undercooked ground beef poses a greater risk of foodborne illness compared with whole-muscle cuts. To reduce this risk, proper handling and cooking practices are essential. The USDA Food Safety and Inspection Service (FSIS) recommends cooking ground beef to an internal temperature of 71°C for 0 seconds, which is sufficient to destroy pathogenic bacteria (USDA FSIS, 2025). Use of a food thermometer is strongly recommended because visual indicators alone are unreliable (Mancini & Hunt, 2005). Safe handling practices also include keeping raw ground beef refrigerated at < 4°C, avoiding

cross contamination with ready-to-eat foods, and washing hands, utensils, and surfaces after contact with raw meat (USDA FSIS, 2025). Prompt refrigeration or freezing of ground beef and proper thawing under refrigeration are also critical components of preventing microbial growth during storage and preparation (USDA FSIS, 2025).

An additional safety concern in ground beef products is the phenomenon of premature browning. Premature browning occurs when ground beef develops a brown, well-done appearance at internal temperatures lower than those required to destroy pathogens (Mancini & Hunt, 2005a). Several factors can accelerate myoglobin denaturation and oxidation, including low muscle pH, prior freezing and thawing, or the state of myoglobin prior to cooking (Mancini & Hunt, 2005). These conditions promote earlier oxidation of oxymyoglobin and faster formation of ferric pigments such as metmyoglobin and hemichromes during heating. As a result, ground beef may develop a brown, well-done appearance at internal temperatures below 71°C, even though pathogenic microorganisms such as *E. coli* O157:H7 may still be present (Mancini & Hunt, 2005a). Because these pigment changes are driven by chemical reactions within myoglobin rather than microbial lethality, visual color alone is an unreliable indicator of doneness in ground beef products.

Meat Color

Consumers often use meat color and the presence of discoloration as an indicator of freshness when making meat purchasing decisions (Mancini & Hunt, 2005b). Therefore, it is essential to understand the biochemical mechanisms and chemistry that dictate meat color stability.

The protein primarily responsible for meat color is myoglobin, an iron porphyrin pigment similar to hemoglobin (Mancini & Hunt, 2005b). In fresh, red meat products, four forms of myoglobin can exist: deoxymyoglobin (DMb), oxymyoglobin (OMb), metmyoglobin (MMb), and carboxymyoglobin (COMb) (Mancini & Hunt, 2005b). The reaction between the different states of myoglobin is shown in Figure 1. 1.

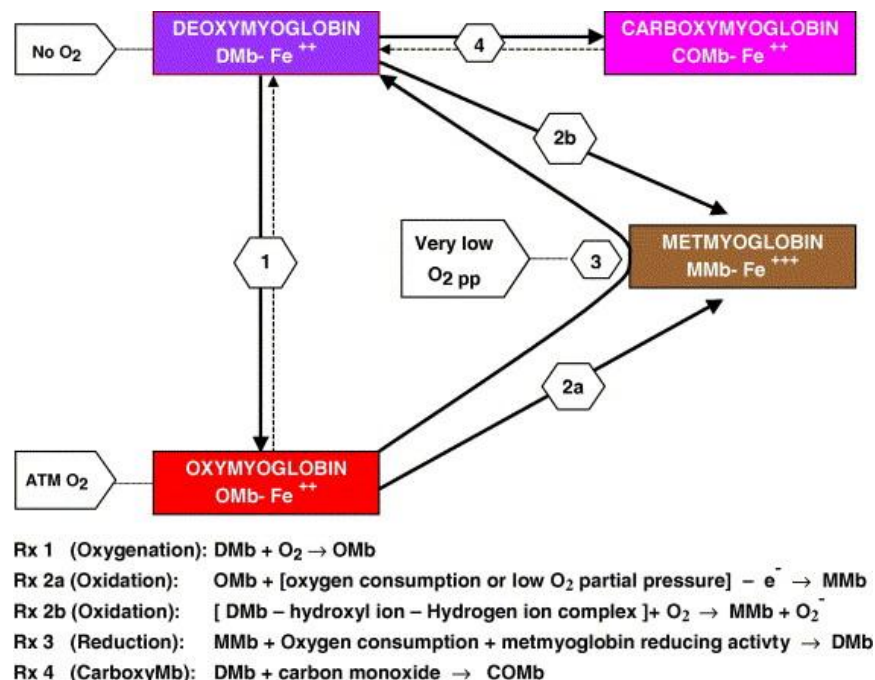


Figure 1.1 Visual myoglobin redox interconversions on the surface of meat (Mancini & Hunt, 2005).

The state of myoglobin is dependent on two key factors: the ligand bound to the 6th coordination site of the heme iron and the valence state of that iron, either ferrous (Fe^{2+}) or ferric (Fe^{3+}) (Mancini & Hunt, 2005b). Shifts among myoglobin forms occur in response to changes in oxygen partial pressure, pH, time, temperature, and competition for oxygen (Mancini & Hunt, 2005b). DMb is present when oxygen is limited and no ligand occupies the sixth coordination site, such as in vacuum-packaged products or freshly cut muscle. This form produces a purplish-red appearance. Upon exposure to oxygen, myoglobin undergoes oxygenation, commonly referred to as “bloom,” forming OMb as oxygen binds to the sixth coordination site while iron

remains in the ferrous state. OMb is responsible for the bright, cherry-red color typically associated with freshness in beef. As oxygen exposure increases, OMb can extend slightly below the meat surface, though its depth is influenced by product type and oxygen availability. When oxygen availability declines or oxidative conditions increase, ferrous iron is oxidized to the ferric state and water replaces oxygen at the binding site, resulting in the formation of MMb. This pigment produces a tannish-brown color that is strongly associated with product rejection by consumers (Mancini & Hunt, 2005; Lybarger et al., 2023; Frink et al., 2025). Carboxymyoglobin forms when carbon monoxide binds to ferrous myoglobin at the sixth coordination site in the absence of oxygen. This complex produces a stable bright red color that is more resistant to oxidation than oxymyoglobin, contributing to extended color stability under specific packaging systems (Mancini & Hunt, 2005).

Visual Color Analysis

Visual color analysis can be conducted using consumer panels or trained sensory panels. Consumer panels are composed of untrained panelists and are used to determine acceptability and willingness to purchase (King et al., 2023). Consumer panels require a large number of panelists to provide information using hedonic or linear scales of their preferences and their perception of a product's attributes and are not used to objectively evaluate meat color characteristics (King et al., 2023). Alternatively, trained sensory panels are a tool used to quantify meat color characteristics using a smaller number of individuals who have been trained to objectively evaluate meat products on anchored scales and are not able to rank personal preferences or acceptability (King et al., 2023).

Instrumental Color Analysis

Instrumental color analysis is an important aspect of meat color research as it provides a truly objective way to measure color in comparison to trained sensory panels. Color can be measured using Commission Internationale de l'Eclairage (CIE) values of L^* , a^* , and b^* . These determine a spectrum of white to black (L^*), green to red (a^*), and blue to yellow (b^*) using a spectrophotometer (Figure 1.2).

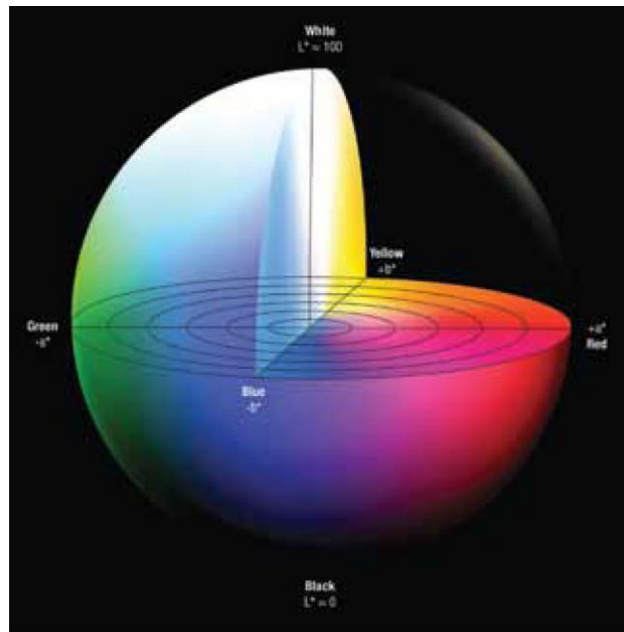


Figure 1.2 Representation of color solid for CIE $L^*a^*b^*$ color space (King et al., 2023).

Instrumental color measurements can be used not only to quantify surface color, but also to estimate the relative proportions of myoglobin redox forms present at the meat surface. Tristimulus values (L^* , a^* , b^*) provide the basis for calculating additional color attributes, including chroma and hue angle (King et al., 2023). Chroma represents color intensity or saturation and is calculated as $(a^2 + b^2)^{1/2}$, whereas hue angle describes the shift in color and is calculated as $[\arctangent(b^*/a^*)]$ (King et al., 2023). In addition to tristimulus values, reflectance data collected across specific wavelengths can be used to estimate the relative proportions of myoglobin forms at the surface. Spectral reflectance ratios at established

isosbestic wavelengths allow for calculation of metmyoglobin, oxymyoglobin, and deoxymyoglobin percentages. According to the AMSA Meat Color Measurement Guidelines, the ratios 572 nm/525 nm, 610 nm/525 nm, and 474 nm/525 nm are used to estimate metmyoglobin, oxymyoglobin, and deoxymyoglobin, respectively (King et al., 2023).

Consumer Perception of Beef Color

Bright, cherry-red color is consistently associated with freshness in beef and strongly influences purchasing behavior (Killinger et al., 2004; Mancini & Hunt, 2005). As surface discoloration develops, consumer willingness to pay declines, often requiring retailers to discount affected products (Greibitus et al., 2013; Thies et al., 2024). The economic impact of color-related markdowns and product loss is substantial, with annual losses to the beef industry estimated at \$3.73 billion (Ramanathan et al., 2022). Collectively, these findings emphasize the importance of understanding consumer perceptions of ground beef products as consumers ultimately determine product acceptability and market value.

Studies have recently used online surveys to quantify how meat color and discoloration influence purchasing decisions in beef consumers. Thies et al. (2024) provide a broad economic perspective on the relationship between discoloration and willingness to pay for beef *longissimus lumborum* steaks. Using an online discrete choice experiment, consumers were shown images of steaks representing progressive days of retail display. Consumers were screened for screen acuity and color perception at the beginning of the survey. Instrumental color measurements confirmed increasing surface metmyoglobin and decreasing redness (a^*) across display time, and these images were incorporated into hypothetical purchasing scenarios. Results showed willingness to pay declined almost linearly as discoloration increased. Compared to day 0 steaks, steaks displayed for extended periods (4, 7, and 9 days) required increasingly larger price reductions to

maintain selection probability. In effect, discoloration shifted the product from a price premium position to one requiring compensation to offset perceived quality loss (Thies et al., 2024).

Another online survey conducted by Feuz et al. (2020) incorporated both beef steaks and ground beef to quantify the relationship between meat discoloration and consumer willingness to pay. This study used beef steaks and ground beef packaged in an oxygen permeable PVC overwrap, placed in coffin-style cases and allowed to naturally discolor over time. Steaks were displayed for 8 days and ground beef for 5 days to achieve full discoloration. Photographs of the products and objective color measurements were taken daily to document the change in discoloration, and spectral data for the calculation of percentage metmyoglobin. Respondents were screened for computer screen display settings and eyesight at the beginning of the survey. Consumers were provided with three photos of either ground beef or steak, with varying levels of discoloration, prices for each, and were asked to indicate which of the three choices they would be most likely to purchase. Two different types of discoloration were assessed: coverage (percentage of surface discoloration) and intensity (darkness of the discoloration). The intensity of discoloration was achieved by digitally manipulating photographs of the products. Findings from this study showed both coverage and intensity of discoloration significantly decreased consumers' willingness to pay, and substantial discounts were needed to offset even moderate discoloration. In their experimental auction framework, steaks and ground beef exhibiting modest discoloration required price discounts approaching 25 to 50% relative to bright, cherry-red product before average bid levels were restored. As the coverage and intensity of discoloration increased, the discounts required to achieve the same willingness to purchase increased. These findings indicate that consumer tolerance for visual deviation from the expected

bright-red color is limited, and that economic consequences begin well before complete surface browning occurs. Most importantly, ground beef followed the same patterns as steaks.

Differentiating from Feuz et al. (2020) and Thies et al. (2024), Lybarger et al. (2023) employed a simulated retail environment in which PVC-overwrapped ground beef packages were displayed in coffin-style cases under fluorescent lighting to closely replicate commercial conditions. Consumers evaluated overall appearance desirability and purchase intent across progressive levels of discoloration, while objective measurements including L^* , a^* , b^* , percent metmyoglobin, percent oxymyoglobin, chroma, hue angle, and trained sensory panel redness and discoloration scores were collected concurrently. The study was conducted in two phases. In Phase 1, consumers evaluated packages spanning the entire range of retail display discoloration. In Phase 2, consumers evaluated samples from a single day of display. This design allowed for direct comparison between objective pigment changes and subjective consumer perception under both broad and controlled evaluation conditions. Using logistic regression modeling, the authors quantified instrumental and sensory thresholds corresponding to specific probabilities of purchase at full price. In Phase 1, a^* values of 21.6, 24.6, 28.3, and 30.5 corresponded to 50%, 75%, 90%, and 95% likelihood of purchase, respectively. Similarly, trained sensory panel discoloration scores of 37.8%, 19.5%, and 1.1% corresponded to 50%, 75%, and 90% purchase likelihood thresholds. Calculated percent metmyoglobin also served as a strong predictor of consumer behavior, with values of 40.1%, 33.6%, 27.1%, and 22.7% associated with 50%, 75%, 90%, and 95% likelihood of purchase, respectively. Collectively, these findings demonstrate that relatively small shifts in instrumental redness and discoloration translate into substantial changes in consumer purchase probability.

Fresh versus Frozen

Freezing is widely used in the meat industry as a method to extend shelf life and facilitate long-term storage and distribution of meat products. Fresh beef is a highly perishable commodity because microbial growth, enzymatic activity and oxidative reactions continue to occur under refrigerated conditions (Dang et al., 2021; Leygonie et al., 2012). While refrigeration slows these processes, it does not prevent them entirely (Dang et al., 2021). As a result, the shelf life of fresh beef is typically limited to days or weeks depending on packaging and storage conditions. In addition to preservation, freezing plays an important role in the global beef supply chain (Leygonie et al., 2012). Frozen storage allows processors and distributors to balance supply and demand, transport products over long distances, and maintain inventories for use in further processing. Frozen beef is also commonly used in manufacturing applications, such as ground beef production, where imported trim may be stored and blended to achieve target lean to fat ratios. Because domestic beef production produces relatively large quantities of higher-fat trim, lean frozen trimmings are often imported to supplement the limited supply of lean trim in the United States (USDA Agricultural Marketing Service, 2025b).

Raw Materials

While freezing effectively slows microbial growth and biochemical reactions, the process introduces physical changes to muscle tissue that may influence the functional properties of raw materials (Dang et al., 2021). One of the primary mechanisms by which freezing affects meat quality is the formation of ice crystals within muscle tissue (Beyer et al., 2024; Dang et al., 2021). During freezing, water within muscle cells transitions into ice, and the size and distribution of ice crystals are largely determined by the rate of freezing (Dang et al., 2021). Slow freezing promotes the formation of large extracellular ice crystals that can disrupt cellular

membranes and muscle fiber structure (Dang et al., 2021). This structural damage reduces the ability of meat to retain water during thawing, often resulting in increased purge loss (Beyer et al., 2024; Park & Kim, 2024).

Freezing may also influence the oxidative stability of lipids in meat. Lipid oxidation occurs through radical-mediated reactions involving unsaturated fatty acids, producing primary hydroperoxides that degrade into secondary compounds such as aldehydes and ketones (Irwin & Hedges, 2004; Wang et al., 2021). These compounds contribute to rancid or off-flavors and are commonly measured through the thiobarbituric acid reactive substances (TBARS) assay as indicators of oxidative deterioration in meat products (AMSA, 2016; Irwin & Hedges, 2004). The oxidative degradation of lipids and myoglobin may influence both color stability and flavor development in products manufactured from frozen raw materials.

Whole Muscle Color Stability

Freezing and thawing may also influence the biochemical stability of proteins and lipids in meat. Although oxidative reactions occur more slowly at frozen temperatures, lipid oxidation can still progress during extended storage under frozen conditions, especially in the presence of oxygen (Dang et al., 2021; Leygonie et al., 2012). Additionally, disruption of cellular compartments during freezing can expose pro-oxidant components, such as iron released from heme pigments, which may further accelerate oxidative processes following thawing (Dang et al., 2021; Leygonie et al., 2012). Furthermore, the crystallization of water during freezing concentrates solutes in the remaining unfrozen water fraction in the muscle, altering the chemical environment surrounding myoglobin and increasing the potential for oxidative reactions (Dang et al., 2021; Leygonie et al., 2012). Oxidative processes that occur during frozen storage or following thawing can accelerate the conversion of oxymyoglobin to metmyoglobin, which may

reduce color stability and promote discoloration during retail display (Leygonie et al., 2012). Freezing can also decrease metmyoglobin reducing activity (MRA), an enzymatic system capable of reducing metmyoglobin back to oxymyoglobin (Leygonie et al., 2012). Reduced MRA further compromises the ability of myoglobin to maintain the bright cherry-red color associated with fresh meat, decreasing the color stability of previously frozen meat products.

Ground Beef Palatability

In ground beef products, palatability is primarily defined by flavor, juiciness, tenderness, texture, and overall liking, with flavor consistently identified as the most important driver of consumer satisfaction (Kerth et al., 2024). Variability in tenderness is largely minimized in ground beef because grinding disrupts the structural integrity of whole muscles. As a result, differences in ground beef eating quality are more associated with fat content, moisture retention, oxidative stability, and processing methodologies (O'Quinn et al., 2024).

Flavor development in beef is largely governed by Maillard reaction chemistry and lipid oxidation reactions (Kerth & Miller, 2015). The Maillard reaction, occurring between reducing sugars and amino acids during cooking, produces volatile compounds responsible for roasted and savory flavor notes (Kerth & Miller, 2015). Lipid oxidation simultaneously generates aldehydes and other secondary compounds that influence flavor as well. Although moderate lipid-derived volatile compounds may contribute positively to beef flavor, excessive oxidation results in rancid or oxidized flavors (Kerth & Miller, 2015). Ground beef is particularly susceptible to oxidative changes during display and storage because grinding increases surface area and disrupts cellular structures (Kerth & Miller, 2015; O'Quinn et al., 2024).

In ground beef, fat percentage serves as a major determinant of ground beef palatability (O'Quinn et al., 2024). In addition to serving as precursors for volatile flavor compounds formed

during cooking, lipids also contribute to lubrication during chewing, enhancing perceived juiciness and mouthfeel (Kerth & Miller, 2015). Laird et al. (2019) evaluated the effects of final grind diameter, fat content, patty thickness, cooking method, meat source, and post-cooking holding time on flavor and texture attributes using trained sensory panels. Ground beef from grain-fed and mature cattle was formulated to 5% and 20% fat levels, coarse ground, and segmented into three final grind treatments: bowl chopped, 0.95 cm, or 0.64 cm. Patties were formed either by hand or machine at 0.64 cm or 2.54 cm thicknesses, cooked to 70°C using either a flat dry-heat surface or a clam-shell steam grill, and held for up to three hours prior to evaluation. Results from trained sensory panels indicated thicker patties (2.54 cm) exhibited greater beef identity, overall sweet, brown/roasted, and fat-like flavor attributes compared to thinner patties (0.64 cm). Thicker patties were also rated higher for umami, salty, bitter, and sweet basic tastes, as well as initial juiciness and perceived particle size. Increased thickness likely contributed to greater moisture retention and enhanced browning reactions, contributing to flavor intensity. Fat content also influenced flavor perception, as ground beef patties with higher fat content (20%) were rated higher for juiciness and overall palatability compared to the 5% fat formulation. Leaner patties exhibited greater cook loss, negatively influencing sensory juiciness scores. Additionally, higher fat levels contributed to increased beef flavor intensity, supporting the role of lipid-derived compounds in characteristic beef flavor development. Grind size also influenced sensory outcomes, with patties ground to 0.64 cm or 0.95 cm had greater fat-like attributes than that of the bowl chopped patties. This demonstrates multiple manufacturing variables, including fat content, patty thickness, and grind size, interact to influence flavor development and perceived palatability in ground beef. These findings highlight the importance

of formulation and processing decisions in determining the sensory characteristics of ground beef products.

Consumer sensory research further demonstrates the influence of formulation variables on ground beef palatability. Davis et al. (2021) evaluated ground beef patties formulated at three fat levels (90/10, 80/20, and 73/27) compared to plant-based ground beef alternatives using both consumer and trained sensory panels. Results showed consumers consistently rated ground beef patties of all formulations higher than plant-based alternatives for overall flavor liking, beef flavor liking, juiciness, and overall liking, while trained panelists found greater beef flavor intensity and lower off-flavor intensity in ground beef products. Among the ground beef products, patties with higher fat content showed higher ratings for juiciness, tenderness, overall flavor liking, and overall liking by consumers. Additionally, higher fat formulations exhibited greater beef flavor intensity and lower off-flavor intensity compared with leaner formulations when evaluated by trained panelists.

In addition to formulation and processing variables, the raw material used to produce ground beef also contributes to differences in palatability. Specifically, the muscle sources used as trim in ground beef formulations can influence flavor development and sensory characteristics. McHenry et al. (2013) evaluated ground beef patties produced from multiple muscle sources, including chuck shoulder clods, boneless short ribs, briskets, top sirloin caps, tenderloin tips, and sirloin tip knuckles, in comparison to conventional chuck-sourced trimmings using trained sensory panelists. Results showed trim source influenced flavor profiles associated with beef identity, browned/grilled, and buttery/beef fat flavor attributes. No trimming source was rated higher than chuck sourced 81/19 trimmings, but briskets and sirloin caps were similar to the 81/19 trimmings for the desirable beef flavor attributes. Tenderloin tips were rated the

lowest for all desirable beef flavor attributes, and highest for sour/acidic flavor attributes. These findings indicate that different muscles contribute unique flavor characteristics when used as grind sources.

Collectively, these studies demonstrate that ground beef palatability is influenced by a combination of formulation, processing conditions, and trim source selection. Variations in fat level, grind characteristics, and muscle source alter moisture retention, lipid-derived flavor compound formation and browning reactions during cooking, ultimately influencing the sensory attributes perceived by consumers.

Objective

Ground beef remains one of the most widely consumed and economically important beef products in the United States, serving as a major outlet for trimmings generated during carcass fabrication. However, maintaining the quality and marketability of ground beef remains challenging because microbial growth, lipid oxidation, and myoglobin oxidation continue during storage and retail display. Among these factors, visual color plays a particularly important role in determining consumer purchasing decisions. Consumers often associate the bright cherry-red color of oxymyoglobin with freshness and interpret brown discoloration caused by metmyoglobin formation as an indication of spoilage. Ground beef production also relies on blending trimmings with varying lean-to-fat ratios sourced from both domestic and international markets. Because domestic beef production generates relatively large quantities of higher-fat trim, lean trimmings are commonly imported and frequently handled in frozen form to support supply chain logistics and manufacturing flexibility. Although freezing allows for extended storage and improved distribution of beef trimmings, it can also introduce structural and biochemical changes that may influence moisture retention, oxidative stability, and color

stability in ground beef products. Despite widespread use of frozen trimmings in ground beef production, limited research has evaluated how combinations of fresh, frozen, and thawed trim influence the resulting quality characteristics of ground beef. Therefore, the objective of this study was to evaluate the impact of varying combinations of fresh, frozen, and thawed beef trim on the resulting quality characteristics of ground beef.

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Chapter 2 - The Cold Chain Question: Effect of Beef Trim Cold Chain Management on Ground Beef Quality, Shelf Life, and Palatability

Introduction

Ground beef is one of the most widely consumed and economically important beef products in the United States (NCBA, 2025). Its affordability and versatility make it a central component of the American diet and domestic beef market. Ground beef also serves an important role in carcass utilization by providing an outlet for trimmings generated during carcass fabrication. As a result, maintaining ground beef quality is important for both consumer satisfaction and industry value.

Ground beef is also a highly perishable product. During refrigerated storage and retail display, microbial growth, discoloration, and lipid oxidation reduce product quality (Faustman et al., 2010; Frink et al., 2026; Mancini & Hunt, 2005). Among these changes, visual color is especially important because consumers associate a bright, cherry-red color with freshness and often interpret discoloration as spoilage (Frink et al., 2026; Lybarger et al., 2023; Mancini & Hunt, 2005). Consequently, shelf life is often determined by consumer perception rather than safety alone, leading to discounting and product loss (Frink et al., 2026; Lybarger et al., 2023; Ramanathan et al., 2022).

Ground beef quality is influenced in part by the raw materials used in its manufacture (McHenry et al., 2013). Ground beef is produced by blending trimmings of different lean points, and the supply of lean trim has become increasingly important as domestic supplies have tightened (Anderson, 2025; North American Meat Institute, 2015). Because U.S. beef production

generates relatively large amounts of higher-fat trim, lean trimmings are often imported to support formulation needs (Anderson, 2025). These imported lean trimmings are commonly handled in frozen form to facilitate storage, transportation, and supply chain flexibility.

Although freezing is an effective tool for extending storage, it can alter the functional properties of meat (Leygonie et al., 2012). Ice crystal formation can disrupt cellular structure, reduce water holding capacity, and accelerate oxidative processes through the release of prooxidant compounds (Dang et al., 2021; Leygonie et al., 2012). Previous work has shown freezing can affect purge loss, oxidation, and retail color stability in whole-muscle beef (Aroeira et al., 2017; Hergenreder et al., 2013; Jeong et al., 2011). However, Beyer et al. (2023) determined freezing did not negatively impact palatability. These effects may be even more important in ground beef because grinding increases surface area, redistributes fat and protein, and increases oxygen exposure (Beavers et al., 2017; McHenry et al., 2013). Despite this, less attention has been given to how the fresh, thawed, or frozen state of beef trim influences the quality of ground beef.

Previous studies have shown that relatively small changes in redness and discoloration can substantially alter consumer purchase intent in ground beef (Frink et al., 2026; Lybarger et al., 2023). However, the effects of beef trim cold chain management may extend beyond visual traits alone and influence broader aspects of ground beef shelf life and eating quality.

While the broad effects of freezing on meat quality are well established, research evaluating how combinations of fresh, frozen, and thawed trim affect the quality, shelf life, and palatability of ground beef remains largely unexplored. Therefore, the objective of this study was to evaluate the impact of varying combinations of fresh, frozen, and thawed beef trim on the shelf life and quality characteristics of ground beef.

Materials and Methods

Sample collection and fabrication

Boxes of beef trim ($N = 36$) were procured from a commercial processing facility and brought back to the Kansas State University (KSU) meat lab under refrigeration (2 - 4°C). Boxes were of varying fat percentages and cold chain management strategies including 8 boxes of frozen 50% lean trim, 8 boxes of frozen 90% lean trim, 6 boxes of fresh 50% lean trim, 6 boxes of fresh 90% lean trim, 4 boxes of frozen 80% lean trim and 2 boxes of fresh 80% lean trim. Frozen trim was collected 10 days prior to fabrication and transported to KSU. Half of the boxes of frozen trim from each lean percentage were kept frozen at -20°C, while the other half were allowed to thaw at 2 - 4°C in the absence of light for 8 days, as determined by a preliminary trial. Fresh trim was collected one week after procuring the frozen trim and 3 days prior to sample fabrication. Using the raw materials described, the following treatments were created: Frozen-50/Frozen-90, Frozen-50/Fresh-90, Fresh-50/Frozen-90, Frozen-80, Fresh-50/Thawed-90, Thawed-50/Fresh-90, Thawed-50/Thawed-90, Fresh-50/Fresh-90, Fresh-80, and Thawed-80.

Processing occurred on two sequential days due to the scope of the project and speed of processing. Each treatment described above was created using the same methodology and formulated to an 80% lean point. For treatments containing trim of two combined lean points, 6.8 kg of 50% lean and 27.2 kg of 90% lean was weighed using a platform scale (Model BBA236; Mettler Toledo, Columbus, OH) to reach the desired lean point. Frozen trim was cut into 1.2 cm x 2.5 cm strips using a band saw (Model #3344; Biro, Marblehead, OH) to fit into the first grinder. Additionally, purge from thawed trim was drained prior to grinding. All trim was initially coarse ground using a 0.95 cm plate using a commercial grinder (Model #4146; Hobart, Troy, OH), then transferred to a mixer-grinder and ground again using a 0.32 cm plate (Model #

4246; Hobart, Troy, OH). When applicable, lean points were combined and mixed in the mixer-grinder for 2 minutes, then fine ground through a 0.32 cm plate.

Approximately 4.3 kg of product collected sequentially from the grinder was designated as one batch per treatment for patty formation ($N = 4$ batches per processing day, $N = 8$ batches total). Each batch was formed into $151 \text{ g} \pm 2 \text{ g}$ patties, with the final 8 patties being selected for evaluation. 3 packages were created from these 8 patties: two packages containing 3 patties, one package containing 2 patties. Patties were placed in 10.2 cm square foam trays on soaker pads, separated by patty paper, then overwrapped with PVC film. The first package (3 patties) was assigned to consumer taste panels (2 patties) and lab analyses (1 patty). The second package (3 patties) was assigned to trained taste panels (2 patties), texture profile analysis (TPA), and shear force measurement (1 patty). The last package (2 patties) was designated for shelf-life evaluations, including consumer visual panels, trained visual panels, and objective color measurements.

All packages were placed randomly into coffin-style cases (Model DMF8; Tyler Refrigeration Corp., Niles, MI) at $2 - 4^{\circ}\text{C}$ under fluorescent lights (32 W Del-Warm White 3,000 K; Philips Lighting Company, Somerset, NJ) with an average case-wide illumination of $2,426 \pm 116 \text{ lx}$. To avoid fogging of packages, cases were programmed to defrost once each day, and packages were rotated within each case section every 24 h.

After 3 days of display, packages containing patties designated for consumer taste panels, lab analyses, trained taste panels, TPA, and shear force were removed from the case. These patties were then placed on trays, labeled with unique 4- digit codes, then crust frozen for approximately 30 minutes. Frozen patties were packaged using a commercial rollstock packaging

machine (Model Bulldog 42a 300; UltraSource, Kansas City, MO) and stored at -20°C until analysis.

Consumer sensory panel evaluation

Consumer sensory panels were conducted at the Kansas State University Meat Color Lab and Sensory Lab. Consumer visual panelists ($N = 64$), and consumer taste panelists ($N = 128$) were recruited from the Manhattan, KS area and compensated monetarily for their participation. Samples were randomly assigned to a panel using an incomplete block design. For all visual and taste sensory evaluation, panelists were asked to record their responses on electronic tablets (Fire HD 8; Amazon, Seattle, WA) using a digital survey (Qualtrics Software, Provo, UT).

For visual panels, evaluations were conducted on packages designated for shelf-life evaluations on day 3 of retail display. Consumers were asked to visually evaluate 1 package of each treatment, presented in a random order within a retail display case, using a 100-point continuous line scale for overall appearance desirability as described by Frink et al. (2025) and Lybarger et al. (2023). Following this evaluation, consumers were asked whether they would purchase the package at retail based on appearance (yes/no). If the response was “No,” consumers were directed to a follow-up question asking whether they would purchase the package at a discounted price (yes/no).

Consumer taste panels were conducted 5 months later and followed similar procedures to previous panels held at KSU (Harr et al., 2022; Beyer et al., 2024; Decker et al., 2024; Frink et al., 2026). Samples were thawed at 2 - 4°C 24 h prior to cooking. Patties were cooked on clamshell-style grills (Cuisinart Griddler Deluxe; Stamford, CT) with a surface temperature of 177°C to a target end-point peak temperature of 73.9°C. Peak temperatures were monitored and recorded using Themapen ONE thermometers (ThermoWorks, American Fork, UT) inserted

into the geometric center of each patty. Patties were equally cut into 8 wedges and served to consumers in a random order. Taste panels were held during the same week in a large, lecture-style classroom under fluorescent lighting. Each session lasted 1h and consisted of either 24 consumers (4 sessions) or 16 consumers (2 sessions). Samples were randomly assigned to a panel using an incomplete block design, such that each consumer evaluated a subset of treatments, balanced across panels to ensure equal representation of all treatments. Consumers were provided with an expectorant cup, fork, and napkin, as well as water, apple juice, and unsalted crackers to cleanse their palette between samples.

Each sample was evaluated for juiciness, tenderness, texture, beef flavor liking, and overall liking. Each trait was evaluated on a 0-100 continuous line scale anchored with descriptive terms at the ends and mid-points: 100 = extremely juicy, tender, firm, and like beef flavor extremely or like overall extremely; 50 = neither juicy nor dry, tough nor tender, firm nor soft or neither like or dislike beef flavor/overall; 0 = extremely dry, tough, soft, and dislike beef flavor extremely or dislike overall extremely. Additionally, consumers rated each trait as either acceptable or unacceptable.

Trained sensory panel evaluation

Trained sensory panelists were trained using the American Meat Science Association (AMSA) meat color measurement and sensory evaluation guidelines (American Meat Science Association, 2016; King et al., 2023). All trained visual panelists were subjected to the Farnsworth Munsell 100 Hue Color Vision Test (Munsell, Grand Rapids, MI), to screen for color blindness, and attended three or more training sessions prior to the start of evaluations, following procedures outlined in Lybarger et al. (2023) and (Frink et al., 2026). Panelists were trained using samples varying in redness and discoloration, representative of the entire scale (0 =

extremely dark red, 100 = bright, cherry red; 0 = no visible discoloration, 100 = complete discoloration). Visual anchors were provided at 2 points on the redness scale as well as 5 reference photos of ground beef at different points of discoloration. Responses were recorded on electronic tablets (Fire HD 8; Amazon, Seattle, WA) using a digital survey platform (Qualtrics Software, Provo, UT). Trained visual panel sessions were conducted at the same time each day. A minimum of 12 panelists evaluated redness and percentage discoloration of the packages designated for shelf-life evaluations using the above described scales.

Trained taste panels participated in a minimum of four 30 minute training sessions one week prior to panels using the methods and anchors described by Davis et al. (2021) and (Frink et al., 2026). Samples were thawed and cooked using the same procedures as consumer sensory panel evaluation. At the start of each panel, a representative sample of ground beef was fed and discussed to allow for calibration and prevent panelist drift. A total of 16 panel sessions were conducted. Samples were randomly assigned to a panel number using an incomplete block design, ensuring each session evaluated a subset of treatments balanced across all sessions to achieve equal representation of all treatments. During panel sessions, 8 trained taste panelists evaluated 5 samples for juiciness, tenderness, texture, beef-flavor intensity, and off-flavor intensity on 100-point continuous line scales (100 = extremely juicy, tender, firm, intense beef-flavor, and extreme off-flavor; 0 = extremely dry, tough, soft, bland beef flavor, and no off-flavor). Samples were evaluated in individual sensory booths under red-light conditions to prevent visual bias. Panelists were provided with water, apple slices, and unsalted crackers to serve as palette cleansers, as well as a napkin and expectorant cup. Responses were recorded using the same electronic tablets (Fire HD 8; Amazon, Seattle, WA) and digital survey (Qualtrics Software, Provo, UT) as trained visual and consumer sensory panel evaluations.

Objective color measurements

Instrumental color measurements were collected from each package designated for visual evaluation prior to each trained panel session. A Hunter Lab Miniscan spectrophotometer (Illuminant A, 2.54 cm aperture, 10° observer, Hunter Lab Associates Laboratory, Reston, VA) was used to collect Commission Internationale de l'Eclairage (CIE) L^* , a^* , and b^* values according to methods described in the AMSA Meat Color Measurement Guidelines (King et al., 2023). Three surface scans were taken per package and the readings were averaged. Additionally, spectral data were collected and used to calculate the percentages of oxymyoglobin (OMb) and metmyoglobin (MMb), following the AMSA Meat Color Measurement Guidelines (King et al., 2023).

Shear force and texture profile analysis

Patties designated for shear force and TPA were thawed and cooked using the same methods described for consumer sensory panel evaluation. Following the AMSA sensory evaluation guidelines (American Meat Science Association, 2016), samples were allowed to cool to room temperature (21-23°C) prior to testing. Two 2.5-cm wide strips were cut from the center of each patty; one to be used for shear force, the other for TPA. To measure shear force, each strip was sheared 6 times perpendicular to the cooked surface using a straight-edge slice-shear force blade attached to an INSTRON Model 5569 testing machine (Instron, Canton, MA). The six shear force values, recorded in kilograms (kg), were averaged to obtain a single shear force value per patty. For TPA, the strip was cut into three 2.5-cm squares to prevent crumbling of the sample. Each square was compressed to 70% of its original height in 2 consecutive cycles between flat, cylindrical plates at a crosshead speed of 100 mm/min. Following the procedures of Bourne (1978), hardness, cohesiveness, springiness, gumminess, and chewiness were calculated.

Hardness was reported as the peak force during the first compression cycle, representing a “first bite”. Cohesiveness was calculated as the ratio of the area under the curve for the second compression to that of the first compression. Springiness was recorded as the interval between the end of the first compression and the start of the second compression. Gumminess was calculated as the product of hardness and cohesiveness, and chewiness was calculated as the product of gumminess and springiness.

Lipid oxidation and proximate analysis

Lipid oxidation was determined using the thiobarbituric reactive substances (TBARS) assay similar to previous procedures done at KSU (Beyer et al., 2024; Dahmer et al., 2022; Decker et al., 2024a; Frink et al., 2026). Samples designated for lab analysis were thawed using the same methods as described previously. The thawed sample was packed into a 15 x 100 mm petri dish (VWR International, Randor, PA), to ensure no air pockets were present in the bottom of the dish. Samples were analyzed for protein, fat, and moisture using a FoodScan 2 (FOSS Analytical, Capital Region, Denmark). These samples were then frozen in liquid nitrogen, powdered using a commercial blender (model 51BL32, Waring Commercial, Torrington, CT), then stored at -80°C until analysis. Approximately 0.3 g of powdered sample was weighed and added to 2 mL prefilled bead tubes. 1.4 mL of trichloroacetic acid (TCA)/ thiobarbituric acid (20% w/v TCA: 15% w/v TBA) and 0.1 mL butylated hydroxytoluene were added to the sample. Samples were homogenized for 45 s using a bead homogenizer (Bead Blaster 24, Benchmark Scientific, Sayreville, NJ) and centrifuged at 2,000 x g for 5 min at 4°C. Supernatant was transferred to a 12 x 75 mm glass tube, then incubated at 70°C in a water bath for 30 minutes. Tubes were then cooled in an ice bath for 5 min. 200 µL of each sample were plated, in duplicate, in a 96- well plate as well as 200 µL of 0 to 25 µM of MDA standards to generate a standard curve. Plates

were read using a spectrophotometer (Eon, BioTek Instruments Inc., Winooski, VT) at 532 nm. The MDA concentration of each sample was calculated from the standard curve and recorded as mg MDA/kg of meat.

Statistical analysis

The statistical analysis was conducted using SAS (v. 9.4; SAS Institute, Inc., Cary, NC) PROC GLIMMIX. Data were analyzed as a completely randomized design with display day added as a repeated measure. The SLICE function was used to evaluate treatments within each day of display. An α of 0.05 was set for a level of significance. The Kenward-Roger adjustment was used in all analyses.

Results

Demographics

Demographic information collected from consumers who participated in the visual and taste panels is presented in Table 2.1. Visual consumer panelists were 48.4% male and 51.6% female, and consumer palatability panelists were 50.4% male and 49.6% female. Most visual and taste panel participants (65.6% and 71.1%, respectively) were between 20 to 29, 40 to 49, or 60 years of age or older. Respondents were predominantly Caucasian/White, representing 81.3% of visual panelists and 71.9% of taste panelists; however, African American, Asian, Latino, Native American, and mixed-race individuals were also represented. Most visual and taste panel participants reported living in households of two to four people (71.9% for both panels). A greater proportion of visual panelists reported being married (54.7%) compared with taste panelists (47.2%). Income levels differed slightly between panels, as 68.3% of visual panelists reported earning more than \$50,000 annually, whereas the majority of taste panelists (51.9%) reported earning less than \$50,000 per year. Panelists were generally well educated, with 51.5%

of visual panelists and 54.7% of taste panelists reporting completion of a college or post-college degree. Consumers who participated in visual evaluations reported lean-to-fat content as the most important factor when purchasing ground beef, followed by price and color. Additionally, most consumers reported eating beef between one and six times per week (82.9% of visual panelists and 83.6% of taste panelists).

Additional data was collected from taste panel participants about their ground beef preferences. Flavor was indicated to be the most important palatability trait when consuming ground beef by 62.5% of consumers; 44.5% of consumers also found flavor to be the most variable palatability trait. When asked about preferred degree of doneness, 25.8% of respondents preferred a medium-well degree of doneness. Lastly, the most common purchasing location for ground beef was a self-service retail case (56.3%), followed by purchasing directly from a processor or whole animal purchase (12.5%).

Consumer sensory panels

Results from consumer visual evaluations on day 3 of retail display are reported in Table 2.3. Appearance liking scores were the greatest ($P < 0.05$) for Fresh-50/Fresh-90, Fresh-80, and Frozen-50/Fresh-90 with scores of 85.7, 84.8, and 81.7, respectively. Samples produced from only thawed trim (Thawed-50/Thawed-90 and Thawed-80) were rated lower ($P < 0.05$) than samples made from thawed trim combined with fresh trim (Thawed-50/Fresh-90 and Fresh-50/Thawed-90). However, these samples still rated higher ($P < 0.05$) than Fresh-50/Frozen-90. In contrast, Frozen-50/Frozen-90 and Frozen-80 yielded the lowest ($P < 0.05$) appearance liking scores (17.8 and 14.4, respectively). Consumer willingness to purchase at retail price followed a similar trend with Fresh-50/Fresh-90, Fresh-80, and Frozen-50/Fresh-90 resulting in the greatest ($P < 0.05$) percentage of samples consumers would purchase compared to all other treatments.

Within the samples made from thawed trim, Thawed-50/Fresh-90 and Fresh-50/Thawed-90 had a higher ($P < 0.05$) percentage of consumers willing to purchase at retail than Thawed-50/Thawed-90. On the other hand, Frozen-50/Frozen-90 resulted in a lower ($P < 0.05$) percentage of samples consumers were willing to purchase compared to all combinations besides Frozen-80. Consumer willingness to purchase at a retail price ranged from over 95.3% for Fresh-50/Fresh-90 and Fresh-80 treatments to under 5% for Frozen-50/Frozen-90 and Frozen-80 samples. When consumers who declined to purchase a sample at retail were asked if they would purchase the product at a discounted price, responses also differed ($P < 0.05$) among treatments. The highest percentage of consumers willing to purchase at a discounted price occurred for Thawed-50/Fresh-90 (76.2%) whereas the lowest percentage was observed for Frozen-80 (4.9%).

Consumer taste panel palatability ratings are shown in Table 2.4. Treatments differed ($P < 0.05$) in juiciness, tenderness, texture, and beef-flavor liking ratings while overall liking and purchasing likelihood were similar ($P > 0.05$) across treatments. The Thawed-50/Fresh-90 resulted in higher ($P < 0.05$) juiciness scores, being similar ($P > 0.05$) to only Fresh-50/Fresh-90 and Thawed-80. The greatest ($P < 0.05$) tenderness scores were observed for Frozen-50/Frozen-90 and Frozen-80, suggesting patties produced from frozen lean trim were perceived as more tender compared to all other combinations. However, texture liking followed an inverse trend to tenderness as the Frozen-50/Frozen-90 and Frozen-80 treatments resulted in the lowest ($P < 0.05$) texture scores compared with all other treatments. The Thawed-50/Fresh-90 treatment resulted in higher ($P < 0.05$) beef-flavor ratings compared to Frozen-80 while being similar to Frozen-50/Frozen-90, Frozen-50/Fresh-90, Fresh-50/Fresh-90, Fresh-80, and Thawed-80. In contrast, Fresh-50/Frozen-90 received lower ($P < 0.05$) beef-flavor ratings, remaining similar to Frozen-50/Frozen-90, Frozen-80, Fresh-50/Thawed-90, Thawed-50/Thawed-90, and Fresh-

50/Fresh-90. These results suggest that incorporating thawed trim with fresh trim supported more favorable flavor development, whereas inclusion of frozen lean trim reduced flavor liking.

The percentage of samples rated acceptable for each palatability trait is presented in Table 2.5. No differences ($P > 0.05$) were observed among treatments for acceptability of juiciness, tenderness, texture, overall liking, or purchase intent. However, Thawed-50/Fresh-90 resulted in the greatest ($P < 0.05$) beef flavor acceptability, remaining similar ($P > 0.05$) only to Frozen-50/Fresh-90.

Trained sensory panels

Trained sensory panel color evaluations are reported in Figure 2.1 and 2.2. On day 0 of display, the Frozen-80 and Frozen-50/Frozen-90 treatments had higher ($P < 0.05$) redness scores compared to all other treatments besides Fresh-50/Frozen-90. Conversely, the Thawed-50/Thawed-90 treatment had the lowest ($P < 0.05$) redness scores, being similar to Fresh-80 and Thawed-50/Fresh-90. On day 1 of retail display, the Frozen-80 treatment maintained higher ($P < 0.05$) redness scores, still being similar to Frozen-50/Frozen-90 and Fresh-50/Frozen-90. As retail display progressed, redness scores declined for all treatments and differences between treatments became less pronounced. The Fresh-50/Frozen-90, Frozen-80, and Fresh-80 treatments had the highest ($P < 0.05$) redness scores by day 2 of display. The lowest ($P < 0.05$) redness scores were found in the Frozen-50/Fresh-90 and Thawed-50/Fresh-90 treatments, with all other treatments similar ($P > 0.05$) to both the highest and lowest scores. Day 3 of display showed the Fresh-50/Fresh-90 treatment had higher ($P < 0.05$) redness scores than Frozen-50/Frozen-90. All other treatments were similar ($P > 0.05$) to both. This changed on day 4 of display, where Fresh-50/Fresh-90 had lower ($P < 0.05$) redness scores than the Frozen-80 treatment, with all other treatments being similar ($P > 0.05$) to both. Trained panelists found no

differences ($P > 0.05$) in redness on day 5 of display, or in discoloration across treatments over the display period. However, discoloration did increase ($P < 0.05$) each day of display, ranging from 3.1% on day 0 to 70.0% on day 5 (Figure 2.2).

Results from trained sensory panel evaluations of palatability traits are presented in Table 2.8. Trained panelists did not detect differences in juiciness among all treatments ($P > 0.05$). Frozen-80 produced the highest ($P < 0.05$) tenderness scores but was similar ($P > 0.05$) to Frozen-50/Frozen-90. While the lowest ($P < 0.05$) tenderness scores were observed for Thawed-50/Thawed-90, Fresh-50/Thawed-90, Fresh-50/Fresh-90, and Fresh-80 treatments ($P > 0.05$). Texture evaluations showed an inverse trend to tenderness due to the inverse anchors of the scales. The Frozen-50/Frozen-90 and Frozen-80 treatments resulted in the lowest texture scores ($P < 0.05$). By contrast, Thawed-50/Thawed-90 had a higher ($P < 0.05$) texture score compared to the Thawed-80 treatment. Trained panelists rated all treatments made from fresh lean trim (Frozen-50/Fresh-90, Thawed-50/Fresh-90, and Fresh-50/Fresh-90), as well as the Fresh-80 and Thawed-80 treatments, the highest ($P < 0.05$) for beef-flavor intensity. However, the treatments made with frozen lean trim and the Frozen-80 treatment resulted in the lowest ($P < 0.05$) beef-flavor intensity scores, with the Fresh-50/Frozen-90 and Frozen-80 treatments being similar ($P > 0.05$) to Fresh-50/Thawed-90 and Thawed-50/Thawed-90. Off-flavor intensity followed an inverse trend to that of beef flavor intensity. The Frozen-80 treatment resulted in the highest off-flavor intensity scores ($P < 0.05$), while remaining similar ($P > 0.05$) to Frozen-50/Frozen-90. Treatments containing fresh or thawed trim combinations generally resulted in lower off-flavor intensity scores compared with the frozen trim combinations, with Fresh-50/Fresh-90, Fresh-80, and Thawed-50/Thawed-90 producing the lowest off-flavor scores ($P < 0.05$). The off-flavor detected by trained panelists was most commonly described as oxidized.

Objective color measurements

Figures 2.3, 2.4, 2.5, and 2.6 display objective color data (CIE L^* , a^* , and spectral data) for each day of display. On day 0 of retail display, Frozen-80 produced the highest ($P < 0.05$) L^* values, indicating the lightest samples, followed by Frozen-50/Frozen-90 and Fresh-50/Frozen-90, then Thawed-80 ($P < 0.05$). In contrast, the remaining treatments containing thawed trim (Fresh-50/Thawed-90, Thawed-50/Fresh-90, and Thawed-50/Thawed-90) and Fresh-80 produced lower L^* values, with Thawed-50/Fresh-90 being similar ($P > 0.05$) to Fresh-50/Thawed-90 and Fresh-80, but higher ($P < 0.05$) than Thawed-50/Thawed-90. A similar pattern was observed for the remaining duration of display, with Frozen-80 having the highest ($P < 0.05$) L^* values with Thawed-50/Thawed-90 producing the lowest ($P < 0.05$) L^* values. Furthermore, all treatments became darker over the display period, with Thawed-50/Thawed-90 resulting in the greatest decline (14.0%).

On day 0 of display, Fresh-50/Frozen-90 and Frozen-50/Frozen-90 produced greater ($P < 0.05$) a^* values (30.7 and 30.1, respectively) compared to all treatments other than Fresh-50/Fresh-90 and Frozen-50/Fresh-90 ($P > 0.05$). However, Thawed-50/Fresh-90, Thawed-50/Thawed-90, Fresh-80, and Thawed-80 produced the lowest ($P < 0.05$) a^* values on day 0 of display. By day 1 of display, Fresh-50/Fresh-90 produced the greatest ($P < 0.05$) a^* values, whereas Frozen-50/Frozen-90 declined substantially and was among the lowest treatments. Notably, Frozen-50/Frozen-90 decreased 23.9% in a^* from day 0 to day 1, indicating a rapid loss in redness early in display. This divergence became even more apparent by day 2, when Fresh-50/Fresh-90 had the greatest ($P < 0.05$) a^* values and Frozen-50/Frozen-90 had the lowest ($P < 0.05$) values. On day 3 of retail display, Fresh-50/Fresh-90 maintained higher ($P < 0.05$) a^* values, similar ($P > 0.05$) to Fresh-80, while Frozen-50/Frozen-90 and Frozen-80 continued to be

the least ($P < 0.05$) red samples, with Fresh-50/Frozen-90 remaining similar ($P > 0.05$). The last two days of display showed treatments made from entirely frozen trim, as well as frozen lean trim (Frozen-50/Frozen-90, Frozen-80, and Fresh-50/Frozen-90) had the lowest ($P < 0.05$) a^* values compared to all other treatments.

Following a similar trend to a^* measurements, percentage of oxymyoglobin (OMb) was highest ($P < 0.05$) in treatments containing frozen lean trim, most notably Fresh-50/Frozen-90 and Frozen-80 which were higher ($P < 0.05$) than Thawed-50/Fresh-90, but similar ($P > 0.05$) to Frozen-50/Frozen-90, Frozen-50/Fresh-90, Fresh-50/Fresh-90, and Fresh-80. The Thawed-50/Thawed-90 treatment calculated the lowest ($P < 0.05$) percentage of OMb on day 0, remaining similar only to Thawed-80. As retail display progressed, OMb percentages declined across treatments. By day 3, treatments containing fresh lean trim, particularly Frozen-50/Fresh-90, Fresh-50/Fresh-90, and Fresh-80 had higher ($P < 0.05$) percentages of OMb than other treatments, with Fresh-50/Fresh-90 having greater ($P < 0.05$) OMb than Frozen-50/Fresh-90.. Days 4 and 5 showed treatments containing frozen lean trim (Frozen-50/Frozen-90, Fresh-50/frozen-90, and Frozen-80) calculated the lowest ($P < 0.05$) percentage of OMb.

Metmyoglobin (MMb) percentages exhibited the opposite pattern of OMb. On day 0 of display, Thawed-50/Thawed-90 had a higher ($P < 0.05$) percentage of MMb compared to all treatments other than Fresh-50/Thawed-90, and Thawed-80. However, the Fresh-50/Fresh-90 treatment had a lower ($P < 0.05$) MMb percentage compared to all treatments besides Frozen-50/Frozen-90, Frozen-50/Fresh-90, Fresh-50/Frozen-90, Frozen-80, Thawed-50/Fresh-90, and Fresh-80. Interestingly, no differences ($P > 0.05$) in the percentage of MMb among treatments were found on day 1 of display. However, as retail display continued, specifically days 4 and 5,

Frozen-50/Frozen-90, Fresh-50/Frozen-90, and Frozen-80 displayed the greatest ($P < 0.05$) percentage of MMb compared to all other treatments.

Shear force, texture profile analysis, and lipid oxidation

Results for shear force, texture profile analysis (TPA), and lipid oxidation (TBARS) are shown in Table 2.9. Treatments derived from only frozen trim (Frozen-50/Frozen-90 and Frozen-80) resulted in the lowest shear force values ($P < 0.05$), followed by Fresh-50/Frozen-90 (1.1 and 1.5 kg, respectively). Conversely, Fresh-50/Fresh-90 had the highest shear force values ($P < 0.05$; 3.9 kg), followed by Frozen-50/Fresh-90, Fresh-50/Thawed-90, Thawed-50/Fresh-90, Thawed-50/Thawed-90, and Thawed-80, with Fresh-80 being similar ($P > 0.05$) to both but higher ($P < 0.05$) than Fresh-50/Frozen-90.

Texture profile analysis measurements showed the Frozen-80 treatment had the lowest ($P < 0.05$) hardness, gumminess, springiness, and chewiness values. Moreover, Frozen-50/Frozen-90 produced the lowest ($P < 0.05$) cohesiveness and springiness values, being similar ($P > 0.05$) to Frozen-80 for both, as well as Thawed-50/Fresh-90 for springiness. In contrast, Fresh-50/Fresh-90 and Fresh-80 produced the most cohesive patties ($P < 0.05$) compared to all other treatments. Proximate analysis showed treatments averaged $19.1\% \pm 2.2\%$ fat, $61.0\% \pm 1.5\%$ moisture, and $16.3\% \pm 0.9\%$ protein.

Lipid oxidation, measured by the TBARS assay, showed treatments containing frozen lean trim had generally higher TBARS values. Frozen-80 resulted in the most lipid oxidation ($P < 0.05$, 3.06 mg MDA/kg), followed by Frozen-50/Frozen-90, then Fresh-50/Frozen-90 (2.71 and 2.26 mg MDA/kg, respectively). In contrast, Fresh-50/Fresh-90, showed the least ($P < 0.05$, 0.40 mg MDA/kg) lipid oxidation, followed by Frozen-50/Fresh-90, Fresh-50/Thawed-90,

Thawed-50/Fresh-90, and Fresh-80. Thawed-50/Thawed-90 was similar ($P > 0.05$) to both the lowest and second lowest values.

Discussion

Much of the existing research surrounding freezing has focused on whole-muscle beef, where freezing and thawing have been shown to affect purge loss, color stability, oxidation, and, in some cases, sensory traits (Jeong et al., 2011; Hergenreder et al., 2013; Aroeira et al., 2017; Beyer et al., 2024; Decker et al., 2024). However, relatively little research has examined how the cold chain management of raw trim affects the quality of the ground beef produced from it. It was previously assumed the fresh and frozen quality differences would translate to the ground counterpart; however, the mechanical changes caused by grinding could further accelerate the impact of freezing. Grinding increases surface area, redistributes fat and proteins, and creates more opportunities for oxygen exposure potentially accelerating both lipid and myoglobin oxidation (Faustman et al., 2010; Leygonie et al., 2012; Mancini & Hunt, 2005). The present study determined the cold chain management does impact meat quality as frozen beef trim decreased in color stability, textural properties, and purchase likelihood while increasing in off flavor and lipid oxidation.

Ground Beef Color and Visual Acceptability

Ground beef quality is shaped by multiple factors, but for fresh retail products, color remains one of the most important drivers of consumer acceptance. Consumers consistently associate bright, cherry-red color with freshness, and deviations from that expected color reduce willingness to purchase (Frink et al., 2026; Lybarger et al., 2023; Mancini & Hunt, 2005). The most obvious practical effect of cold chain management was found in the consumer visual data. Consumers strongly preferred treatments produced from fresh trim or combinations containing

fresh trim, whereas treatments produced entirely from frozen trim received the lowest appearance liking scores and the lowest purchase likelihood values. Consumers routinely use beef color as a proxy for freshness, and even small changes in redness or discoloration can cause meaningful declines in purchase intent (Feuz et al., 2020; Lybarger et al., 2023; Thies et al., 2024). The difference in retail purchase intent, which ranged from 95.3% for the most acceptable treatments (Fresh-50/Fresh-90 and Fresh-80) to 3.1% for the least acceptable treatment (Frozen-50/Frozen-90), indicates potential for a substantial loss in retail marketability. This decline is especially notable when compared with Lybarger et al. (2023), who reported that an appearance score of 49.8 corresponded with a 50% likelihood of purchase. By comparison, Frozen-50/Frozen-90 received an appearance score of 17.8 but resulted in a 3.1% purchase intent, indicating that grinding trim directly from the frozen state reduced visual acceptability to a level far below the threshold associated with meaningful consumer willingness to purchase. Furthermore, ground beef produced from combinations of fresh and thawed trim resulted in significantly higher consumer appearance liking scores and corresponding purchase likelihood, which suggests thawing trim prior to grinding produced a product more acceptable to consumers.

Trained panelists detected treatment differences in redness during early and mid-display, although discoloration scores did not differ across treatments. This distinction is important as trained panelists evaluate redness and discoloration as separate traits, whereas consumers respond to the overall visual impression of the product without prior training (King et al., 2023; Lybarger et al., 2023). Thus, the absence of treatment differences in discoloration could indicate the consumer responses were heavily driven by a vast variation in redness. These differences in redness and overall appearance were sufficient enough to influence consumer willingness to purchase without massive changes in discoloration which is in contrast to the study conducted by

Lybarger et al. (2023). Lybarger et al. (2023) reported a trained panel redness score of 53.6 corresponded with 50% consumer purchase intent. In the present study, Frozen-50/Frozen-90 fell well below that threshold, resulting in only 3.1% purchase intent and a trained panel redness score of 35.8 on the day of consumer evaluations. Additionally, Lybarger et al. (2023) deduced consumers to be sensitive to discoloration and attributed changes in purchase likelihood to be heavily driven by discoloration levels, with a 50% consumer purchase intent at a 37.8 trained panel discoloration score. This study supports even with equal discoloration; consumers use other visual cues to make purchasing decisions.

Consequently, even when discoloration did not differ among treatments, reductions in redness and overall appearance still greatly reduced retail acceptability. In other words, the product did not need to exhibit dramatically greater visible discoloration for consumers to reject it if redness, brightness, and general appearance already deteriorated and shifted from what is normally found on a retail shelf (Feuz et al., 2020; Frink et al., 2026; Lybarger et al., 2023; Thies et al., 2024). Collectively, these results demonstrate that visual differences of this magnitude can translate into meaningful losses in retail marketability and product value even with the same discoloration.

This magnitude of color change is further supported by instrumental color data. Lybarger et al. (2023) showed that a^* values and metmyoglobin percentage were closely tied to purchase probability in ground beef, and the present study followed that same pattern. In the present study, Frozen-50/Frozen-90 resulted in an a^* value of 11.8 on the day of consumer evaluations, which was far below the a^* value of 21.6 that Lybarger et al. (2023) associated with 50% consumer purchase intent. This massive change in a^* values help explain the differences in purchase intent without the same decline of discoloration. Additionally, Frozen-80 consistently produced the

highest L^* values, indicating the lightest appearance, whereas thawed trim treatments, particularly Thawed-50/Thawed-90, were darker across much of display.

Redness values and the relative proportions of OMb and MMb changed over time in a way that revealed lower color stability in treatments containing frozen lean trim. The rapid drop of redness scores and a^* values for the treatments containing frozen trim is supported in literature and indicates a rapid loss of color stability contributing to the reduced scores and lower consumer purchasing likelihood.

Early in display, some frozen trim treatments exhibited relatively high a^* values and OMb percentages. This pattern is also consistent with previous work showing that freezing can damage muscle cell membranes, releasing prooxidant compounds that may promote initial bloom at the meat surface (Aroeira et al., 2017; Beyer et al., 2024; Leygonie et al., 2012). However, those same changes can create conditions that accelerate myoglobin oxidation and reduce color stability during display (Faustman et al., 2010; Mancini & Hunt, 2005). That instability became more apparent as display progressed, as treatments containing frozen lean trim, including Frozen-50/Frozen-90, Fresh-50/Frozen-90, and Frozen-80, lost redness more rapidly and accumulated greater MMb percentages during later display. This agrees with findings from whole-muscle beef studies in which frozen product may initially appear comparable to fresh product but deteriorates more rapidly during retail display (Aroeira et al., 2017; Hergenreder et al., 2013; Jeong et al., 2011). During later display, treatments containing thawed trim exhibited increased a^* values and greater OMb percentages relative to earlier display days, with trends that more closely aligned with fresh trim treatments than with treatments ground directly from the frozen state. This suggests that the major source of quality loss was not frozen storage alone, but the use of trim in a frozen state during grinding. These objective color data support the consumer

results, as treatments with more favorable instrumental color characteristics on the day of consumer evaluation were also the treatments that received the greatest appearance liking scores and the highest percentage of samples consumers were willing to purchase at full retail price. This demonstrates instrumental color differences were directly associated with meaningful differences in retail marketability and product value.

Ground Beef Flavor and Lipid Oxidation

The off-flavor and flavor liking results lead to one of the most applicable findings of the study highlighting not only a loss of marketability but palatability. Trained panelists found greater off-flavor intensity in the frozen-only treatments, particularly Frozen-80 and Frozen-50/Frozen-90 and described the off-flavor most commonly as oxidized. Consumer panels showed differences in beef-flavor liking and acceptability that generally favored treatments containing fresh or thawed trim. In the present study, both groups identified treatments made from frozen trim, especially frozen lean trim, were more prone to off flavor development. The TBARS data represented one of the most important findings of the present study because they provided a direct explanation for the flavor deterioration observed in treatments containing frozen lean trim. Using 1 mg MDA/kg of meat as the reported human detection threshold for lipid oxidation, four treatments exceeded that value (Zhang et al., 2019). This pattern was supported by trained sensory panel detection with greater oxidized off-flavor development in those same treatments. Among all treatments, Frozen-80 resulted in the greatest lipid oxidation, followed by Frozen-50/Frozen-90 and Fresh-50/Frozen-90, whereas Fresh-50/Fresh-90 had the lowest oxidation values. The difference between the highest and lowest treatments exceeded sevenfold, indicating a substantial loss in oxidative stability. Although lipid oxidation is known to increase throughout retail display in ground beef, the present study demonstrated that trim state prior to grinding had

a major influence on the magnitude of oxidation even on day 3 of display (Frink et al., 2026). Prior to this study, a range of this magnitude was not found for this display period highlighting the rapid deterioration of quality from frozen beef trim used in ground beef.

Almost all previous work explored whole muscle cuts whereas the effects of freezing beef trim prior to grinding remain relatively unexplored (Rahman et al., 2015; Setyabrata & Kim, 2019). Setyabrata & Kim (2019) reported greater lipid oxidation in previously frozen and thawed strip steaks than in never-frozen strip steaks on d 0 and d 7 of display, but the magnitude of those differences was considerably smaller than what was observed in the present study. In contrast, Beyer et al. (2024) reported no differences in lipid oxidation between fresh and previously frozen strip steaks when no display period was included indicating the lipid oxidation occurs during the display period and not during the frozen storage. Taken together, these reports suggest that the effects of freezing on oxidative stability likely depend on product form, storage history, and the presence or absence of retail display, which may explain the inconsistency across studies.

This pattern is also consistent with the known effects of freezing and comminution on meat systems. Freezing can disrupt membrane integrity and cellular structure, exposing lipids, myoglobin, and other prooxidant components to oxygen, while grinding further accelerates oxidation by increasing surface area and distributing those substrates throughout the product (Faustman et al., 2010; Mancini & Hunt, 2005). As a result, ground beef is particularly susceptible to oxidative deterioration, and any damage caused by frozen storage may be amplified once trim is ground.

The same phenomenon that caused a rapid loss of color stability could be attributing to the magnitude of differences in lipid oxidation. While protein and fat oxidation have different mechanisms, they are generally accepted to occur at the time and due to similar oxidants

(Faustman et al., 2010; Mancini & Hunt, 2005). Moreso, in the present study, TBARS values aligned closely with trained sensory panel responses, strengthening the conclusion that predominately frozen beef trim increased lipid oxidation and, consequently, off-flavor development. Therefore, the greater oxidation observed in treatments containing frozen trim likely contributed directly to the greater off-flavor intensity detected by trained panelists and the poorer consumer flavor responses observed in those same treatments. When considered alongside the trained sensory and color data, these results indicate that treatments containing predominately frozen trim deteriorated in quality more rapidly than the other trim combinations through reduced color stability, greater oxidative deterioration, and increased off-flavor development. These pathways interact in meat, with oxidative changes in one system capable of accelerating deterioration in the other system (Faustman et al., 2010; Mancini & Hunt, 2005). That overlap strongly suggests grinding trim from a frozen state altered the product in a way that promoted oxidation broadly, rather than affecting only one quality trait at a time. This may explain why the same frozen-only treatments repeatedly emerged as the lowest performers across multiple measurements.

Ground Beef Juiciness, Texture, and Structural Properties

Both consumer and trained sensory panels identified textural differences among treatments. Consumers rated the frozen-only treatments as more tender, and they also rated them as softer for texture. Trained panelists described the same pattern, with frozen treatments receiving greater tenderness scores but lower texture scores due to the inverse of the anchors. This distinction is important in ground beef, where grinding already reduces much of the variation in toughness associated with whole-muscle cuts and shifts palatability differences toward factors such as product structure, moisture retention, lipid stability, and processing

conditions (Beavers et al., 2017; McHenry et al., 2013; O’Quinn et al., 2024). Previous work has shown that relatively small processing changes can alter sensory outcomes in ground beef. Beavers et al. (2017), for example, reported patties with a grind size of 0.64 cm had higher consumer ratings for overall liking, flavor liking, and texture liking than bowl-chopped patties, indicating that grind characteristics can influence the eating experience in addition to composition. In the present study, the greater tenderness and reduced texture scores in frozen-only treatments suggests cold chain management strategy functioned in a similar way by altering the physical structure of the final product. These results suggest that grinding trim from a frozen state produced a softer, less cohesive product matrix.

The shear force and TPA data strongly supported that interpretation. Frozen-80 and Frozen-50/Frozen-90 produced the lowest shear force values, which aligned with the higher tenderness scores reported by both consumers and trained panelists. At the same time, those same treatments also had the lowest hardness, cohesiveness, gumminess, and chewiness values. In contrast, fresh and thawed combinations, particularly Fresh-50/Fresh-90, produced a firmer and more cohesive product. These measurements indicate that patties made from frozen trim were mechanically weaker and less structurally integrated after cooking. This helps explain why both consumers and trained panelists perceived them as tender but texturally softer. This mechanical explanation is supported by previous research describing the structural effects of freezing on meat. Ice crystal formation during freezing can disrupt muscle fibers and cell membranes, reduce water-holding capacity, and increase purge loss after thawing (Dang et al., 2021; Leygonie et al., 2012; Park & Kim, 2024). In a ground system, those changes would be expected to alter the way lean and fat particles interact and bind during grinding and cooking.

The present TPA results suggest that such disruption of cellular structure reduced the ability of the frozen treatments to form a cohesive cooked matrix.

Conclusion

These results indicate the most severe quality losses occurred when trim was ground directly from the frozen state, particularly when the lean component remained frozen. Frozen treatments resulted in the lowest purchase intent, accumulated the most oxidation, developed the greatest off-flavor intensity, and produced the least cohesive cooked texture. In contrast, treatments produced from fresh or thawed trim maintained greater overall quality and were generally more similar to one another across shelf life and palatability measurements. Collectively, these results indicate that frozen storage of beef trim is not inherently the primary source of quality loss. Rather, the greatest deterioration occurred when trim was ground while still frozen and displayed in a retail case. Given the continued importance of frozen trim in the beef supply chain for transportation, storage, and import applications, these findings suggest that frozen trim can remain part of the beef supply chain, provided it is thawed prior to grinding rather than ground while still frozen.

Table 2.1 Consumer panelist demographic characteristics from visual evaluation (N = 64) and taste evaluation (N = 128).

Characteristic	Response	Percentage of consumers (visual)	Percentage of consumers (taste)
Gender	Male	48.4	50.4
	Female	51.6	49.6
Age	Under 20	7.8	4.7
	20 to 29 years old	21.9	36.7
	30 to 39 years old	14.1	12.5
	40 to 49 years old	23.4	15.6
	50 to 59 years old	12.5	11.7
	60 or over	20.3	18.8
Ethnic origin	African American	0.0	0.8
	Asian	10.9	11.7
	Caucasian/White	81.3	71.9
	Latino	4.7	13.3
	Native American	0.0	0.8
	Mixed Race	1.6	0.8
	Other	1.6	0.8
Marital status	Single	45.3	52.8
	Married	54.7	47.2
Household size	1 person	17.2	23.4
	2 People	40.6	43.8
	3 People	18.8	14.8
	4 People	12.5	13.3
	5 People	7.8	1.6
	6 People	3.1	1.6
	> 6 People	0.0	1.6
Household income level	< \$25,000	19.0	34.6
	\$25,000 - \$34,999	6.3	7.1
	\$35,000 - \$49,999	6.3	10.2
	\$50,000 - \$74,999	22.2	13.4
	\$75,000 - \$99,999	12.7	12.6
	\$100,000 - \$149,999	17.5	14.2
	\$150,000 - \$199,999	15.9	5.5
	> \$199,999	0.0	2.4
Education level	Non-High School Graduate	1.6	0.8
	High School Graduate	15.6	14.8
	Some College / Technical School	31.3	29.7
	College Graduate	28.1	35.9
	Post-College Graduate	23.4	18.8
Most important factor when purchasing ground beef	Color	18.8	
	Lean/Fat Content	45.3	
	Packaging Content	0.0	
	Price	26.6	
	Primal (ex: ground chuck or ground round)	1.6	
	Production Practices (ex. grass-fed, natural, USDA Organic)	6.3	
	Other	1.6	
Weekly beef consumption	0 times	1.6	0.8
	1 to 3 times	64.1	52.3
	4 to 6 times	18.8	31.3
	7 to 9 times	9.4	7.0
	10 or more times	6.3	8.6

Table 2.2 Consumer panelist ground beef preference characteristics from taste evaluation (N = 128).

Characteristic	Response	Percentage of consumers
Most important palatability trait when consuming ground beef	Flavor	62.5
	Tenderness	20.3
	Juiciness	17.2
Most variable palatability trait when consuming ground beef	Flavor	44.5
	Tenderness	32.0
	Juiciness	23.5
Preferred degree of doneness when consuming ground beef	Very Rare	0.0
	Rare	2.3
	Medium- Rare	27.3
	Medium	24.2
	Medium- Well	25.8
	Well Done	18.0
	Very Well Done	2.3
Most common source of purchasing ground beef	Full- service meat counter	9.4
	Self- service case/ pre-packaged	56.3
	Local butcher shop	10.2
	Self- sourced (from your own animals)	6.3
	Purchased directly and processed (whole/ half beef)	12.5
	Subscription service (ButcherBox, Good Ranchers, etc.)	1.6
	Other	3.9

Table 2.3 Least-squares means for consumer appearance liking, and percentage of samples consumers would purchase at a retail or discounted price.

Treatment	Appearance Liking ²	% Retail ³	% Discounted ⁴
Frozen-50/Frozen-90	17.78 ^e	3.1 ^f	14.5 ^{cd}
Frozen-50/Fresh-90	81.69 ^a	93.8 ^a	75.0 ^{ab}
Fresh-50/Frozen-90	29.85 ^d	14.1 ^e	23.6 ^{bcd}
Frozen-80	14.35 ^e	4.7 ^{ef}	4.9 ^d
Fresh-50/Thawed-90	59.77 ^b	56.3 ^{bc}	46.4 ^{abc}
Thawed-50/Fresh-90	62.94 ^b	67.2 ^b	76.2 ^a
Thawed-50/Thawed-90	42.67 ^c	32.8 ^d	39.5 ^{abc}
Fresh-50/Fresh-90	85.66 ^a	95.3 ^a	33.3 ^{abcd}
Fresh-80	84.82 ^a	95.3 ^a	66.7 ^{abc}
Thawed-80	47.81 ^c	45.3 ^{cd}	40.0 ^{abc}
SEM ¹	4.78	0.72	1.22
<i>P</i> - value	< 0.01	< 0.01	< 0.01

^{a-f}Least-squares means within the same column without a common superscript differ ($P < 0.05$).

¹Standard error (largest) of least-squares means. SEM = standard error of the mean.

²Sensory scores: 0 = extremely dislike; 100 = extremely like.

³Percentage of samples consumers would purchase at retail price.

⁴Percentage of samples consumers would not purchase at retail price but would be purchased at a discounted price.

Table 2.4 Least-squares means for consumer (N = 128) ratings of palatability attributes.

Treatment	Juiciness ²	Tenderness ²	Texture ²	Beef- Flavor ³	Overall Liking ³	Purchase Likelihood ⁴
Frozen-50/Frozen-90	67.3 ^{ab}	70.0 ^a	46.4 ^d	57.7 ^{abcde}	62.2	58.0
Frozen-50/Fresh-90	71.5 ^a	66.8 ^{ab}	54.5 ^{bc}	63.1 ^{abc}	65.7	61.4
Fresh-50/Frozen-90	54.1 ^c	61.6 ^{bc}	54.1 ^c	51.7 ^e	54.4	50.0
Frozen-80	64.0 ^{ab}	69.4 ^a	40.5 ^d	54.7 ^{de}	58.7	54.8
Fresh-50/Thawed-90	61.0 ^{bc}	54.6 ^d	59.6 ^{abc}	56.0 ^{cde}	58.6	55.2
Thawed-50/Fresh-90	63.2 ^{ab}	58.1 ^{cd}	61.0 ^{ab}	65.5 ^a	63.7	64.9
Thawed-50/Thawed-90	65.1 ^{ab}	58.0 ^{cd}	61.7 ^a	57.3 ^{bcde}	59.5	56.5
Fresh-50/Fresh-90	65.4 ^{ab}	56.9 ^{cd}	59.3 ^{abc}	58.8 ^{abcde}	59.6	57.1
Fresh-80	65.2 ^{ab}	61.4 ^{bcd}	57.8 ^{abc}	64.1 ^{ab}	61.0	60.7
Thawed-80	61.4 ^{bc}	60.0 ^{bcd}	62.1 ^a	61.8 ^{abcd}	62.0	60.6
SEM ¹	3.52	2.83	3.13	3.10	3.11	3.47
<i>P</i> -value	0.04	< 0.01	< 0.01	0.02	0.29	0.10

^{a-e}Least-squares means within the same column without a common superscript differ ($P < 0.05$).

¹Standard error (largest) of least-squares means. SEM = standard error of the mean.

²Sensory scores: 0 = extremely dry, tough, soft; 100 = extremely juicy, tender, firm.

³Sensory scores: 0 = extremely dislike; 100 = extremely like.

⁴Sensory scores: 0 = extremely unlikely; 100 = extremely likely.

Table 2.5 Least-squares means for percentage of samples rated as acceptable for palatability characteristics by consumers (N = 128).

Treatment	Juiciness	Tenderness	Texture	Beef-Flavor	Overall Liking	Purchase Intent ²
Frozen-50/Frozen-90	89.5	89.7	88.9	78.6 ^b	84.4	69.8
Frozen-50/Fresh-90	90.0	94.3	92.9	86.1 ^{ab}	91.6	75.4
Fresh-50/Frozen-90	72.6	90.2	92.2	73.3 ^b	83.2	60.9
Frozen-80	77.6	89.2	87.0	75.8 ^b	76.9	63.6
Fresh-50/Thawed-90	79.2	85.4	82.1	76.3 ^b	77.5	63.0
Thawed-50/Fresh-90	91.6	88.3	87.8	96.3 ^a	96.9	81.3
Thawed-50/Thawed-90	84.2	83.6	85.6	73.2 ^b	86.0	64.9
Fresh-50/Fresh-90	84.2	74.9	84.8	75.8 ^b	80.7	62.3
Fresh-80	86.9	91.1	89.0	80.5 ^b	89.1	74.8
Thawed-80	87.2	87.0	86.9	80.1 ^b	86.3	67.6
SEM ¹	5.10	4.76	4.17	5.17	5.15	5.99
<i>P</i> - value	0.13	0.21	0.69	0.03	0.14	0.16

^{a-b}Least-squares means within the same column without a common superscript differ ($P < 0.05$).

¹Standard error (largest) of least-squares means. SEM = standard error of the mean.

²Percentage of samples consumers would purchase based on the overall liking of the sample.

Table 2.6 Least-squares means for trained sensory panelist palatability scores for all treatments.

Treatment	Juiciness	Tenderness	Texture	Beef-Flavor	Off-Flavor
Frozen-50/Frozen-90	55.2	67.4 ^{ab}	43.6 ^d	33.8 ^d	38.3 ^{ab}
Frozen-50/Fresh-90	57.3	60.3 ^{cd}	65.0 ^{ab}	39.5 ^a	4.4 ^e
Fresh-50/Frozen-90	57.6	66.1 ^b	52.6 ^c	35.6 ^{cd}	32.8 ^b
Frozen-80	57.3	71.3 ^a	39.3 ^d	34.7 ^{cd}	48.1 ^a
Fresh-50/Thawed-90	57.1	59.7 ^{de}	65.5 ^{ab}	37.0 ^{bc}	27.5 ^{bc}
Thawed-50/Fresh-90	63.8	64.5 ^b	63.7 ^{ab}	40.0 ^a	3.7 ^e
Thawed-50/Thawed-90	54.2	56.4 ^e	68.2 ^a	36.7 ^{bc}	18.3 ^{cd}
Fresh-50/Fresh-90	59.5	59.9 ^{de}	66.9 ^{ab}	39.8 ^a	12.3 ^{de}
Fresh-80	55.7	59.5 ^{de}	65.6 ^{ab}	38.8 ^{ab}	12.4 ^{de}
Thawed-80	58.5	64.2 ^{bc}	62.9 ^b	39.8 ^a	19.3 ^{cd}
SEM ¹	2.17	1.59	2.14	0.91	5.21
<i>P</i> - value	0.10	< 0.01	< 0.01	< 0.01	< 0.01

^{a-e}Least-squares means within the same column without a common superscript differ ($P < 0.05$).

¹Standard error (largest) of least-squares means. SEM = standard error of the mean.

²Sensory scores: 0 = extremely dry, tough, soft, bland, no off-flavor; 100 = extremely juicy, tender, firm, intense, extreme off-flavor.

Table 2.7 Shear force, texture profile analysis (TPA), and TBARS least-squares means for all treatments.

Treatment	Shear force (kg)	Hardness	Cohesiveness	Springiness	Gumminess	Chewiness	TBARS ³
Frozen-50/Frozen-90	1.5 ^d	11.6 ^c	0.26 ^d	0.62 ^{de}	3.0 ^c	1.9 ^d	2.71 ^b
Frozen-50/Fresh-90	3.3 ^b	17.2 ^a	0.30 ^b	0.66 ^{abc}	5.2 ^a	3.3 ^{abc}	0.68 ^e
Fresh-50/Frozen-90	1.9 ^c	12.0 ^c	0.28 ^c	0.64 ^{cd}	3.4 ^c	2.2 ^d	2.26 ^c
Frozen-80	1.1 ^d	9.0 ^d	0.25 ^d	0.60 ^c	2.3 ^d	1.3 ^e	3.06 ^a
Fresh-50/Thawed-90	3.5 ^b	17.1 ^a	0.30 ^b	0.66 ^{abc}	5.2 ^a	3.4 ^{abc}	0.78 ^{de}
Thawed-50/Fresh-90	3.4 ^b	17.1 ^a	0.30 ^b	0.64 ^{bcd}	5.2 ^a	3.4 ^{bc}	0.67 ^e
Thawed-50/Thawed-90	3.3 ^b	18.3 ^a	0.29 ^{bc}	0.66 ^{abc}	5.3 ^a	3.5 ^{ab}	0.55 ^{ef}
Fresh-50/Fresh-90	3.9 ^a	17.1 ^a	0.33 ^a	0.68 ^a	5.7 ^a	3.9 ^a	0.40 ^f
Fresh-80	3.6 ^{ab}	17.0 ^a	0.33 ^a	0.65 ^{bc}	5.7 ^a	3.7 ^{ab}	0.65 ^e
Thawed-80	3.4 ^b	14.6 ^b	0.30 ^b	0.67 ^{ab}	4.4 ^b	2.9 ^c	1.00 ^d
SEM ¹	0.17	1.3	0.01	0.01	0.35	0.23	0.09
<i>P</i> -value	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	<0.01

^{a-e}Least-squares means within the same column without a common superscript differ ($P < 0.05$)

¹Standard error (largest) of least-squares means. SEM = standard error of the mean.

²Texture profile analysis methods as described by Bourne (1978).

³TBARS values reported as mg MDA/kg.

Figure 2.1 Trained panel redness scores by treatment across a retail display period.

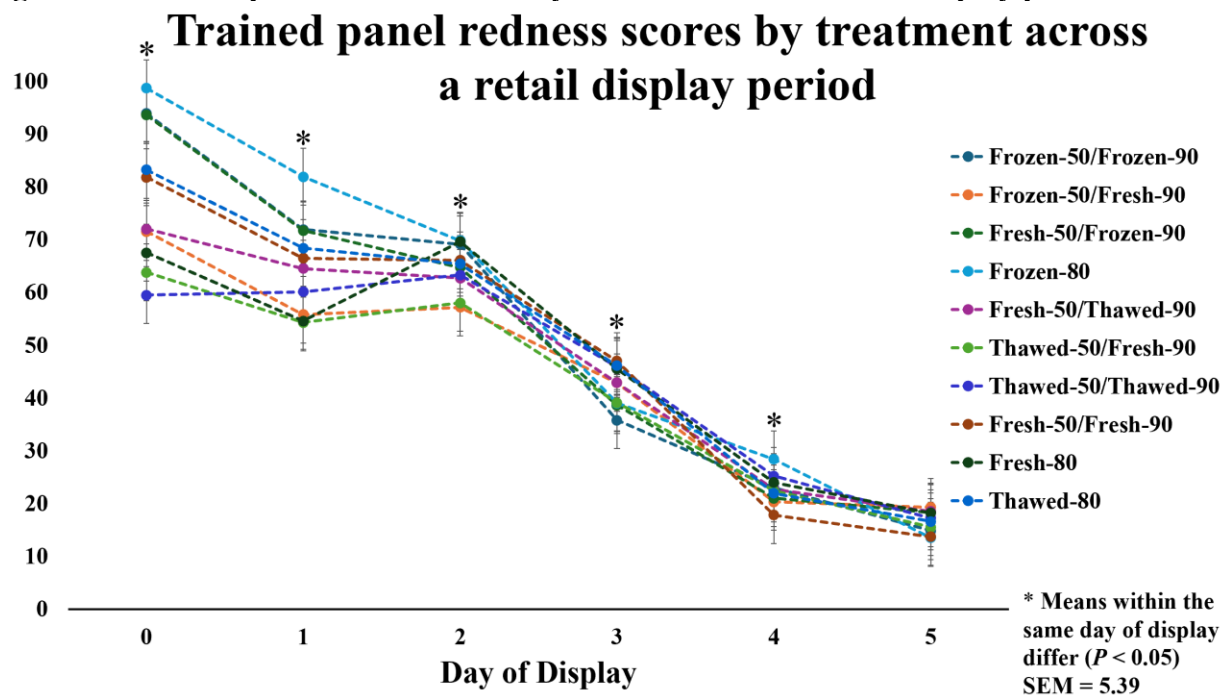


Figure 2.2 Trained panel discoloration scores by treatment across a retail display period.

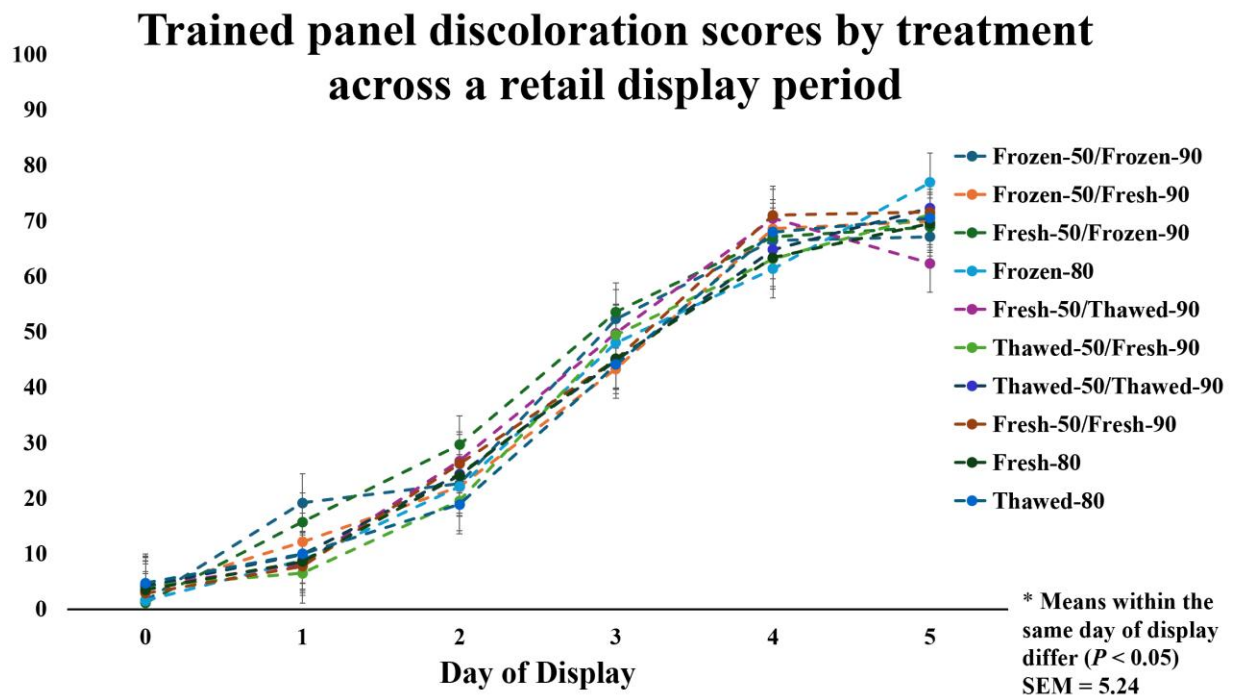


Figure 2.3 L^* values by treatment across a retail display period.

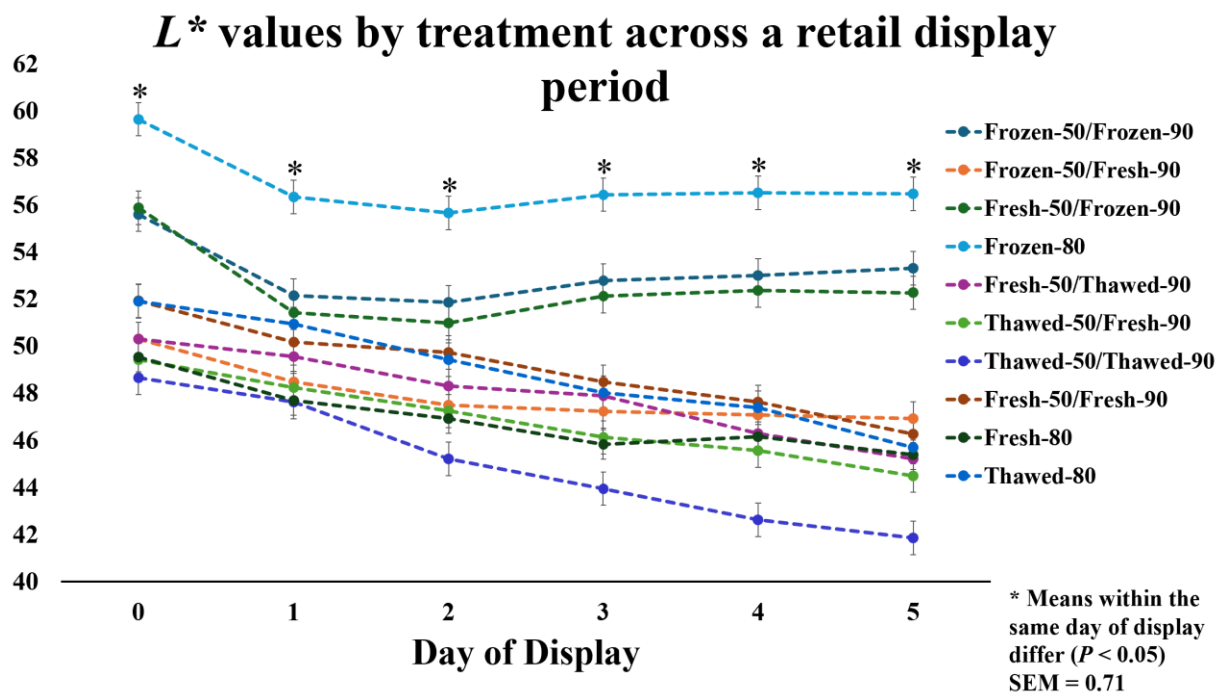


Figure 2.4 a^* values by treatment across a retail display period.

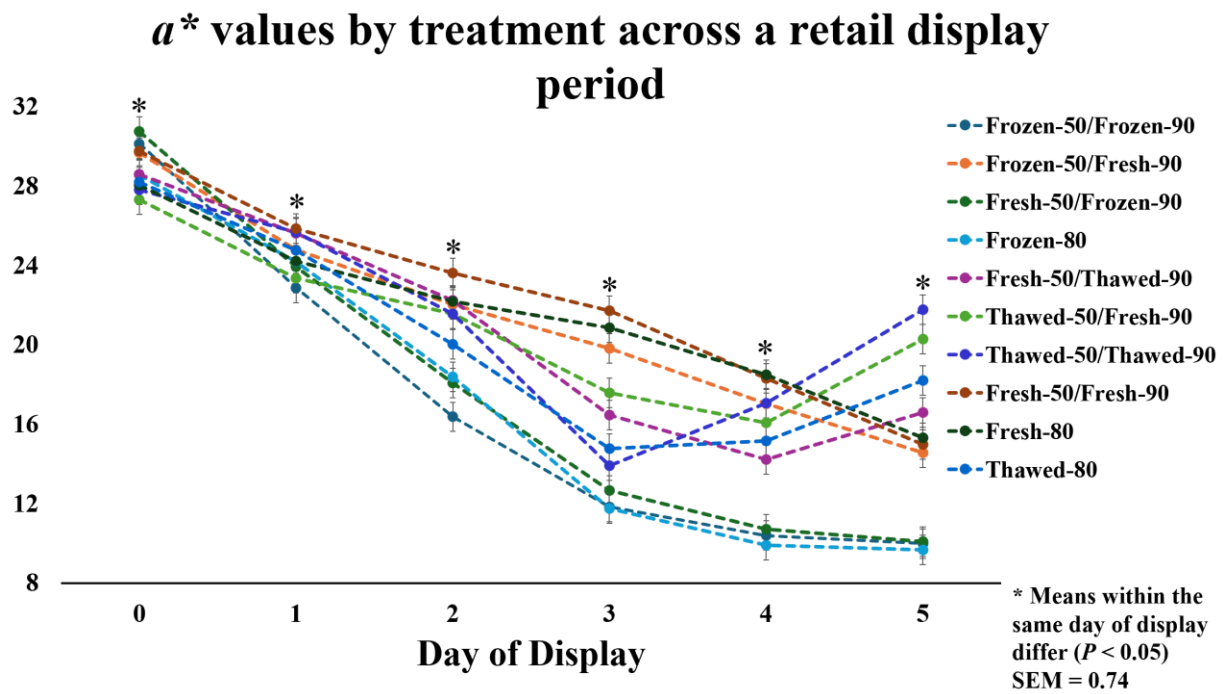


Figure 2.5 Percentage of oxymyoglobin by treatment across a period of retail display.

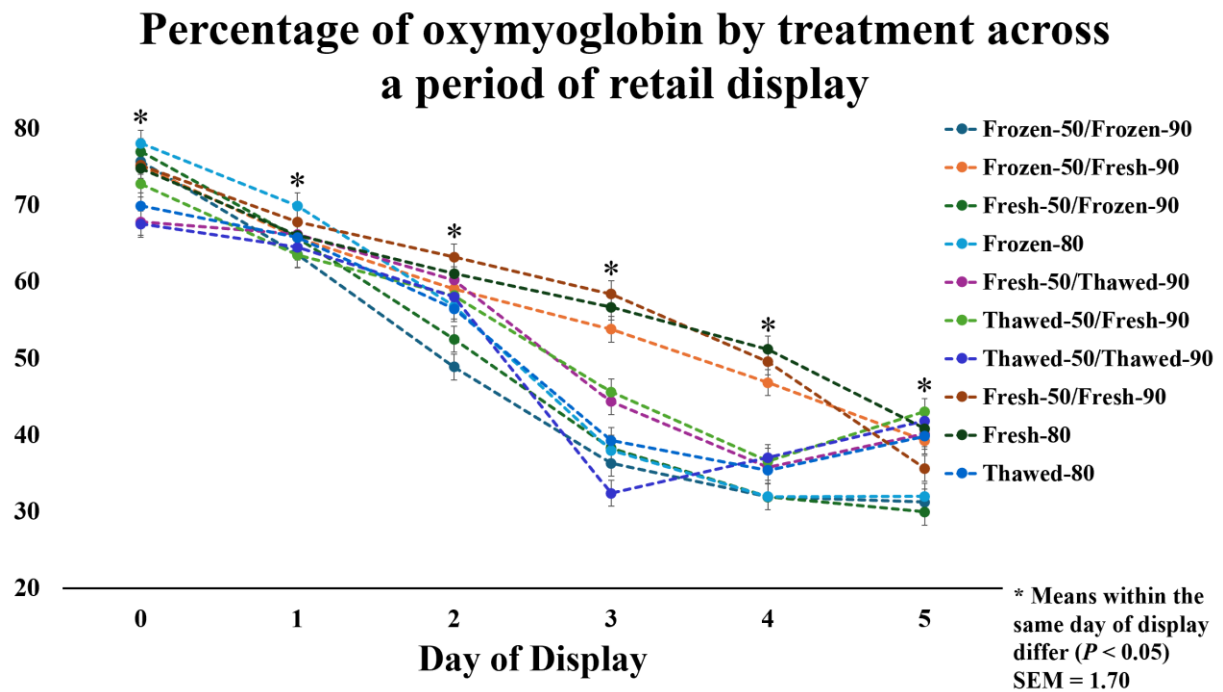
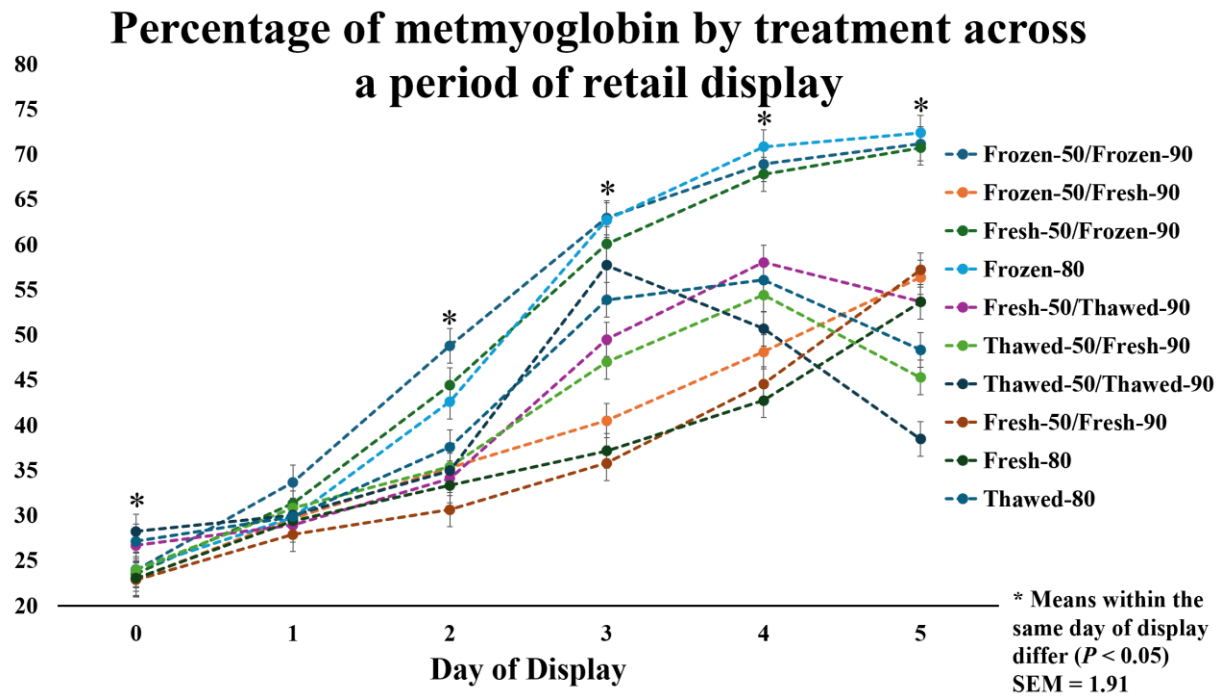


Figure 2.6 Percentage of metmyoglobin by treatment across a period of retail display.



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Appendix A - Day of Display Photographs

Day 0 of Display



Day 1 of Display



Day 2 of Display



Day 3 of Display



Day 4 of Display



Day 5 of Display



Appendix B - Fresh Ground Beef Purchasing Motivators

Appendix Table B.1. Fresh Ground Beef Purchasing Motivators

Characteristic	Importance of each trait ¹
Price	77.8 ^a
Lean to fat ratio	74.9 ^a
Color	72.1 ^{ab}
Nutrient content	67.7 ^{abc}
Animal welfare	66.6 ^{abc}
Size, weight, and thickness	61.6 ^{bcd}
Antibiotic use in the animal	57.2 ^{cde}
Locally raised	56.3 ^{cdef}
Country of Origin Labeling	55.1 ^{cdefg}
Fresh never frozen	52.4 ^{defg}
Primal source	51.2 ^{defgh}
Growth hormone use in the animal	50.9 ^{defgh}
Animal fed a forage-based diet	49.7 ^{defgh}
Natural or Organic claims	46.0 ^{efghi}
Packaging type	44.3 ^{fghi}
Breed	43.1 ^{ghi}
Animal fed a corn based diet	42.9 ^{ghi}
Brand of product	39.0 ^{hi}
Preformed patties	35.4 ⁱ
SEM ²	2.54
<i>P</i> - value	< 0.01

^{a-i}Least squares means without a common superscript differ ($P < 0.05$).

¹Purchasing motivators: 0 = extremely unimportant, 100 = extremely important.

²SEM (largest) of the least square means.

Appendix C - Sensory Panel Evaluation Forms

Informed Consent Statement

1. I volunteer to participate in research involving Sensory Evaluation of Meat. This research will be conducted by personnel in the Department of Animal Sciences and Industry at Kansas State University.

2. I fully understand the purpose of the research is for the evaluation of beef steaks, pork chops, lamb chops, goat meat, poultry meat, ground meat, and processed meat products from the previously mentioned species for the sensory traits of tenderness, juiciness, flavor intensity, connective tissue amount, off flavor presence, odor, and color and sensory evaluation will last approximately one hour.

3. I understand that there are minimal risks associated with participating and that those risks are related to possible food allergies. All meat products will be USDA inspected and all ingredients are GRAS (generally accepted as safe) by FDA.

4. I understand that my performance as an individual will be treated as research data and will in no way be associated with me for other than identification purposes, thereby assuring confidentiality of my performance and responses.

5. My participation in this study is purely voluntary; I understand that my refusal to participate will involve no penalty or loss of benefits to which I am otherwise entitled and that I may discontinue participation at any time without penalty or loss of benefits to which I am otherwise entitled.

6. If I have any questions concerning my rights as a research subject, injuries or emergencies resulting from my participation, I understand that I can contact the Committee on Research Involving Human Subjects, 203 Fairchild Hall, Kansas State University, Manhattan, KS 66506, at (785) 532-3224.

7. If I have questions about the rationale or method of the study, I understand that I may contact, Dr. Travis O'Quinn, 247 Weber Hall, Kansas State University, Manhattan, KS 66506, at (785) 532-3469 or Sally Stroda, 107 Weber Hall, at 785-532-1273.

I have read the Subject Orientation and Test Procedure statement and signed this informed consent statement, this _____ day of _____, _____.

Printed name

Signature

Consumer Sensory Panel Ballot- Visual



Demographics

Color Consumer Panel Sample Ballot

Please tell us a little about yourself.

Panelist Initials

Gender

- ☐ Male
☐ Female
-

Age

- ☐ Under 20
☐ 20 to 29 years old
☐ 30 to 39 years old
☐ 40 to 49 years old
☐ 50 to 59 years old
☐ 60 or over
-

Ethnic Origin

- ☐ African American
☐ Asian
☐ Caucasian/White
☐ Latino
☐ Native American
☐ Other
☐ Mixed Race
-

Marital Status

- ☐ Single
☐ Married

Household Size

- ☐ 1 person
 - ☐ 2 People
 - ☐ 3 People
 - ☐ 4 People
 - ☐ 5 People
 - ☐ 6 People
 - ☐ > 6 People
-

Annual Household Income

- ☐ < \$25,000
 - ☐ \$25,000 - \$34,999
 - ☐ \$35,000 - \$49,999
 - ☐ \$50,000 - \$74,999
 - ☐ \$75,000 - \$99,999
 - ☐ \$100,000 - \$149,999
 - ☐ \$150,000 - \$199,999
 - ☐ > \$199,999
-

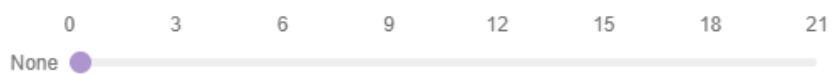
Highest Level of Education Completed

- ☐ Non-High School Graduate
 - ☐ High School Graduate
 - ☐ Some College / Technical School
 - ☐ College Graduate
 - ☐ Post-College Graduate
-

When purchasing ground beef, what trait is the most important to you?

- ☐ Color
 - ☐ Lean/Fat Content
 - ☐ Packaging Content
 - ☐ Price
 - ☐ Primal (ex: ground chuck or ground round)
 - ☐ Production Practices (ex: grass-fed, natural, USDA Organic)
 - ☐ Other
-

How many times a week do you consume ground beef?



Sample Number

4788

Overall Appearance

Extremely Undesirable
0

Neither Desirable or Undesirable
50

Extremely Desirable
100

Appearance



Would you purchase the sample at retail?

Yes

No



Would you purchase the sample at retail if it was discounted?

Yes

No



Consumer Sensory Panel Ballot- Taste

KANSAS STATE
UNIVERSITY

Sample Number

7320

Juiciness

Extremely Dry
0

Neither Juicy nor Dry
50

Extremely Juicy
100

Juiciness

Was the sample acceptable for juiciness?

Acceptable

Unacceptable

Tenderness

Extremely Tough
0

Neither Tough nor Tender
50

Extremely Tender
100

Tenderness

Was the sample acceptable for tenderness?

Acceptable

Unacceptable

Texture

Extremely Soft
0

Neither Soft nor Firm
50

Extremely Firm
100

Texture

Was the sample acceptable for texture?

Acceptable

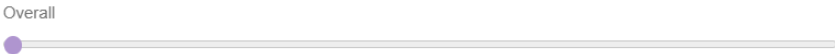
Unacceptable



Was the sample acceptable for flavor?

Acceptable

Unacceptable



Was the sample acceptable overall?

Acceptable

Unacceptable

How likely would you be to purchase this sample?



Based on **overall liking**, would you purchase this sample?

Yes

No



Trained Sensory Panel Ballot- Visual



Participant Initials

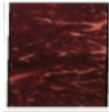
Date(MM/DD)

Time

Sample ID

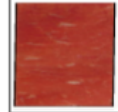
Overall Redness Score

Extremely Dark Red



0

Bright Cherry Red



100

Redness

☐ NA

Total Discoloration Score (% Metmyoglobin)

No Visible Discoloration
0

50% Discoloration
50

Complete Discoloration
100

Discoloration

☐ NA



Trained Sensory Panel Ballot- Taste



Panelist Initials

Today's Date (MM/DD)

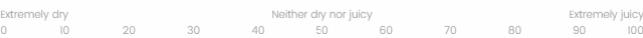
Panel Time

☐ AM

☐ PM

Sample

Juiciness



Juiciness



Tenderness



Tenderness



Texture

Extremely soft 0 10 20 30 40 50 60 70 80 90 100
Neither soft nor firm
Extremely firm

Texture



Beef-Flavor Intensity

Extremely bland 0 10 20 30 40 50 60 70 80 90 100
Extremely intense

Beef-Flavor



Off-Flavor

No off-flavor 0 10 20 30 40 50 60 70 80 90 100
Extreme off-flavor

Off-Flavor

☐ Not Applicable



If off-flavor is present, please describe.