SHELF LIFE OF FIVE MEAT PRODUCTS DISPLAYED UNDER LIGHT EMITTING DIODE OR FLUORESCENT LIGHTING

by

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Abstract

Light emitting diode (LED) and fluorescent (FLS) lighting effects on enhanced pork loin chops, beef *longissimus dorsi* and *semimembranosus* steaks, ground beef, and ground turkey displayed in two retail display cases set up with similar operational temperatures were evaluated using visual and instrumental color, *Enterobacteriaceae* (EB) and aerobic plate counts (APC), internal product and case temperatures, and thiobarbituric acid reactive substances (TBARS).

Visual discoloration of the five meat products increased ($P<0.05$) as display time increased. Beef *longissimus dorsi* steaks, ground beef, and the superficial portion of beef *semimembranosus* steaks had less ($P<0.05$) visual discoloration under LED lighting than FLS. Compared to FLS, pork loin chops under LED lighting had higher ($P<0.05$) L* values and a lower ($P<0.05$) a/b ratio. The deep portion *semimembranosus* steak under LED was redder ($P<0.05$) and the superficial portion had a lower ($P<0.05$) a/b ratio; LED deep and superficial portion *semimembranosus* steaks had higher ($P<0.05$) saturation index values at 5.18 and 4.47, respectively, on d 0 than FLS. Pork chops under LED lighting had lower ($P<0.05$) APC populations than FLS by the end of display. Enterobacteriaceae populations fluctuated throughout display on ground turkey under FLS lighting while populations remained stable under LED. APC populations increased as display time increased for pork loin chops, ground beef and ground turkey, but not beef *longissimus dorsi* steaks possibly due to initial case-ready postmortem age. As display time increased, EB populations increased ($P<0.05$) for pork loin chops, ground beef and ground turkey. The internal temperature of all products, except beef *longissimus dorsi* steaks, was lower ($P<0.05$) in the LED case. FLS case temperatures were higher ($P<0.05$) by 0.56 to 1.11°C than LED over the duration of the study. Pork loin chops, ground turkey, and beef *semimembranosus* steaks had higher ($P<0.05$) TBARS values by 0.06 to 0.24 mg malonaldehyde/kg under LED lighting, but lighting type did not affect ($P>0.05$) lipid oxidation of beef *longissimus dorsi* steaks or ground beef. LED lighting results in lower display case temperatures, lower internal product temperatures, and extended color life; however, lipid oxidation was increased in some cuts under LED lighting.

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CHAPTER 1 - Impact of Display Lighting on the Color Stability and Shelf Life of Five Fresh Meat Products

Retail customers do not have methods to estimate tenderness, juiciness or flavor when evaluating meat cuts for purchase. Instead, color is one of the major criteria in selecting meat items (Kropf, 1993). During refrigerated display, fresh meat color changes and customers discriminate against discolored meats. Meat items with discoloration must be discounted or discarded leading to revenue losses up to $1 billion for the meat industry (Smith, Belk, Sofos, Tatum, & Williams, 2000).

Myoglobin is the primary pigment responsible for meat color. Pigment concentration and the physical parameters of meat, including light scattering and absorbing properties, affect meat color (Kropf, 1993). Myoglobin protein exists as deoxymyoglobin, oxymyoglobin, or metmyoglobin depending upon the state of the iron molecule as well as the occupation of the sixth ligand. Oxymyoglobin presents a bright red color to meat and possesses an oxygen molecule on the sixth ligand with the reduced form of iron (Faustman & Cassens, 1990). Metmyoglobin is the pigment responsible for the undesirable brown color of meat that occurs when iron has been oxidized and water occupies the sixth ligand (Faustman & Cassens, 1990).

Meat color is the result of the interaction of many factors (Kropf, 1993). Metmyoglobin formation depends on the reducing ability unique to each beef muscle (Ledward, Smith, Clarke, & Nicholson, 1977). Once meat is placed in retail display, physical factors begin to influence fresh meat color. Lowering display temperatures 3 to 5 °C will retard discoloration (MacDougall & Taylor 1975). The availability of oxygen to bind with myoglobin affects the rate of discoloration. Oxygen partial pressure between 6-7.5 mmHg is the optimum level promoting metmyoglobin formation (George & Stratman, 1952). Bacterial contamination of meat will affect product color. Short loins inoculated with *Pseudomonas fragi* were found to promote discoloration (Bala, Marshall, Stringer, & Naumann 1977). Lipid oxidation products promote metmyoglobin formation which was greater in a study with oxymyoglobin treated with oxidized liposomes versus freshly prepared liposomes (Chan, Faustman, & Decker, 1997). Diet (French, Stanton, Rawless, O'Riordan, Monhan, Caffery, & Moloney 2000; Baublits, Brown, Pohlman, Johnson, Onks, Loveday, Morrow, Sandelin, Coblentz, Richards, & Pugh 2004; Realini, Duckett, Brito, Dalla Rizza, & De Mattos 2004), genetics, and breed (Brewer, Jensen, Sosnicki, Fields, Wilson, & McKeith, 2002; Brewer, Sosnicki, Fields, Hankes, Ryan, Zhu, & McKeith, 2004) also influence meat color. These variables must be well understood in order to contend with the complexity of meat color.

The meat industry is aware of the major role lighting type and intensity has on the appearance of meat in retail display. Lighting technology has developed to extend fresh meat color. A fluorescent (FLS) bulb housing an ultraviolet-filter plate of polycarbonate extended fresh pork sausage display life by 12 days compared to a standard supermarket FLS tube (Martínez, Cilla, Antonio, & Roncalés, 2007). Newer technologies in lighting offer the ability to enhance meat color plus reduce other costly inputs for meat retail display. Light emitting diode (LED) lighting offers advantages for display by being more energy efficient and having reduced heat generation throughout display.

LED technology began in the 1950's with commercial production starting in the late 1960's (DOE, 2009). Currently, less than an estimated 1 percent of the refrigerated display cases have LED lighting technology installed (DOE, 2008). Phosphor converted LEDs have higher efficacies compared to incandescent and compact fluorescent light bulbs leading to significant energy savings (Arik, 2009). The United States Department of Energy (DOE) realizes the potential cost and energy savings LED lighting holds due solely to efficiency. Goals have been set by the United States government for the fiscal year 2015 to produce LED lighting systems costing less than $2/klm with a color-rendering index (CRI) greater than 80, correlated color temperature (CCT) less than 5000 K, and 126 lm/W luminaire that emits approximately 1000 lumens (DOE, 2009). Currently, warm white LED systems with CCT less than 3300°K possess 40-60 lm/W while compact fluorescent lighting possesses 35-60 lm/W. Although both technologies possess similar efficacies, fluorescent technology is close to maxing out on efficacy while LED systems hold the potential to improve two-fold on energy efficiency (DOE, 2009). In addition, LED lighting provides longer operating life, lower maintenance and life cycle costs, minimal light loss, directional illumination, adjustable color, and uniform illumination (DOE, 2008). LED lighting will make a strong appearance in retail display meat cases with potential cost savings, energy savings, and lower heat generation. Energy savings up to 2.1 TWh of electricity is possible if the entire refrigerated market converted to LED lighting (DOE, 2008). As LED lighting provides lower energy costs, longer operating life, and lower operating temperatures, research is needed to evaluate how LED lighting affects the color stability and shelf life of fresh meat.

The objective of this study was to determine the effects of LED and FLS lighting on visual and instrumental meat color and shelf-life properties of five types of fresh meat products displayed in two retail display cases running at similar temperature profiles.

CHAPTER 2 - Review of Literature

Effect of Meat Color on Purchasing Decisions

Historically, the first encounter with refrigerated retail meat cuts in self-service meat cases was with meat products packaged on Styrofoam® trays and overwrapped with polyvinyl chloride (PVC) plastic (McMillin, 2008). This packaging style allowed for oxygen to bind to the meat pigment myoglobin resulting in a process called “bloom”, a red color due to the formation of oxymyoglobin. Consequently, consumers associated the bright red color with fresh and wholesome meat items (Jenkins & Herrington, 1991). Today, consumers continue to use color as one of the major criteria in selecting meat products (Kropf, 1993) as they do not have methods to estimate tenderness, juiciness or flavor of packaged retail cuts on display. Strong relationships exist between the desired meat color and purchasing intent with a consumer preference towards red colored beef items (Carpenter, Cornforth, & Whittier, 2001). Consumers begin rejecting products for purchase once discoloration of the meat in display reaches 20% (Kropf, 1993) to 40% (Greene, Hsin, & Zipser, 1971) discoloration.

Bias towards meat products with the bloomed color has not been linked to palatability. Untrained panelists evaluated beef loin steaks for raw color and purchasing preference, along with cooked flavor, juiciness, and tenderness (Carpenter et al., 2001). While panelists observed a significant difference in color and reported purchasing preferences for red colored steaks, no differences existed in flavor, juiciness, or tenderness between the different colored steaks (Carpenter et al., 2001). In an additional study, discoloration in retail display beef steaks was considered unacceptable to the consumer (Jeremiah, Carpenter, & Smith, 1972). However, the taste panel indicated no relationship between fresh meat color and cooked palatability of the steaks (Jeremiah et al., 1972).

Economics of Meat Color

Meat color stability is defined as the duration of an acceptable, saleable color (Kropf, 1993). Shelf life of meat products usually ends as a result of discoloration instead of bacterial spoilage (Smith, Morgan, Sofos, Tatum, & Schmidt, 1995). Once a meat cut reaches an unacceptable percentage discoloration the consumer will choose not to purchase the product. Eye of round steaks expressing more than 40% discoloration were rejected for purchase by a trained color panel (Greene, et al., 1971). When discoloration accumulates on a meat item, the product must be discounted, reprocessed into a lower valued item, or discarded. Therefore, any meat products with discoloration must be discounted or discarded leading to large revenue losses up to $1 billion for retailers (Smith, et al., 2000).

Myoglobin Chemistry

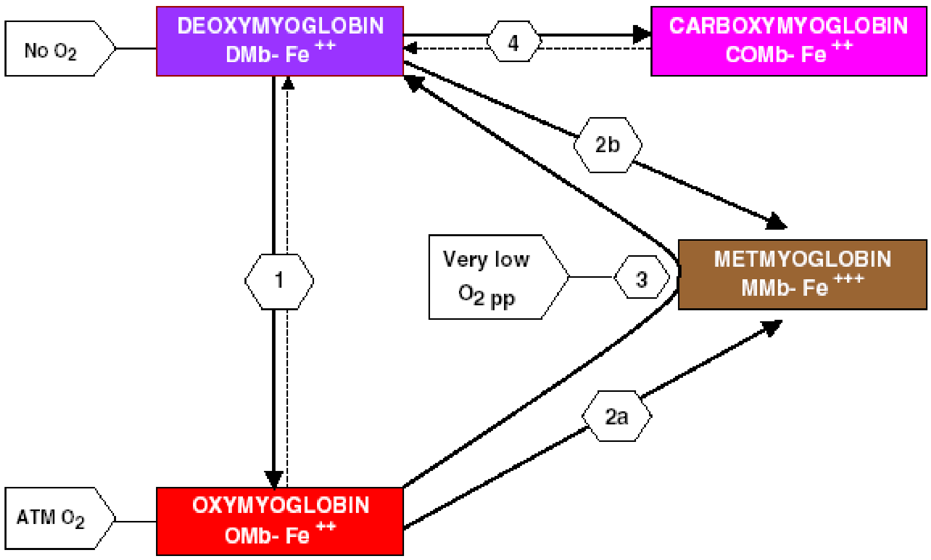
States of Myoglobin

Myoglobin is the main pigment responsible for meat color (Faustman & Cassens, 1990). Myoglobin consists of an iron molecule within a heme ring in either the ferric (Fe^{3+}) or ferrous (Fe^{2+}) state, and a protoporphyrin ring (Faustman & Cassens, 1990). The concentration of myoglobin and other pigments and the physical parameters of meat, including light scattering and absorbing properties, influence meat color (Kropf, 1993).

Myoglobin in fresh meat exists as deoxymyoglobin, oxymyoglobin, or metmyoglobin depending upon the state of the iron molecule as well as the occupation of the sixth ligand (Fig. 2-1). Deoxymyoglobin exhibits a purple color with iron in the reduced state with the sixth ligand vacant (Faustman & Cassens, 1990). Oxymyoglobin presents a bright red meat color and possesses an oxygen molecule on the sixth ligand with the reduced form of iron (Faustman & Cassens, 1990). Metmyoglobin is the pigment responsible for the undesirable brown color on meat. Discoloration occurs when iron has been oxidized and water occupies the sixth ligand (Faustman & Cassens, 1990). The pigments in greater concentration will determine the color observed by consumers. Higher concentrations of the oxymyoglobin pigment are the target for processors and retailers since this is the color preferred by consumers.

Fig. 2-1. Myoglobin pigment in the different states of existence (From Mancini & Hunt, 2005).

O_2= Oxygen, DMb= Deoxymyoglobin, Fe^{++}=Ferrous iron, ATM= Atmospheric, OMb= Oxymyoglobin, O_2 pp=Oxygen partial pressure, MMb=Metmyoglobin, Fe^{+++}=Ferric iron, COMb= Carboxymyoglobin.



Metmyoglobin Reducing Activity

The dominance of metmyoglobin as the pigment in a meat product depends upon several factors including the inherent reducing ability of meat (Mancini & Hunt, 2005; Kanner, 1994). Competition for dominant pigment between oxymyoglobin and metmyoglobin is regulated by metmyoglobin reduction activity (MRA) which is unique to each muscle (Ledward et al., 1977). Metmyoglobin reduction activity is the enzymatic pathway of reducing the iron molecule in metmyoglobin back to the Fe^{2+} state in the presence of the coenzyme nicotinimide dinucleotide (NADH) (Renerre, 1990). The ability to reduce iron in metmyoglobin has been reported to be more dependent on the availability of NADH than MRA (Bekhit, Geesink, Ilian, Morton, & Bickerstaffe, 2003). Lactate dehydrogenase is an endogenous enzyme in beef that replenishes the supply of NADH in lactate enhanced beef by converting the lactate into pyruvate and NADH (Mancini, Hunt, Kim, & Lawrence, 2004). This replenished supply of NADH restores MRA and increases color stability. One study has related the location of MRA activity to microsomes and intact mitochondria of muscles (Echevarne, Renerre, & Labas, 1990). Slow-twitch muscle fibers possess greater potential for having more microsomes and intact mitochondria than fast-twitch muscle fibers. Additional NADH may be produced from the reversal of the electron transport chain in mitochondria (Giddings, 1974). Once a combination of decreasing pH, loss of substrates or coenzymes, and loss of functional and structural integrity of mitochondria occurs, MRA ceases to function (Giddings, 1974).

Oxygen Consumption Rate

Myoglobin's role in muscle tissues is to transport oxygen to mitochondria in cells for energy production (Wittenberg & Wittenberg, 1975). When oxygen is attached, myoglobin is in the oxymyoglobin form resulting in a bright red pigment (Faustman & Cassens, 1990). After oxygen has been delivered to the mitochondria, myoglobin has a vacancy at the sixth ligand resulting in either deoxymyoglobin or oxidation to the metmyoglobin pigment (Faustman & Cassens, 1990). High oxygen consumption rate (OCR) by mitochondria in an open meat system results in greater amounts of metmyoglobin formation (Tang, Faustman, Hoagland, Mancini, Seyfert, & Hunt, 2005). With higher OCR, the oxygen surrounding the meat will be used up and myoglobin will be susceptible to becoming the brown metmyoglobin pigment through oxidation (Lanari & Cassens, 1991). High OCR is detrimental to the functionality of the enzymic reducing system leading to autoxidation of myoglobin (Ledward, 1985). Muscles with weaker color stability have been linked with high mitochondrial content up to 0.5 mg/ml at pH 5.6 (Tang et al., 2005) and high oxygen uptake (Lanari & Cassens, 1991). Faster rates of pH decline and lower final pH may inhibit the respiratory activity of mitochondria (Lanari & Cassens, 1991). Muscles with a lower pH were found to have lower OCR leading to improved color stability (Lanari & Cassens, 1991; Tang et al., 2005). Oxygen consumption rate was found to decrease over time (Tang et al., 2005) up to 48 h postmortem (Lanari & Cassens, 1991). Lanari and Cassens (1991) concluded that OCR has greater impact on color stability compared to MRA since samples with the weakest color stability possessed the highest reducing activities.

Factors Affecting Discoloration of Meat

Meat color is the result of the interaction of many factors (Kropf, 1993), including intrinsic and extrinsic factors. Understanding the influence each factor has upon meat color along with the relationship to other parameters will allow processors and retailers to maximize color life of fresh meat products.

Intrinsic Factors

Breed and genetics of an animal affect fresh meat color (Brewer et al., 2002, 2004). For example, Holstein cattle were found to have greater OCR leading to weaker color stability in the *longissimus dorsi* and *gluteus medias* steaks compared to steaks from crossbred cattle (Lanari & Cassens, 1991). Furthermore, they found color stability to be muscle dependent with the *longissimus dorsi* having greater color stability compared to the *gluteus medias*. Supporting this conclusion is a study by Faustman and Cassens (1991) who reported that *longissimus dorsi* muscles accumulated 9.2% less metmyoglobin than *gluteus medias* muscles. Compared to fast-twitch glycolytic or fast-twitch oxidative-glycolytic muscle fibers, slow-twitch oxidative muscle fibers contain a greater amount of myoglobin and possess higher enzymic reducing activity resulting in greater red color and color stability (Renerre, 1990).

Animal diets can influence fresh meat color and color stability (French et al., 2000; Baublits et al., 2004; Realini, Duckett, Britto, Dalla Rizza, & De Mattos, 2004). One example is the incorporation of vitamin E into the diets of cattle which retarded lipid and pigment oxidation thereby improving color stability of beef (Faustman, Cassens, Shaefer, Buege, Williams, & Scheller, 1989). The rate of rigor has an influence on ultimate meat pH and enzyme activity (Renerre, 1990). Cuts with lower pH values have reduced enzyme activity and promote autoxidation of myoglobin (Renerre, 1990).

Extrinsic Factors

Temperature

Once meat products are displayed for customers in retail stores, physical factors begin to influence the color of fresh meat. Temperature is considered to have one of the largest impacts on meat color stability (MacDougall, 1982). Lowering display temperatures 3 to 5 °C will retard discoloration rate by half (MacDougall & Taylor, 1975). Wavelength reflectance ratios of meat samples stored at 0 °C and 5 °C revealed a faster accumulation of metmyoglobin on the meat surface at 5 °C by a factor of four (Hood, 1980). Enzyme respiratory activity increases with increasing temperatures leading to increased OCR and decreased oxygen pressure (Renerre, 1990). Keeping display temperatures low suppresses enzyme activity and allows oxygen to penetrate deeper into the meat surface creating a thicker layer of oxymyoglobin above the metmyoglobin layer (Renerre, 1990).

Grinding

Grinding meat will influence the display color. Meat ground twice was found to destroy the reducing ability of meat leading to a faster accumulation of discoloration (Ledward et al., 1977). Ground muscle was found to discolor five times faster than oxymyoglobin in solution leading to the possibility that inherent catalysts are mixed with pigments through grinding (Ledward et al., 1977). Govindarajan & Hultin (1977) stated that grinding compromises the integrity of the cellular structure and combines unsaturated lipids from the membrane with catalytic oxidizing reagents leading to lipid oxidation products that can oxidize oxymyoglobin. Metmyoglobin formation is also found in areas of low oxygen pressure caused by grinding meat (Kropf, 1980).

Bacterial Contamination

Bacterial contamination of a product affects fresh meat color. Short loins inoculated with *Pseudomonas fragi* expressed greater discoloration compared to control samples (Bala, 1977). Aerobic bacteria such as *Pseudomonas*, *Achromobacter* and *Flavobacterium* metabolize oxygen reducing the oxygen pressure at the meat surface resulting in an increase in metmyoglobin content (Renerre, 1990). Beef steaks inoculated with aerobic bacteria had oxygen uptakes greater than 160 µl/30min compared to control steaks at approximately 20 µl/30min (Robach & Costilow, 1961). Myoglobin denaturation can occur when proteolytic enzymes from bacteria come into contact with the pigment (Lawrie, 1985). Sonically treated cell-free *Pseduomonas geniculata* populations were inoculated onto beef steaks that discolored faster than the controls suggesting that the bacteria's enzymes caused discoloration (Robach & Costilow, 1961). Lawrie also suggests discoloration of fresh meat can be related to pigments produced by microorganisms. A green discoloration may appear on fresh meat from the interaction of the hydrogen peroxide by-products from bacteria (Jensen, 1945) and myoglobin producing Choleglobin (Lawrie, 1985). Nicol, Shaw, and Ledward (1970) found an increase in green discoloration with the presence of hydrogen sulfide produced by bacteria on meat products with pH values 6 or greater. Interventions to control microbiological growth through the use of products such as potassium sorbate, sodium acetate, sodium tripolyphosphate, and/or tetrasodium pyrophosphate can prevent metmyoglobin formation (Renerre, 1990).

Chilling Rate

The rate at which the temperature of muscle on a carcass declines affects the visual, instrumental, and color stability of meat products (Sammel, Hunt, Kropf, Hachmeister, Kastner, & Johnson, 2002). Muscles further from the carcass surface will decrease in temperature at a slower rate and proceed through glycolysis faster (Sammel et al., 2002). Rapid rates of glycolysis lead to faster pH declines which denature proteins and open up muscle structure causing light scattering effects that are negative to meat color (MacDougall, 1982). The color of vacuum packaged beef muscles was more uniform over 5 d display at 3 °C when excised 1-2 h after harvest compared to 48 h (Nichols & Cross, 1980). Sammel et al. (2002) found similar CIE a*, oxymyoglobin and metmyoglobin percentages for hot-boned deep portions and cold-boned superficial portions of *semimembranosus* steaks. Visual color scores indicated better color stability for the superficial and deep portions of hot-boned and the superficial portion of cold-boned *semimembranosus* steaks compared to the cold-boned deep portion on d 3. Furthermore, Sammel et al. (2002) found chilling rates decreased aerobic reducing activities and affected the color stability of meat. Therefore, muscles with more rapid chilling rates will have increased redness, decreased discoloration, and greater consumer appeal.

Oxygen Pressure

The amount of oxygen available to bind with myoglobin affects the state of myoglobin. Oxygen partial pressures of 6-7.5 mmHg provide the optimum level to promote metmyoglobin formation in muscle foods (George & Stratman, 1952). Oxygen pressures below 1.4 mmHg promote the deoxygenated state of myoglobin (Mancini & Hunt, 2005). Excluding oxygen entirely from the environment surrounding meat products minimizes metmyoglobin formation (Faustman & Cassens, 1990). Vacuum packaging meat products almost eliminates oxygen pressure resulting in prevention of autoxidation (Taylor, 1985). When oxygen is present, the amount of pressure influences the depth of oxygen penetration beneath the meat's surface (Mancini & Hunt, 2005). High OCR have been suggested to prevent the development of oxymyoglobin (Ashmore, Parker, & Doerr, 1972). Oxygen consumption rates have been shown to differ between species at 48 h postmortem with lamb having a greater rate than pork which is greater than beef. With the greater OCR, lamb can be expected to have lower color stability compared to pork and beef (Atkinson & Follett, 1973). Oxygen consumption rates were found to differ between muscles (Morley, 1971). Mincing of postrigor muscle does not affect the oxygen consumption rate (Bendall & Taylor, 1972), but mincing does create localized areas of low oxygen pressure leading to metmyoglobin formation (Kropf, 1980).

Lipid Oxidation

Lipid and oxymyoglobin oxidation are interrelated in fresh meat products (Schaefer, Liu, Faustman, & Yin, 1995) and can be catalyzed from by-products of both processes (Liu, Lanari, & Schaefer, 1995). Chan and others (1997) found that the secondary lipid by-products propional, decanal, nonanal, hexanal, 2-nonenal and 2-heptenal accelerated oxymyoglobin oxidation compared to a control. Holstein *gluteus medius* ground meat metmyoglobin formation had a correlation coefficient of 0.91 with TBA values (Faustman et al., 1989). Suman, Faustman, Stamer, & Liebler (2006) looked at the effect of the aldehyde lipid oxidation by-product 4-hydroxy-2-nonenal on the oxidation of oxymyoglobin and found a strong correlation in beef products. Additionally, lipid peroxidation promotes metmyoglobin formation in muscle foods (Kanner, 1994). Increased levels of unsaturated fatty acids in liposome and microsome membranes have been found to accelerate oxidation of oxymyoglobin (Yin & Faustman, 1994). Ascorbic acid will act as an oxygen scavenger as well as an antioxidant with natural and synthetic antioxidants to retard lipid oxidation and prevent metmyoglobin formation (Renerre, 1990). Reduction in the formation of thiobarbituric-acid reactive substances (TBARS) and metmyoglobin accumulation occurred when higher inherent levels of lipid-soluble α-tocopherol antioxidants were present in beef (Yin, Faustman, Riesen, & Williams, 1993).

Meat color is a complex concept with both extrinsic and intrinsic factors interacting and influencing the outcome of display color. An understanding of all the factors will result in maximizing color life of fresh retail meat products.

Packaging

Packaging is a vital component of meat products as it provides protection from physical, chemical, and biological hazards as well as containing the product, communicating to consumers as a marketing tool, and providing ease of use and convenience (Yam, Takhistov, & Miltz, 2005). A variety of packaging options exist adding complexity to fresh meat color. Color will vary between meat products packaged in a modified atmosphere (MAP) or placed on a tray and overwrapped with PVC plastic wrap. The most common styles of packaging meat products for retail display are PVC wrap on a Styrofoam® tray and MAP (Charles, Williams, & Rodick, 2006).

Polyvinyl Chloride Packaging

Polyvinyl chloride packaging with a Styrofoam® tray was the first style of packaging put into practice when lighted self-service refrigerated meat cases were integrated into retail markets (McMillin, 2008). The flexible plastic wrap is not only a moisture barrier but also air-permeable allowing oxygen to contact the meat surface creating the bright red color of oxymyoglobin (Brody, 2002). Consumers seeing meat displayed for the first time associated the bright red color with freshness and wholesomeness for prepackaged meat products (Jenkins & Harrington, 1991). Although the packaging allows for "bloom" to occur, the color stability of fresh meat is not an advantage for this packaging system. Visual and instrumental evaluations of discoloration on porcine vertebrae revealed a disadvantage for PVC packaging (Raines, 2006). Instrumental a*/b* (with lower scores indicating greater discoloration) for PVC packaged vertebrae were between 0.99 to 1.07 compared to 1.20 to 1.31 for low-oxygen MAP and 1.02 to 1.24 for high oxygen MAP (Raines, Dikeman, Grobbel, & Yancey, 2006). Moreover, visual color scores of PVC samples were more discolored on d 8 than high oxygen MAP (Raines et al., 2006). Polyvinyl chloride packaging influences other quality aspects of fresh meat. *Longissimus dorsi* steaks stored in PVC packaging had an increased pH level, darker color, greater lipid oxidation and greater mesophilic populations compared to vacuum packaged or MAP steaks (D'Agata, Nuvoloni, Pedonese, Russo, D'Ascenzi, & Preziuso, 2010). Therefore, PVC is not conducive to prolonging the color shelf life of fresh meat products.

Modified Atmosphere Packaging

Modified atmosphere packaging involves the removal of air or substitution of air with a specific atmosphere encompassing the food item within sealed vapor-barrier materials (McMillin, Huang, Ho, & Smith, 1999). Many benefits exist for MAP ranging from shelf life to meat quality. Due to the economic influencer of centrally packaged meats and a consumer driven need for increased convenience, case-ready packaging such as MAP has penetrated the retail market at a growing rate (Eilert, 2005). Case-ready fresh meat products increased 11% in linear footage in the self-service meat display from 2002 to 2004 with 95% of the poultry products displayed in a case-ready format such as MAP (Eilert, 2005).

The increase in MAP packaged products is a result of an array of atmospheres developed for confronting unique phenomena in meat products. High oxygen atmospheres are conducive to maintaining the bright red bloomed color associated with fresh beef (McMillin, 1996). Color panelists in a study indicated more desirable color up to d 4 of display for beef *longissimus lumborum* steaks packaged in a high oxygen atmosphere compared to low-oxygen (Grobbel, Dikeman, Hunt, & Milliken, 2008). However, by d 7 the steaks in the low-oxygen atmosphere were more desirable. Ground turkey in MAP containing 8% O_2 with CO_2 and N_2 comprising the remaining amount had a lower a* value compared to ground turkey packaged in only 20% CO_2 and 80% N_2 (Saucier, Gendron, & Gariépy, 2000). Other gases can be incorporated into packaging to target specific quality or shelf life characteristics. Atmospheres containing 1% CO compared to a high oxygen atmosphere without CO resulted in a reduction of psychrotrophic bacteria populations on beef loin steaks and ground beef (Luño, Beltrán, & Roncalés, 1998). Low oxygen atmospheres offer alternative benefits, but come with the challenge of undesirable color. Meat products either vacuum packaged or packaged in a low oxygen MAP possess reduced oxidative rancidity leading to a more pleasurable eating experience for the consumer (Eilert, 2005). With low concentrations of oxygen, the purple deoxymyoglobin pigment will dominate myoglobin concentration; a color deemed less desirable than the bright red oxymyoglobin (McMillin, 2008). Oxygen scavengers, needed to maintain a low oxygen atmosphere, incorporated into anaerobic packages will lead to increased product cost as well. (McMillin, 2008).

Retail Display Lighting Effect on Meat Shelf Life

The meat industry is aware of the major role lighting type and intensity has on the appearance of meat in retail display. Kropf (1980) has provided an exhaustive review of retail display lighting effects on meat color. Energy from lighting catalyzes the formation of metmyoglobin in fresh, frozen and cured meats (Renerre, 1990). Not only does lighting affect fresh meat color but also odor, microbial growth, and lipid oxidation (Kropf, 1980; Djenane, Sánchez-Escalante, Beltrán, & Roncáles,2003; Martínez, 2007; & Andersen & Skibsted, 1991).

Lighting Effect on Odor

Odor of fresh meat products was found to be affected by light source. Fresh pork sausages held in the dark or displayed under fluorescent lighting with a UV-filter remained acceptable to panelists four days longer than sausages under standard fluorescent lighting (Martínez, 2007). Beef steaks packaged in MAP displayed under low UV or UV-free lighting were reported to have less perceivable off-odors on d 20 compared to samples under standard fluorescent lighting (Djenane et al., 2003).

Lighting Effect on Microbial Populations

Maclean, MacGregor, Anderson, & Woolsey (2009) have shown the inactivation of pathogens using 405 nm wavelength LED light. Suspended cultures were exposed to high-intensity LED light for up to 400 min. At 30 min of light exposure, log reductions from 2.6 to 5.0 could be seen for *Staphylococcus aureus, Clostridium perfringens* and *Escherichia coli*. Although this lighting showed an effective method of reducing pathogens, retail display lighting with a wavelength near the UV spectrum is detrimental to product color and the high intensity of the lighting is impractical for refrigerated display.

There has been limited research on the effect of traditional display lighting on microbial populations. Standard fluorescent lighting increased psychrotropic aerobic populations on fresh pork sausages stored at 2 °C that were packaged in collagen casings placed on polypropylene trays inside a pouch made of polyethylene and polyamide laminate with a high oxygen atmosphere. Psychrotropic aerobic populations increased from the fourth day of display to the end of display under standard fluorescent lighting compared to samples displayed in the dark or under UV-filtered lighting (Martínez, 2007). Beef steaks packaged on polystyrene trays in a high oxygen pouch made of a polyethylene and polyamide laminate and displayed at 1 °C under standard fluorescent lighting and UV-free lighting had similar results, but significant differences were not observed until d 15 of display (Djenane et al., 2003). The display time difference in observing significant variation can be attributed to lower initial counts as well as antioxidant ingredients used with the beef steaks. In contrast, fresh prerigor pork sausage patties displayed in either a dark room or under 2150 lux fluorescent lighting showed no differences in total aerobic plate counts (Seyfert, Hunt, Grobbel, Ryan, Johnson & Monderen, 2006).

Lighting Effect on Lipid Oxidation

Photooxidation of lipids as a result of display lighting occurs in meat products. Fresh pork sausages held in the dark or displayed under fluorescent lighting with a UV-filter recorded lower TBARS values (Martínez et al., 2007). Samples with TBARS values above 1.5 had detectable odor according to panelists; a correlation between panel odor scores and TBARS values existed at 0.93 (Martínez et al., 2007). Therefore, TBARS values can be used to determine detectable levels of lipid oxidation by consumers for fresh pork sausage. A study with frozen pork patties by Anderson & Skibsted (1991) has linked UV light to inducing photooxidation of lipids which is in agreement with results from studies by Martínez et al. (2007) with fresh pork sausage and Djenane et al. in 2003 involving beef *longissimus dorsi* steaks.

Lighting Effect on Color

Display case lighting has a considerable influence on meat color stability. The meat industry is aware of the major role lighting type and intensity has on the appearance and shelf life of meat on display. Correlated color temperature (CCT), color rendering index (CRI) and the color spectrum of a light source affect appearance (Konica Minolta, 2007) and color stability of fresh meat products. CCT is measured in kelvin and relates directly to the color of the radiant energy reflected from the object (Konica Minolta, 2007). Darker objects, such as red meats, will record lower CCT values compared to lighter colors while light pigmented meats will have higher CCT values. Lighting sources with CCT's closest to the color of the object under display will have the most desired appearance to observers. The AMSA Guidelines for Meat Color Evaluation recommend Illuminant A with a CCT of 2856 K (Konica Minolta, 2007) as the light source for instrumental color measurement of samples because it correlates best with visual color scores and has a stronger emphasis on the red portion of the color spectrum. Color rendering index is a measurement on a scale from 1 to 100, with 100 being the most desirable, describing the ability of a light source to portray colors of an object against a "perfect" light reference (DOE, 2011). When lighting sources have low CRI values, undesired effects in appearance occur such as pinkish fat or yellowish bone (Kropf, 1980). Color is a part of the electromagnetic spectrum spanning from 380 to 780 nm (Konica Minolta, 2007) with violet having the shortest wavelength and red possessing the largest wavelengths. Therefore, a light source with an emission spectrum mostly in the red section between 630 nm and 700 nm is desirable for fresh red meats (Kropf, 1980).

Research has shown significant differences in color shelf life for meat products displayed under different lighting sources. As discussed under extrinsic factors, elevated temperatures promote discoloration of meat. Any lighting type with increased operating temperature is detrimental to fresh meat color (Hood, 1980). Display lighting photochemical effects impact color as well (Renerre, 1990). Ultraviolet light penetrates into meat and denatures the globin in myoglobin causing discoloration (Lawrie, 1985). Visual evaluation of pork sausages displayed under fluorescent lighting with a UV-filter plate of polycarbonate indicated an end to color shelf life at d 12 versus products displayed under traditional fluorescent lighting or low-UV with a color life ending on d 8 (Martínez, 2007). Instrumental a* values supported the extended color life with samples displayed in the dark and under UV-filter being greater than samples displayed under standard or low-UV lighting for the first 8 days of display (Martínez, 2007). Studies from Djenane, Sánchez-Escalante, Beltrán, & Roncáles (2001) and Bertelsen and Boegh-Soernesen (1986) resulted in similar conclusions attributing UV light to severely discoloring fresh meat. New technologies in lighting offer alternative pathways for confronting not only meat color, but also other costly inputs for meat retail display. Light Emitting Diode (LED) lighting offers numerous advantages for display due to being more energy efficient and generating less heat.

LED Lighting

LED technology began in the 1950's with commercial production starting in the late 60's (DOE, 2009). Currently, less than an estimated 1% of the refrigerated display cases have LED lighting technology installed (DOE, 2008). According to LED Magazine (2011), 1,463 companies around the world distribute LED lighting. Phosphor converted LEDs have higher efficacies compared to incandescent and compact fluorescent light bulbs leading to significant energy savings (Arik, 2009). One study conducted in a Eugene, Oregon Albertsons retail grocery store compared the energy savings of LED lighting versus FLS lighting in freezer cases. Four 5-door upright freezer cases and two 3-door freezer cases were retrofitted with LED lighting while the same set up on the opposite side of the aisle contained fluorescent lighting. The freezer cases with LED lighting pulled 1.6 fewer amps reducing wattage 192 watts per 5-door case leading to 61% energy savings per year (PNNL, 2009). However, the installed LED lighting had 36% reduced illuminance compared to the fluorescent lighting because the fluorescent lighting was above typical industry recommendations. A portion of the energy savings can be attributed to the lower illuminance (PNNL, 2009).

The United States Department of Energy (DOE) realizes the potential cost and energy savings LED lighting holds due solely to the efficiency. Goals have been set for the fiscal year 2015 to produce LED lighting systems costing less than $2/klm with a CRI greater than 80, correlated CCT less than 5000°K, and 126 lm/W luminaire that emits approximately 1000 lumens (DOE, 2009). Currently, warm white LED systems with CCT less than 3300 °K possess 40-60 lm/W while compact fluorescent lighting possesses 35-60 lm/W. Although both technologies possess similar efficacies, FLS technology is in its mature stages while LED systems hold the potential to improve two-fold on energy efficiency (DOE, 2009). In addition, LED lighting provides longer operating life, lower maintenance and life cycle costs, minimal light loss, directional illumination, adjustable color, and uniform illumination (DOE, 2008). LED lighting will make a strong appearance in retail display meat cases with potential cost and energy savings and lower heat generation. Energy savings up to 2.1 TWh of electricity is possible if the entire refrigerated market switched to LED lighting (DOE, 2008). As LED lighting provides lower energy costs, longer operating life, and lower operating temperatures, research is needed to evaluate how LED lighting affects the color stability and shelf life of fresh meat.

Relationship Between Visual and Instrumental Color

Visual Color Evaluation

According to the American Meat Science Association (1991), visual color panels are closely related to consumer perceptions of meat products. There are two types of visual color panels, preference and descriptive. Preference evaluations use untrained panelists to estimate consumer preferences while descriptive evaluations use trained color panelists to detect differences between treatments. Variability in results can come from the repeatability of human judgement, lighting, visual deficiencies of the eye and appearance factors other than color. To minimize variability, pictorial color standards and appropriate scales must be customized to each color panel. Preliminary studies result in scales that will encompass the spectrum of sample colors most likely to appear throughout the study. Many descriptive scales are used in visually evaluating meat color. “Worst point” color scales ask panelists to score the most discolored 2 cm area of a product whereas “overall” color scales average the discoloration across the entire surface of a product. Percent discoloration and consumer preference scales are used to determine time periods for retail discounting or discarding products along with estimating consumer preferences.

Instrumental Color Analysis

The Meat Color Measurement Guidelines from the American Meat Science Association (1991) report that instrumental color measurements are used to provide objective results to support visual observations, provide a basis for product acceptance or rejection, document color deterioration over time and estimate the proportion of myoglobin states. Instrumental data must be used to represent relative color differences as opposed to “absolute” descriptions of color. Product color can be instrumentally measured either through pigment extraction or reflectance. The reflectance color measurement method is a more rapid approach that can be used repeatedly on the same samples. For meat samples, illuminant A should be the light source used as it places more emphasis on the red portion of the color spectrum and correlates with visual scores better. Reflectance data can be reported as CIE Lab-values also known as L* (light), a*(red) and b*(yellow). Hue angle ($\tan^{-1}$b*/a*), a/b (a*/b*) and saturation index ($((a^{*2} + b^{*2})^{(1/2)})$) are calculations of instrumental data used to monitor discoloration. Lower values of a/b and saturation and higher values of hue angle are indicators of discoloration (AMSA, 1991).

Relationship of Visual and Instrumental Color

Describing and evaluating color for humans is a subjective practice. Consumers psychologically perceive color by a mixture of stimuli from three primary colors which can be measured in physical quantities (MacDougall, 1982). One study asked panelists to categorize beef *longissimus dorsi* steaks into one of 10 reference standards using visual color and compared those results with instrumental color measurements categorizing the steaks. Using L*a*b*C*and H*, instrumental measurements placed the steaks in the same category as visual observations 83.3% of the time (Goñi, Indurain, Hernandez, & Berian, 2007). Jeremiah et al. (1972) found visual color to correlate with instrumental value and chroma 81% and 73% of the time, respectively. Pork *longissimus lumborum* visual color was reported to have a 92% and 90% correlation with illuminant A-Hunter L* and hue angle values, respectively (Brewer, Zhu, Bidner, Meisinger, & McKeith, 2000).

CHAPTER 3 - Shelf Life of Five Meat Products Displayed Under Light Emitting Diode or Fluorescent Lighting

Abstract

Light Emitting Diode (LED) lighting used in retail display cases offers economical savings in energy use and generates less heat compared with fluorescent (FLS) lighting. This study compared the effects of LED and FLS lighting on visual and instrumental meat color and shelf-life properties of five meat products displayed in two Hussmann retail display cases set up with the same operational and temperature profiles so that lighting was the single variable. For each treatment, 24 enhanced pork loin chops, 36 beef *longissimus dorsi* steaks, 24 ground beef, 24 ground turkey, and 36 beef *semimembranosus* steaks were used. Pork loin chops and beef *longissimus dorsi* steaks were received in mother bags containing 0.4% CO–35% CO_2– 64.6% N_2. Beef *semimembranosus* steaks were cut fresh from subprimals prior to display. Ground turkey was displayed in high-oxygen (75% O_2 and 19% CO_2) modified atmosphere packaging (MAP) while the remaining products were displayed on foam trays with moisture absorbent pads and overwrapped with polyvinyl chloride film. Visual color, instrumental color, internal product temperatures, case temperatures and thiobarbituric acid reactive substances (TBARS) values and except for beef *semimembranosus* steaks, aerobic plate counts (APC) and *Enterobacteriaceae* counts (EB) were measured.

As expected, visual color scores of the five meat products indicated color deterioration increased as display time increased. Beef *longissimus dorsi* steaks, ground beef, and the superficial portion of beef *semimembranosus* steaks had less ($P<0.05$) visual discoloration under LED lighting than FLS. For instrumental color, pork loin chops under LED lighting had higher ($P<0.05$) L* values. The superficial and deep portions of beef *semimembranosus* steaks were slightly ($P<0.05$) more intense red under LED lighting. For all other products, no differences ($P>0.05$) were found for a* values or saturation indices. There was no lighting type main effect ($P>0.05$) on APC or EB populations. Pork loin chops and ground turkey had a lighting type by day interaction for APC and EB populations, respectively. At the end of display, chops under LED lighting had lower APC populations than FLS. Ground turkey under FLS lighting fluctuated throughout display with higher EB populations at the end compared to samples under LED lighting remaining constant throughout the study. As expected, APC populations increased as display time increased for pork loin chops, ground beef, and ground turkey. APC populations for beef *longissimus dorsi* steaks did not change ($P>0.05$) during display, however display life was limited due to initial case-ready age. EB populations increased ($P<0.05$) for pork loin chops, ground beef and ground turkey as display time increased. The internal temperature of all products, except beef *longissimus dorsi* steaks, was lower ($P<0.05$) in the LED case. FLS case temperatures were higher ($P<0.05$) by 0.56 to 1.11 °C over the duration of the study compared to the LED case. Pork loin chops, ground turkey, and beef *semimembranosus* steaks had higher ($P<0.05$) TBARS values by 0.06 to 0.24 mg malonaldehyde/kg under LED lighting, but lighting type did not affect ($P>0.05$) TBARS of beef *longissimus dorsi* steaks or ground beef. LED lighting results in lower display case temperatures, lower internal product temperatures, and extended color life; however, lipid oxidation was increased in some cuts under LED lighting.

Introduction

Retail customers do not have methods to estimate tenderness, juiciness or flavor when evaluating meat cuts for purchase. Instead, color is one of the major criteria in selecting meat items (Kropf, 1993). During refrigerated display, fresh meat color changes and customers discriminate against discolored meats. Meat items with discoloration must be discounted or discarded leading to revenue losses up to $1 billion for the meat industry (Smith, Belk, Sofos, Tatum, & Williams, 2000).

Myoglobin is the primary pigment responsible for meat color. Pigment concentration and the physical parameters of meat, including light scattering and absorbing properties, affect meat color (Kropf, 1993). Myoglobin protein exists as deoxymyoglobin, oxymyoglobin, or metmyoglobin depending upon the state of the iron molecule as well as the occupation of the sixth ligand (Faustman & Cassens, 1990).

Meat color is the result of the interaction of many factors (Kropf, 1993). These factors include interaction of metmyoglobin reducing activity, display temperatures, oxygen pressure and consumption rate, bacterial contamination, lipid oxidation, animal diet, animal genetics, and animal breed (Ledward, Smith, Clarke, & Nicholson, 1977; MacDougall & Taylor 1975; George & Stratman, 1952; Bala, Marshall, Stringer, & Naumann 1977; Chan, Faustman, & Decker, 1997; French, Stanton, Rawless, O'Riordan, Monhan, Caffery, & Moloney 2000; Brewer, Jensen, Sosnicki, Fields, Wilson, & McKeith, 2002; Brewer, Sosnicki, Fields, Hankes, Ryan, Zhu, & McKeith, 2004). These variables must be well understood in order to contend with the complexity of meat color.

The meat industry is aware of the major role lighting type and intensity has on the appearance of meat in retail display. Lighting technology has developed to extend fresh meat color. Newer technologies in lighting offer the ability to enhance meat color plus reduce other costly inputs for meat retail display. Light emitting diode (LED) lighting offers advantages for display by being more energy efficient and having reduced heat generation throughout display.

Currently, less than an estimated 1% of the refrigerated display cases have LED lighting technology installed (DOE, 2008). Phosphor converted LEDs have higher efficacies compared to incandescent and compact fluorescent light bulbs leading to significant energy savings (Arik, 2009). The Department of Energy (DOE) realizes the potential cost and energy savings LED lighting holds due solely to efficiency. Goals have been set by the United States government for the fiscal year 2015 to produce LED lighting systems costing less than $2/klm with a color-rendering index (CRI) greater than 80, correlated color temperature (CCT) less than 5000 K, and 126 lm/W luminaire that emits approximately 1000 lumens (DOE, 2009). Furthermore, LED lighting provides longer operating life, lower maintenance and life cycle costs, minimal light loss, directional illumination, adjustable color, and uniform illumination (DOE, 2008). Energy savings up to 2.1 TWh of electricity is possible if the entire refrigerated market converted to LED lighting (DOE, 2008). As LED lighting provides potential for lower energy costs, longer operating life, and lower operating temperatures, research is needed to evaluate how LED lighting affects the color stability and shelf life of fresh meat.

The objective of this study was to determine the effects of LED and FLS lighting on visual and instrumental meat color and shelf-life properties of five fresh meat products displayed in two retail display cases running at similar temperature profiles.

Materials and Methods

Retail Display Cases

Two Hussmann Ingersoll 8 foot M5X (Bridgeton, MO) meat retail display cases were installed in the Kansas State University (KSU) Meat Color Lab. One case was equipped with FLS lights, the other with LED lights. The cases were installed end-to-end with condenser units equipped with an on/off cycle counter and an hour meter in an adjacent room. Defrost cycles occurred simultaneously every six h. To minimize end-temperature fluctuations and to simulate end-to-end case placement, a 1.03 x 1.74 x .05 m piece of Owens Corning Formulator 150 insulation (Toledo, OH) was attached to the outside end of each case.

Case temperatures were adjusted to operate as close as possible with case lighting off and similar condenser cycling. Temperatures were confirmed with 30 RD-Temp-XT Temperature Loggers (Omega Engineering, Stamford, CT) to be similar during 2-3 d of dark operation before d 0 of the study. Each display case had four adjustable shelves consisting of two sections and the fixed bottom shelf. The top shelf width was 35.66 cm, shelf 2 was 40.64 cm, shelves 3 and 4 were 45.72 cm, and the bottom shelf was 72.39 cm wide. Shelves were arranged identically in both cases and were similar in vertical spacing to cases in Manhattan, KS supermarkets. As product was removed from a case for analyses, a 454 g plastic water bag was positioned in the vacant location to simulate full display case. The average room temperature was 18.3 °C.

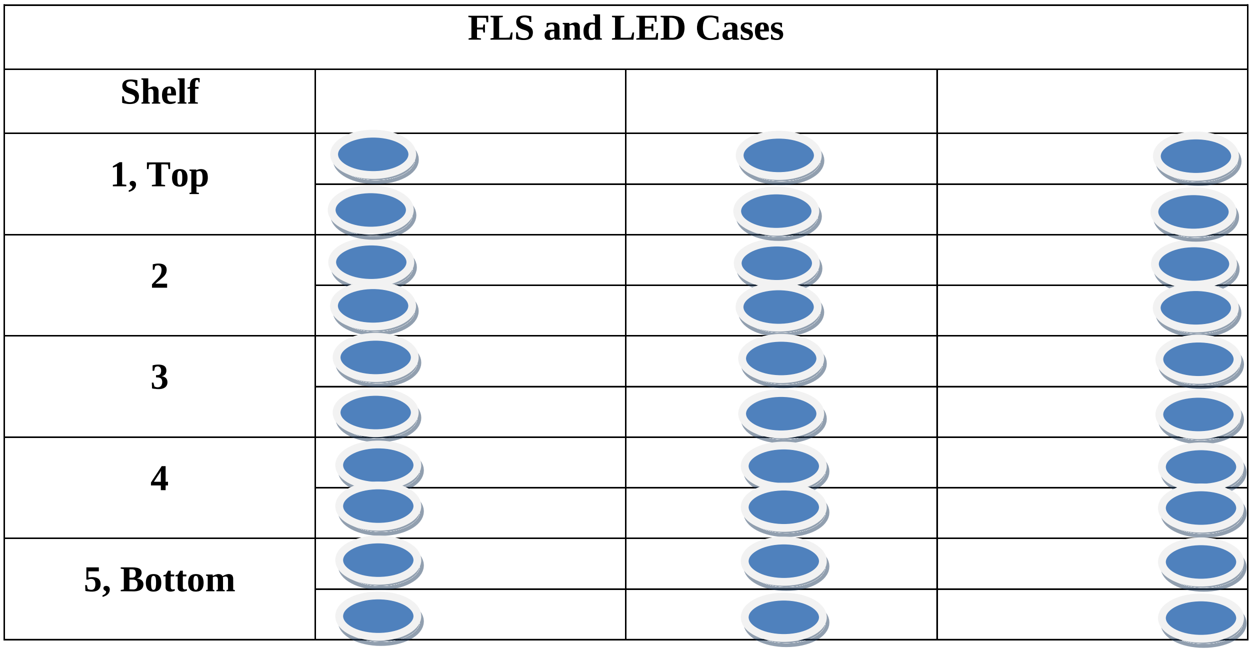
Display Lighting

The meat products in both cases were illuminated 24 h/d. In the LED case, a canopy lighting fixture (Hussmann® EcoShine Model Nos. 4441720 and 4441721, Bridgeton, MO) positioned above the top shelf had a CCT of 2867 K and a CRI of 93. The bottom four shelves were illuminated with LED light bars (Hussmann® EcoShine Model No. 4441590, Bridgeton, MO) having a CCT of 3007 K and a CRI of 95.7. Lighting intensity in the LED case averaged 1627 lm. The FLS lighting (Sylvania Octron, F032/835/ECO, Danvers, MA) had a CCT of 3500 K, a CRI of 82 and lighting intensity averaging 1712 lm.

Case Temperatures

Case temperatures were monitored throughout the study using I-button Thermochrons (DS1921 G Maxim Direct, Sunnyvale, CA). Six I-buttons were located on each shelf with two each on the far left, far right, and center positions of each shelf for a total of 30 temperature data loggers per case (Fig. 3-1). Temperatures were recorded every ten min throughout the study.

Fig. 3-1. I-button temperature logger locations in fluorescent (FLS) and light emitting diode (LED) display cases.



Raw Materials and Packaging for Display

Five types of fresh meat products were obtained from a commercial supplier (Cargill Meat Solutions, Wichita, KS) and stored in a 4.4 °C cooler for up to 2 d before reprocessing and/or repackaging for display.

Pork loin chops: Pork loin chops (1.91 cm thick, 6 d postmortem) enhanced at 12% with pork stock, lactate, phosphate, salt, and natural ingredients were received in packages of four chops enclosed in a mother bag which had been flushed with 0.4% CO– 35% CO_2 – 64.6% N_2. Chops were randomly selected from the mother bag and individually packaged on 13.34 x 13.34 x 1.27 cm 1S foam trays (Dyne-a-pak Inc., Laval, QC, Canada) with Dry-Loc (ac-50, Cryovac, Duncan, SC) moisture absorbent pads and overwrapped with polyvinyl chloride (PVC) film (23,250 cc/m^2/24h @23 °C and 0% RH, Borden Packaging and Industrial Products, North Andover, MA).

Beef *longissimus dorsi* steaks: United States Department of Agriculture (USDA) select/low choice beef *longissimus dorsi* steaks enhanced at 8% pump with beef stock, lactate, phosphate, salt and natural flavorings were received as individually packaged steaks (1.27 cm thick, 9 d case-ready date) on foam trays with PVC overwrap in a mother bag which had been flushed with 0.4% CO– 35% CO_2 – 64.6% N_2. Steaks were removed from the no-oxygen mother bag, and individually re-packaged on 21.59 x 11.43 x 1.43 cm 17S foam trays containing a moisture absorbent pad and overwrapped with PVC.

Ground beef: Coarse ground beef (85% lean and 15% fat) was received in 4.54 kg chubs. On d 0, coarse ground beef was re-ground at the KSU Meat Lab through a 0.32cm plate, and then 454 g ground beef was placed on a moisture absorbent pad on 20.96 x 14.61 x 1.59 cm foam trays and overwrapped with PVC.

Ground turkey: Ground turkey containing rosemary was case-ready, in a 454 g/modified atmosphere package (MAP) containing 70% O_2 – 20% CO_2 – 10% N_2.

Beef *semimembranosus* steaks: One day prior to display, vacuum packaged USDA select/low choice beef *semimembranosus* subprimals were trimmed of external fat and the adductor muscle at KSU, re-vacuum packaged, and then stored in a 4.4 °C cooler. On d 0, steaks were manually cut 2.54 cm thick and placed on a moisture absorbent pad on 26.19 x 13.81 x 1.27 cm foam trays and overwrapped with PVC.

Within each product type, products were randomly selected for replication and display location on a specific shelf. The top shelf of each case held four replications of six enhanced pork loin chops, the second shelf held six replications of six beef *longissimus dorsi* steaks, the third shelf held four replications of six ground beef, the fourth shelf held four replications of six ground turkey, and the bottom shelf held six replications of six beef *semimembranosus* steaks. In total, 48 enhanced pork loin chop packages, 72 beef *longissimus dorsi* steak packages, 48 ground beef packages, 48 ground turkey packages, and 72 beef *semimembranosus* steak packages were evaluated for initial pH, visual and instrumental color, internal temperature, subjective odor, thiobarbituric acid reactive substances (TBARS), and except for beef *semimembranosus* steaks, microbial populations during display. Packaged products were put into display immediately after final packaging (d 0) and displayed until the end of visual color life as determined by an average visual color panel score of 4.

Initial pH

The meat pH of all raw materials was measured on 4 to 8 randomly selected samples from each replication on d 0 by inserting a pH probe (Hanna Instruments; H199163; Woonsocket, RI) attached to an Accumet Basic pH Meter (Fisher Scientific, Pittsburgh, PA) into the samples at three locations.

Visual Color

All visual panelists had passed the Farnsworth-Munsell 100-Hue Test for color blindness and ability to detect differences in hue and were oriented with actual product, pictorial references, and the scoring ballot before the study started. A minimum of 8 trained color panelists evaluated meat color daily to the nearest 0.5 increment using 8-point scales unique to each product. Pork loin chop and ground turkey visual color scale: 1= very bright reddish pink, 2= bright reddish pink, 3= dull reddish pink, 4= slightly grayish pink, 5= grayish pink, 6= slightly tannish gray, 7= moderately tannish gray, 8= tan to brown. Beef *longissimus dorsi* and superficial portion of *semimembranosus* steaks, and ground beef color scale: 1= very bright red, 2= bright red, 3= dull red, 4= slightly dark red, 5= moderately dark red, 6= dark red to tannish red, 7= dark reddish tan, 8= tan to brown. Beef *semimembranosus* deep portion steak visual color scale: 1= very bright pinkish red, 2= bright pinkish red, 3= dull pinkish red, 4= slightly dark pinkish red, 5= moderately dark pinkish red, 6= dark pinkish red to tannish pink, 7= dark pinkish tan, 8= tan to brown. An average visual panel score of 2.5 and 4 represented the middle and end (estimated as the point of objectionable color in retail displays) of product color shelf life, respectively. The color of pork loin chops, beef *longissimus dorsi* steaks, ground turkey, and beef *semimembranosus* steaks were evaluated by panelists once per day at a standardized time. The superficial and deep portions of *semimembranosus* steaks were evaluated separately for color. Ground beef was visually scored every 12 h through d 2 of display, and then every 24 h for the remaining display time.

Instrumental Color

Two packages from each replicate were analyzed for CIE L*, a*, and b* for Illuminant A, an aperature of 31.8 mm and the 10° Observer using a HunterLab MiniScan™ EZ (Model 4500; Reston, VA). Three measurements were taken on each package through the overwrap film for all products except ground turkey. Color of ground turkey was determined by removing the MAP film and directly pressing the aperture covered with clear plastic wrap onto the meat surface. Hue angle, saturation index and a/b ratios were determined. Measurements were taken once daily at a standardized time except for ground beef which was measured every 12 h for the first 2 days, and ground turkey which was measured on d 0, 1, 2, 3, and 7.

Product Internal Temperature

Internal product temperature was measured daily at the geometric center of one sample per replicate using a thermocouple (Omegaette® HH300 Series Thermometer, Stamford, CT) except for ground turkey which was measured on d 0, 1, 2, 3, and 7.

Gas Concentration

The gas concentration in all of the original mother bags for pork loin chops and beef *longissimus dorsi* steaks were analyzed using a gas analyzer (Bridge Hi/Lo-Ox Tri–Gas MAP CO/CO2/O2 Analyzer, Model 900131; Alameda, CA). Using the same gas analyzer, the atmosphere of one package per replicate of ground turkey was measured on d 0, 1, 2, 3, and 7 of display.

Odor

Odor was scored immediately after opening a package on d 0 and at the end of display. Three trained odor panelists subjectively evaluated off-odors using a five-point scale: 1 = no off-odor, 2 = slight, 3 = small, 4 = moderate and 5 = extreme off-odor.

TBARS

Product oxidation was analyzed using the TBARS procedures of Witte et al. (1970). On d 0 and the end of display, a sample from the upper 0.64 cm of the displayed surface was removed with a knife and stored in a bag (Whirl-Pak, Nasco, Modesta, CA) at -80 °C until analyzed within 30 days.

Microbiology

For each replicate, two packages of each product under FLS and LED lighting except beef *semimembranosus* steaks were evaluated for microbial populations at the beginning, middle, and end of color shelf life. Initial microbial testing was performed on d 0 for all products. The middle sampling day was determined by an average visual color panel score of 2.5 and the end with an average color score of 4. As a result, each product had a unique middle and end microbial sampling day. Aerobic Plate Count (APC) and *Enterobacteriaceae* (EB) populations were determined using Petrifilm™ (3M Microbiology Products; St. Paul, MN). Enhanced pork loin chops were aseptically cored using a 2.54 cm diameter corer to obtain a 25 g sample that was stomached (Stomacher 400 Lab Blender, Seward Medical, London, UK) with 225 mL sterile 0.1% peptone diluent (Difco, BD) for 1 min in a filter bag (FILTRA-BAG, no. 01-002-57, Fisher Scientific, Pittsburg, PA). Each sample was serial diluted in 0.1% peptone water and dilutions were plated in duplicate. For beef *longissimus dorsi* steaks, a 50 cm^2 area of sample was swabbed (BactciSwab II®, Remel, Lenexa, KS), placed into 9 mL 0.1% peptone diluent, and serial diluted before plating in duplicate. For ground beef and ground turkey, 25 g samples collected from the 0.64 cm outer illuminated surface were stomached for 1 min in 225 mL of 0.1% peptone diluent in filter bags, serially diluted with 0.1% peptone, and then plated in duplicate. Plates for APC and EB populations were incubated at 32 °C for 48 h and 24 h, respectively, prior to enumeration.

Statistical Analysis

This was a completely randomized design with sub-sampling. Replication was used as a covariate. Data were analyzed using the PROC Mixed procedure in SAS 9.2. The Kenward-Roger (KR) adjustment was used for degrees of freedom. Effects tested in the model included replication, lighting type (LED vs. FLS), day of display, and the lighting type by day of display interaction. The least significant difference procedure was used to separate means ($P < 0.05$).

Results and Discussion

Main effects and interactions between lighting type and day of display are summarized in Tables 1 to 3.

Table 1. Probability values for lighting type, day of display, and lighting type by day of display interactions for visual and L*, a* and b* instrumental color.

Statistical Analysis	Pork Chop	Beef *longissimus dorsi* steak	Ground Beef	Ground Turkey	Beef Superficial Portion *semimem-branosus* Steak	Beef Deep Portion *semimem-branosus* Steak
Visual Color						
Lighting Type	0.3054	0.0089	0.0161	0.8397	0.0237	0.1200
Day of Display	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Lighting Type by Day of Display	0.5969	0.2899	0.9531	0.4463	0.9977	0.9251
Instrumental Color						
L*						
Lighting Type	<0.0001	0.5649	0.9160	0.1908	0.4172	0.6783
Day of Display	0.9990	0.0588	0.0004	0.0014	<0.0001	<0.0001
Lighting Type by Day of Display	0.8329	0.9768	0.9923	0.2610	0.1839	0.5826
a*						
Lighting Type	0.6367	0.2703	0.6972	0.4183	0.0724	0.0198
Day of Display	0.0789	<0.0001	<0.0001	0.0013	<0.0001	<0.0001
Lighting Type by Day of Display	0.9993	0.6061	0.9956	0.9289	0.0024	0.1555
b*						
Lighting Type	0.0002	0.2314	0.9782	0.1923	0.0019	0.0191
Day of Display	0.8467	<0.0001	<0.0001	0.0309	<0.0001	<0.0001
Lighting Type by Day of Display	0.9424	0.6426	0.9234	0.1151	<0.0001	0.0007

Table 2. Probability values for lighting type, day of display, and lighting type by day of display interactions for saturation index, a/b ratio and hue angle.

Statistical Analysis	Pork Chop	Beef *longissimus dorsi* steak	Ground Beef	Ground Turkey	Beef Superficial Portion *semimem-branosus* Steak	Beef Deep Portion *semimem-branosus* Steak
Instrumental Color						
Saturation Index						
Lighting Type	0.1061	0.2541	0.7917	0.3317	0.0143	0.0160
Day of Display	0.2269	<0.0001	<0.0001	0.0026	<0.0001	<0.0001
Lighting Type by Day of Display	0.9945	0.6215	0.9857	0.7242	0.0004	0.0194
a/b Ratio						
Lighting Type	0.0348	0.5701	0.4939	0.7482	0.0095	0.6541
Day of Display	0.1338	<0.0001	<0.0001	0.0006	<0.0001	<0.0001
Lighting Type by Day of Display	1.0000	0.4233	0.9990	0.8135	0.0967	0.0109
Hue Angle						
Lighting Type	0.0438	0.5678	0.5381	0.7273	0.0107	0.5262
Day of Display	0.1329	<0.0001	<0.0001	0.0011	<0.0001	<0.0001
Lighting Type by Day of Display	1.0000	0.4578	0.9994	0.8168	0.1166	0.0207

Table 3. Probability values for lighting type, day of display, and lighting type by day of display interactions for thiobarbituric acid reactive substances (TBARS), aerobic plate counts and *Enterobacteriaceae* counts.

Statistical Analysis	Pork Chop	Beef *longissimus dorsi* Steak	Ground Beef	Ground Turkey	Beef *semimembranosus* Steak
TBARS					
Lighting Type	0.0136	0.7104	0.9644	0.0371	0.0009
Day of Display	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Lighting Type by Day of Display	0.2405	0.1942	0.3509	0.3523	0.6600
Aerobic Plate Count					
Lighting Type	0.0230	0.6620	0.1431	0.7072	-
Day of Display	<0.0001	0.8682	0.0011	<0.0001	-
Lighting Type by Day of Display	0.0096	0.2531	0.8645	0.8547	-
***Enterobacteriaceae* Count**					
Lighting Type	0.2303	0.2609	0.7766	0.1394	-
Day of Display	0.0138	0.7037	0.0212	0.0002	-
Lighting Type by Day of Display	0.1875	0.0365	0.7008	0.0001	-

Initial Conditions

Mean initial pH of the five products are shown in Table 4. The pH of beef *longissimus dorsi* and *semimembranosus* steaks were similar (P>0.05). The pH of the ground turkey may be higher due to added rosemary ingredients. The mother bag gas concentration for pork loin chop and beef *longissimus dorsi* steaks are shown in Table 4. The MAP atmospheres of ground turkey during storage is shown in Table 5. These gas mixtures are typical of high-oxygen supplier specifications targeting a shelf life of 6-10 d (McMillin, 2008).

Table 4. Least squares means (Lsmeans) for pH of five meat products and gas compositions of products received in mother bags.

Trait	Pork Loin Chops	Beef *longissimus dorsi* Steaks	Ground Beef	Ground Turkey	Beef *semimembranosus* Steaks
pH	5.78[c]	5.62[d]	5.92[b]	6.43[a]	5.61[d]
Gas (%)					
CO	0.16	0.15	---	---	---
CO_2	29.70	26.00	---	---	---
O_2	4.70	0.13	---	---	---

[a-d] Lsmeans within row having a different superscript letter differ ($P<0.05$). CO= Carbon monoxide, CO_2= Carbon dioxide, O_2= Oxygen.

Table 5. Gas composition of pre-packaged modified atmosphere ground turkey during refrigerated display under fluorescent (FLS) or light emitting diode (LED) lighting.

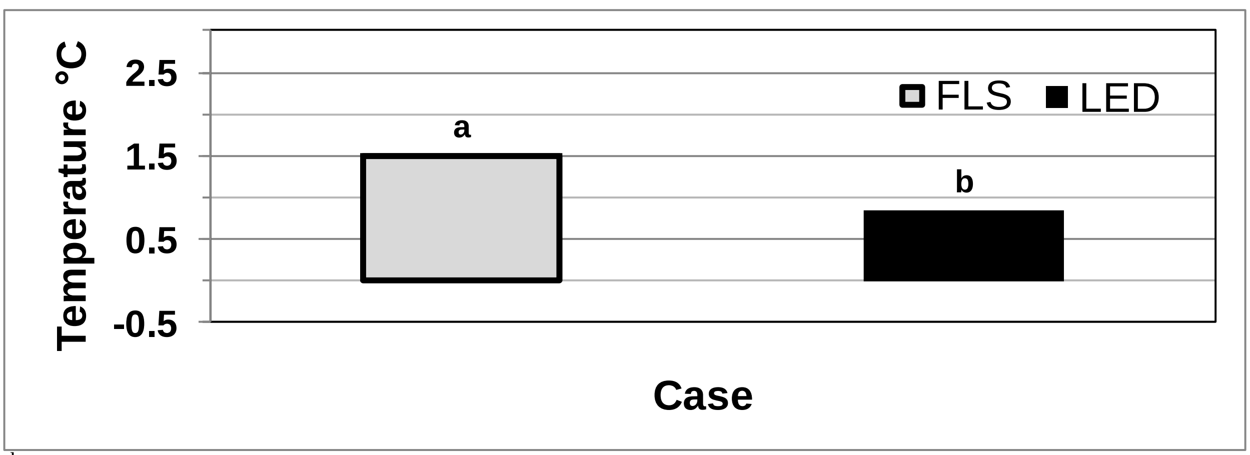
Day of Display	CO %		CO_2 %		O_2 %	
	FLS	LED	FLS	LED	FLS	LED
0	0.02	0.03	19.05	17.09	70.85	70.51
1	0.04	0.00	18.05	17.33	73.75	72.76
2	0.04	0.03	20.35	20.23	77.47	77.78
3	0.00	0.00	18.23	18.48	78.78	80.55
7	0.00	0.00	18.32	17.63	71.65	69.25

Case Temperatures and Cycling

Throughout display, the pooled LED mean case temperature was 0.84 °C which was lower ($P<0.05$) than the FLS case with a pooled mean case temperature of 1.53 °C (Fig. 3-2). Temperatures at the front of the shelves at the left, center, and right case sections were more than 1 °C higher ($P<0.05$) compared to the back of the shelves (Fig. 3-3). Due to a small gap between shelf sections in each row allowing cool air to flow freely in the center of the case, temperatures at the row centers tended to be 0.37-1.00 °C lower than the sides. No differences ($P>0.05$) were observed for mean temperatures between any of the five shelves. Average ambient temperature of the room housing the cases was 18.3 °C. The cycles, run hours and average case condenser cycle per hour during display for LED and FLS cases are shown in Table 6.

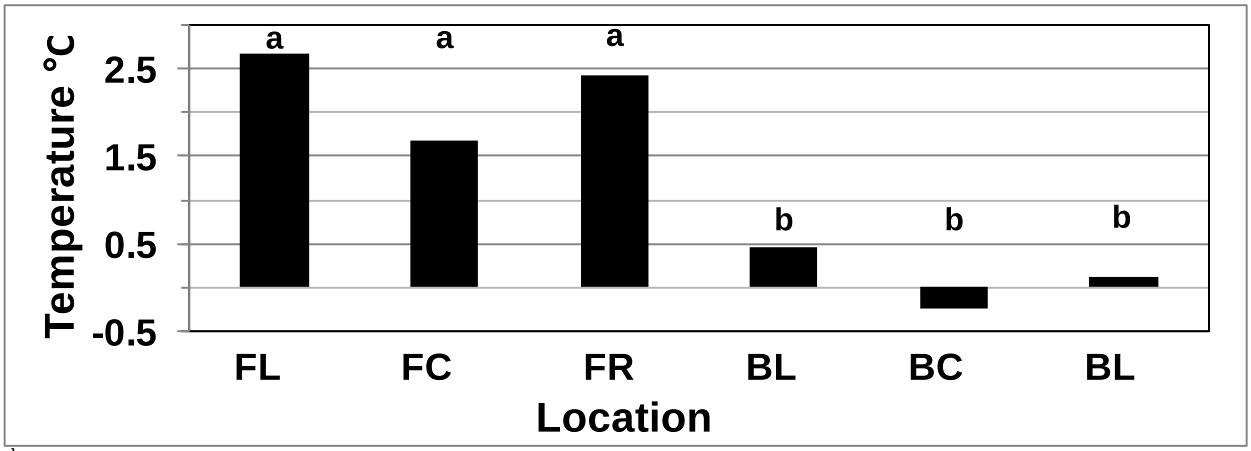
A national retail survey as cited by Mancini and others (2002) reported average display case temperatures of 4.4 °C for retail meat display. Temperatures used in this study were colder than that cited by Mancini and others (2002). Display cases equipped with LED lighting recorded fewer condenser cycles/h and maintained 0.69 °C lower case temperatures than cases with FLS lighting. Although numerous factors affect case operation efficiency, lower temperature values indicate shelf life advantages for products held under LED lighting. The case with LED lighting had an operating efficiency advantage while maintaining lower case temperatures compared to the case with FLS lighting. This agrees with a 2008 report from the DOE reporting greater compressor energy use due to additional heat generated from FLS display lighting. Not only does an LED case operate with greater efficiency in energy use, but also sustains lower temperatures than a FLS lighted case (DOE, 2008).

Fig. 3-2. Least squares means (Lsmeans) for case temperature pooled from 30 locations in refrigerated display cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



[ab] Lsmeans with different superscript letters differ (P<0.05). Standard error = 0.08.

Fig. 3-3. Least squares means (Lsmeans) for case temperature[1] at six shelf locations in refrigerated display cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



[ab] Lsmeans with different superscript letters differ (P<0.05). Standard error = 0.14.
[1] Locations are: FL= front of shelves on left side of case, FC= front of shelves in center of case, FR= front of shelves on right side of case, BL= back of shelves on left side of case, BC= back of shelves in center of case, BR= back of shelves on right side of case.

Table 6. Display case condenser cycling and run time during display using fluorescent (FLS) or light emitting diode (LED) lighting.

Case	Cycles	Run Hours	Cycles/h
FLS	1878	104.4	18.0
LED	1222	113.9	10.7

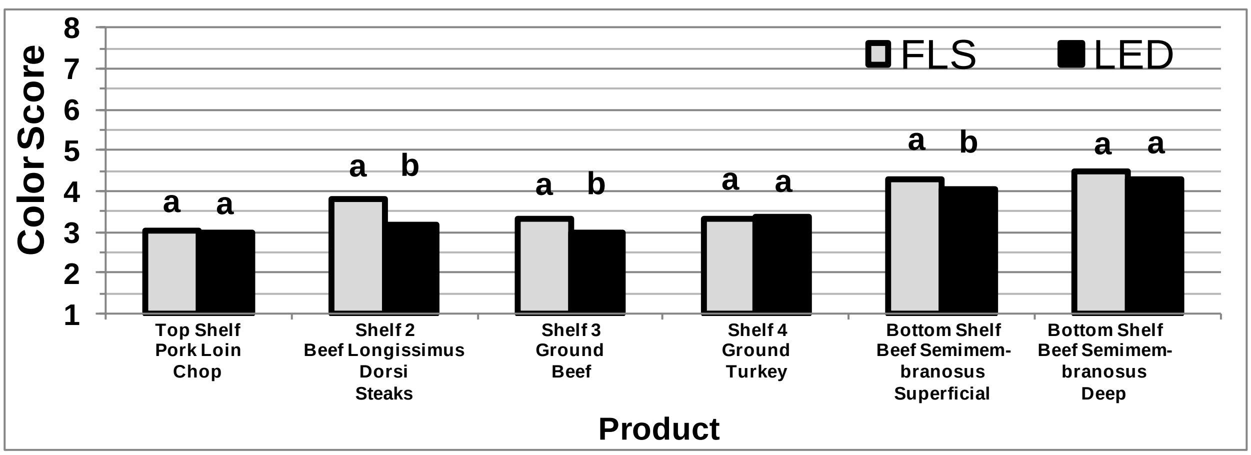
Visual Color Evaluation

Of all five meat products on display, beef *longissimus dorsi* steaks, ground beef and the superficial portion of beef *semimembranosus* steaks had better (P<0.05) color stability under LED lighting based on evaluations by trained color panelists (Fig. 3-4), resulting in an extended color shelf life and economic benefits for retailers. The color shelf life of pork loin chops and ground turkey, both light pigmented products, was driven by day of display and not lighting type.

No interactions (P>0.05) between lighting type and day of display for visual color existed for any of the five meat products. As expected, visual discoloration increased for all products as display time increased (Figs. 3-5 to 3-10). End product color shelf life for pork loin chops, beef *longissimus dorsi* steaks, ground beef, ground turkey and beef *semimembranosus* steaks, as determined by the panelists' scores were 8, 2, 4, 7, and 4 d respectively.

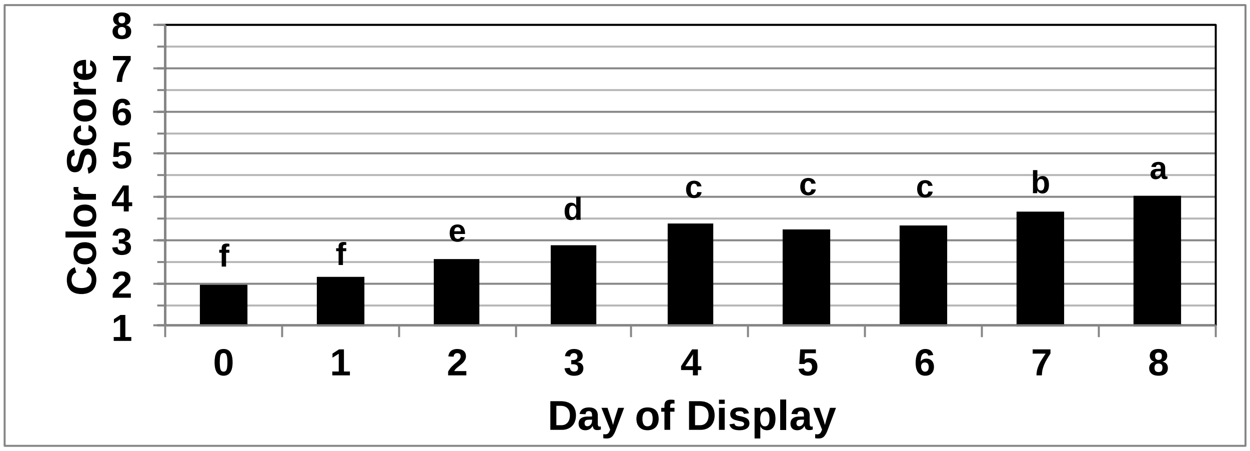
Visual color evaluation for beef *longissimus dorsi* and the superficial portion of beef *semimembranosus* steaks under LED lighting showed an extended color life by 0.5 to 1 day compared to FLS lighting; however, there was no significant interaction for lighting type by day of display. *Semimembranosus* steaks typically have a two-toned appearance with the deep portion of the muscle being paler and more susceptible to discoloration compared to the superficial portion which holds color longer (Sammel et al., 2002; Lee, Yancey, Apple, Sawyer & Baublits, 2006). Thus, the inner portion often determines acceptable color life for this muscle. Visual color results shown in Fig. 3-4 demonstrate that the superficial portion of beef *semimembranosus* steaks should be displayed under LED lighting for extended shelf life.

Fig. 3-4. Least squares means (Lsmeans) for visual color of five products[1] displayed in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting[2].



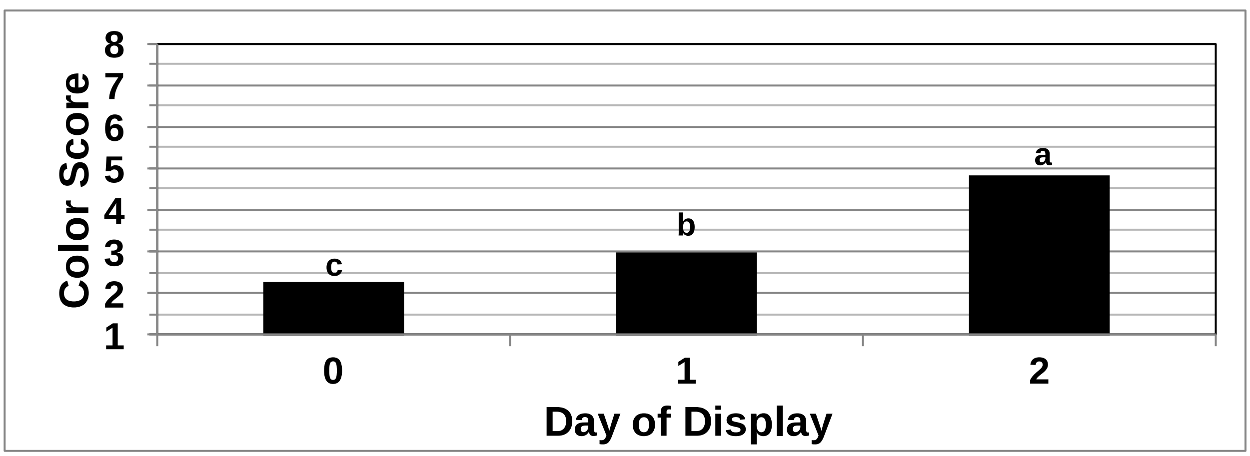
[ab] Lsmeans within each product having a different superscript letter differ (P<0.05).
[1] Visual color score: Pork loin chop and ground turkey 1=very bright reddish pink, 4=slightly grayish pink, 8=tan to brown; beef *longissimus dorsi* steak, ground beef, beef *semimembranosus* superficial 1=very bright red, 4=slightly dark red, 8=tan to brown; beef *semimembranosus* deep 1=very bright pinkish red, 4=slightly dark pinkish red, 8=tan to brown.
[2] Standard error: Pork loin chop=0.03, beef *longissimus dorsi* steak=0.16, ground beef=0.10, ground turkey=0.05, beef *semimembranosus* superficial=0.08, beef *semimembranosus* deep=0.07.

Fig. 3-5. Least squares means (Lsmeans) for visual color[1] of pork loin chops over 8 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



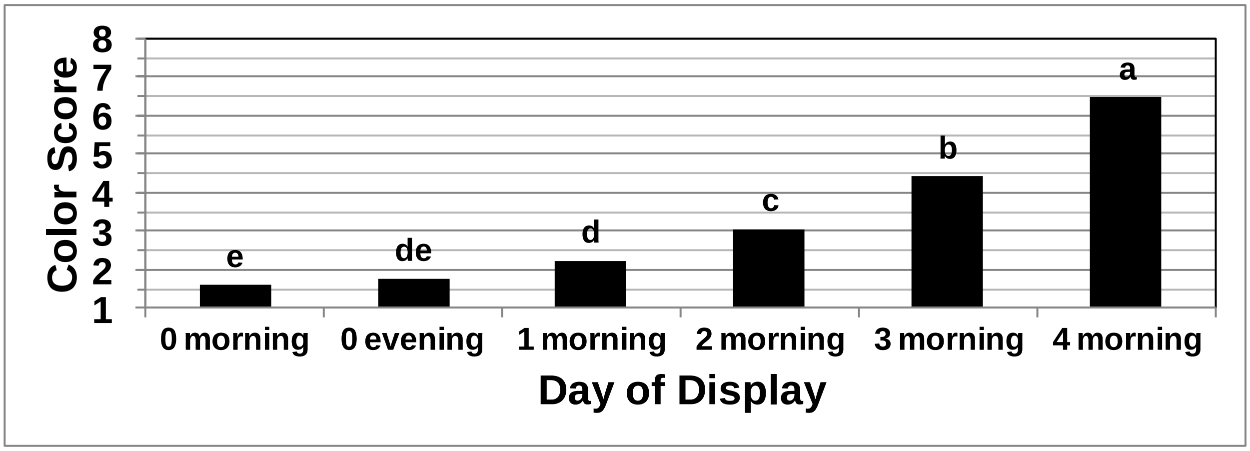
[ab] Lsmeans with different superscript letters differ (P<0.05). Standard error = 0.07.
[1] Color scale ranged from 1 to 8 with 1= very bright reddish pink, 4= slightly grayish pink, and 8= tan to brown.

Fig. 3-6 Least squares means (Lsmeans) for visual color[1] of beef *longissimus dorsi* steaks over 2 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



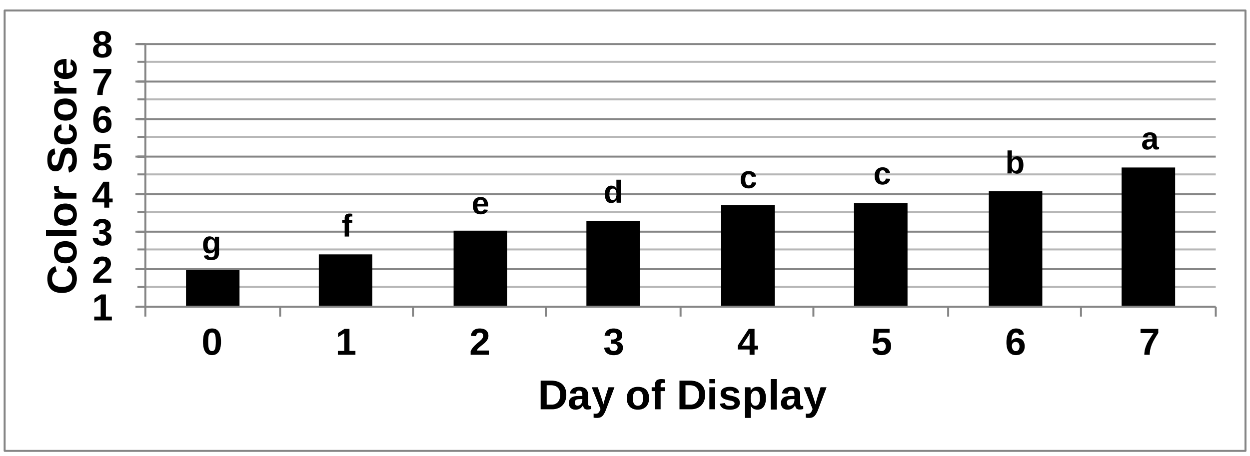
[ab] Lsmeans with different superscript letters differ (P<0.05). Standard error = 0.23.
[1] Color scale ranged from 1 to 8 with 1=very bright red, 4= slightly dark red, and 8= tan to brown.

Fig. 3-7. Least squares means (Lsmeans) for visual color[1] of ground beef over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



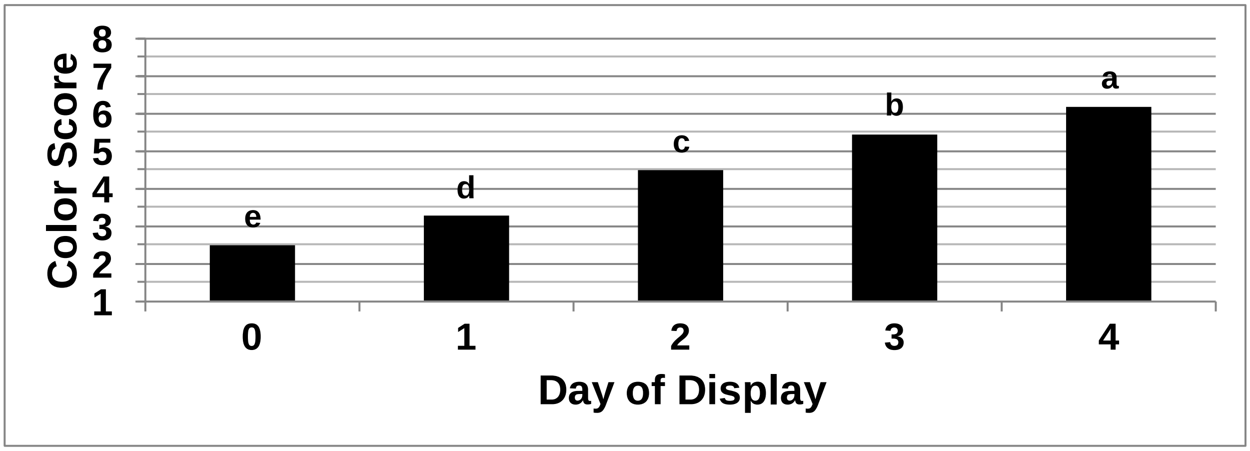
[ab] Lsmeans with different superscript letters differ ($P<0.05$). Standard error = 0.19.
[1] Color scale ranged from 1 to 8 with 1= very bright red, 4= slightly dark red, and 8= tan to brown.

Fig. 3-8. Least squares means (Lsmeans) for visual color[1] of ground turkey over 7 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



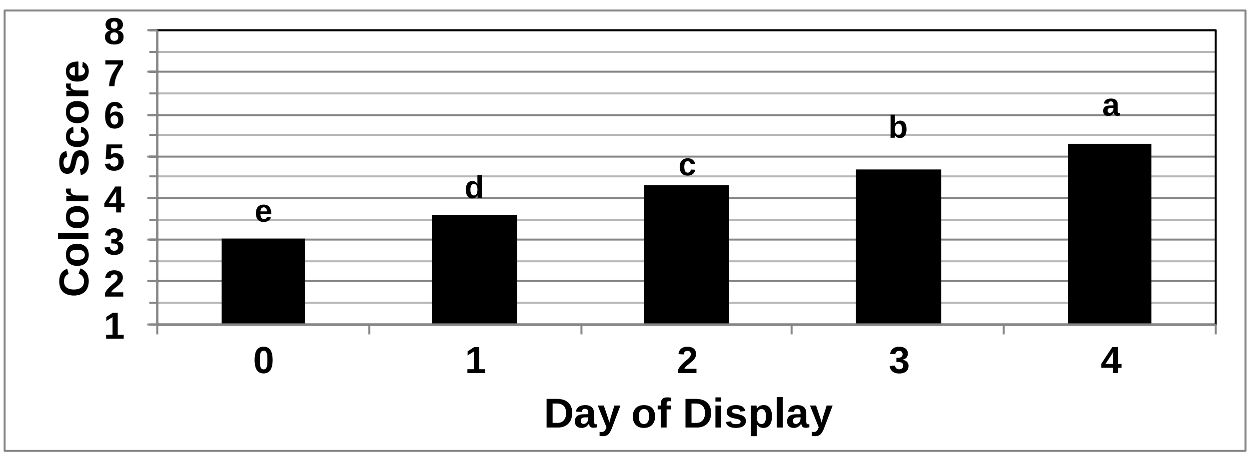
[ab] Lsmeans with different superscript letters differ ($P<0.05$). Standard error =0.09.
[1] Color scale ranged from 1 to 8 with 1= very bright reddish pink, 4= slightly grayish pink, and 8= tan to brown.

Fig. 3-9. Least squares means (Lsmeans) for visual color[1] of beef *semimembranosus* deep portion steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



[ab] Lsmeans with different superscript letters differ (P<0.05). Standard error =0.11.
[1] Color scale ranged from 1 to 8 with 1= very bright pinkish red, 4= slightly dark pinkish red, and 8= tan to brown.

Fig. 3-10. Least squares means (Lsmeans) for visual color[1] of beef *semimembranosus* superficial portion steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



[ab] Lsmeans with different superscript letters differ (P<0.05). Standard error =0.12.
[1] Color scale ranged from 1 to 8 with 1= very bright red, 4= slightly dark red, and 8= tan to brown.

Instrumental Color Measurements

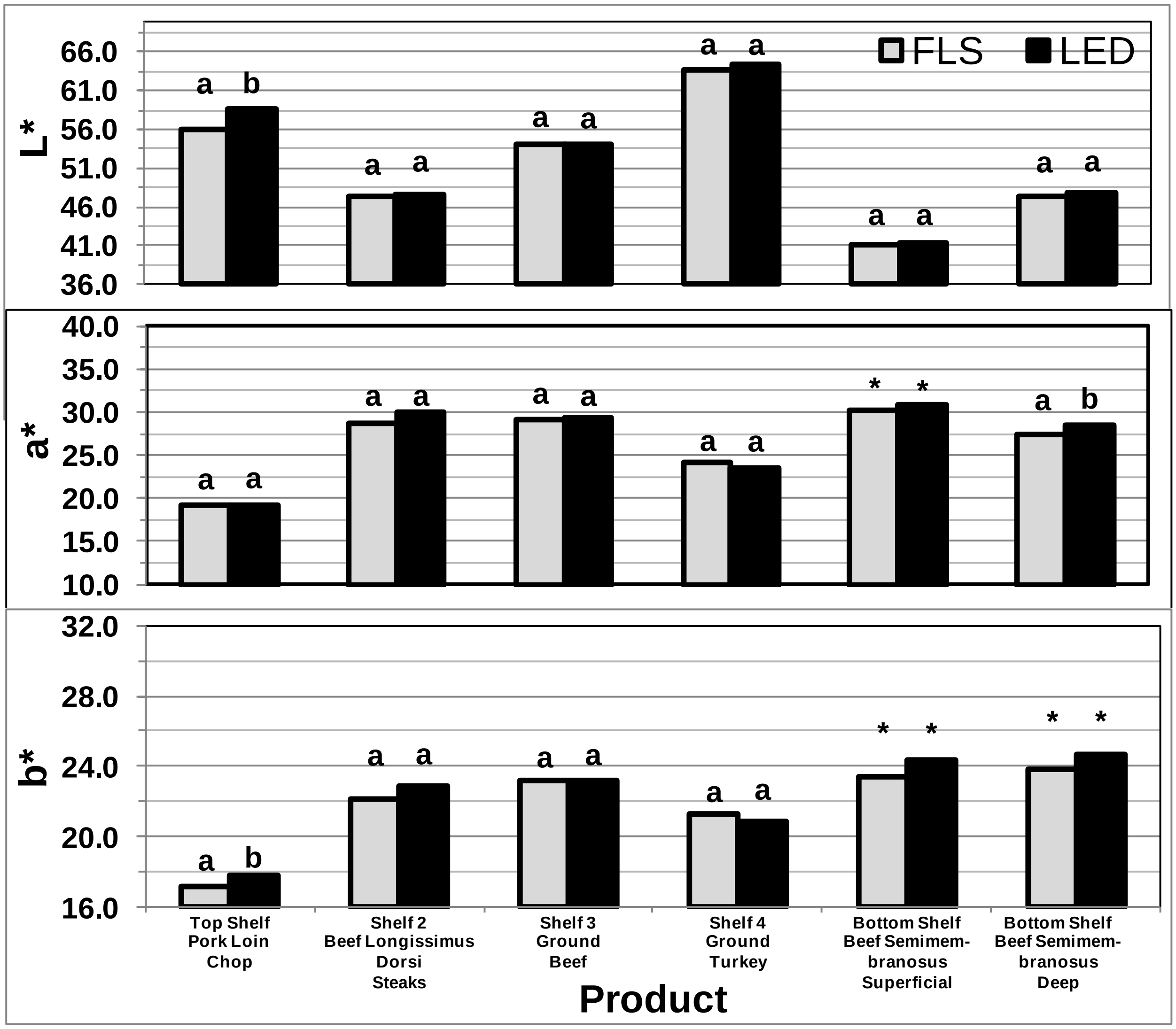
There were no lighting type by day of display interactions for instrumental L* (Table 1). Pork loin chops was the only product to have a higher (P<0.05) L* value under LED lighting than FLS lighting (Fig. 3-11). The deep portion beef *semimembranosus* steaks had a higher (P<0.05) a* value at 28.5 under LED lighting in comparison to 27.41 under FLS lighting. The superficial portion of *semimembranosus* steaks had an interaction between lighting type and day of display with the d 0 LED steaks having a greater a* value than the FLS d 0 steaks (Table 7). All other display day a* values were the same (P>0.05) regardless of lighting type. Beef *longissimus dorsi* steaks, ground beef, ground turkey, and the deep and superficial portions of beef *semimembranosus* steaks all expressed decreased (P<0.05) a* values over time.

Pork loin chops displayed under LED lighting had higher (P<0.05) b* values then when displayed under FLS lighting (Fig. 3-11). A lighting type by day of display interaction occurred for b* for the deep and superficial portions of the beef *semimembranosus* steaks (Table 1). The superficial portion beef *semimembranosus* steaks displayed under LED lighting had a higher (P<0.05) b* value of 27.92 on day 0 compared to the 24.19 b* value for the FLS sample on day 0 while all other values were similar regardless of lighting type or day of display (Table 8). The deep portion of beef *semimembranosus* steaks under LED lighting had a d 0 b* value of 30.75 whereas the FLS samples had a d 0 b* value of 26.52 with all other values being similar regardless of lighting type or day of display (Table 9). Beef *longissimus dorsi* steaks, ground beef and ground turkey had lower (P<0.05) b* values as display time increased.

The saturation index was similar (P>0.05) for all products, except beef *semimembranosus* steaks, under LED or FLS lighting (Table 2). There was an interaction of lighting type and day of display for the superficial and deep portions of beef *semimembranosus* steaks with LED samples having a higher (P<0.05) saturation index at 47.91 compared to 42.73 under FLS lighting on d 0 before becoming similar throughout the rest of display (Tables 10 to 11). Beef *longissimus dorsi* steaks, ground beef and ground turkey had lower (P<0.05) saturation index values as display time increased.

Pork loin chops and the superficial portion of beef *semimembranosus* steaks had lower (P<0.05) a/b ratio’s under LED lighting (Fig. 3-12). Beef *longissimus dorsi* steaks, ground beef and ground turkey had lower (P<0.05) a/b ratios as display time increased. An interaction between lighting type and day of display existed where deep portion beef *semimembranosus*

Fig. 3-11. Least squares means (Lsmeans) for L*[1], a*[2] and b*[3] instrumental color values of five products displayed in refrigerated cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



[ab] Lsmeans within each product having a different superscript letter differ (P<0.05).

[1] L* standard error: Pork loin chop= 0.3, beef *longissimus dorsi* steak= 0.47, ground beef= 0.5, ground turkey= 0.36, beef *semimembranosus* superficial= 0.36, beef *semimembranosus* deep= 0.38.

[2] a* standard error: Pork loin chop= 0.21, beef *longissimus dorsi* steak= 0.65, ground beef= 0.54, ground turkey= 0.55, beef *semimembranosus* superficial= 0.22, beef *semimembranosus* deep= 0.3.

[3] b* standard error: Pork loin chop= 0.11, beef *longissimus dorsi* steak= 0.42, ground beef= 0.3, ground turkey= 0.23, beef *semimembranosus* superficial= 0.22, beef *semimembranosus* deep= 0.24.

* These products had an interaction between lighting type and day of display.

Table 7. Least squares means (Lsmeans) for a* values of the superficial portion of *semimembranosus* steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.

	Day of Storage				
Lighting Type	**0**	**1**	**2**	**3**	**4**
LED	35.32^{ab}	32.86^{ac}	29.03^{ad}	28.61^{ad}	28.35^{ad}
FLS	32.56^{bc}	31.54^{ac}	29.96^{ad}	29.13^{ade}	28.09^{ae}

^{ab} Lsmeans within each column having a different superscript letter differ ($P < 0.05$).
^{ce} Lsmeans within each row having a different superscript letter differ ($P < 0.05$).
Standard error: 0.50

Table 8. Least squares means (Lsmeans) for b* values of the superficial portion of *semimembranosus* steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.

	Day of Storage				
Lighting Type	**0**	**1**	**2**	**3**	**4**
LED	27.92^{ac}	25.87^{ad}	22.74^{ae}	22.31^{ae}	23.12^{ae}
FLS	24.19^{bc}	24.11^{bc}	23.11^{acd}	22.65^{ad}	23.02^{ad}

^{ab} Lsmeans within each column having a different superscript letter differ ($P < 0.05$).
^{ce} Lsmeans within each row having a different superscript letter differ ($P < 0.05$).
Standard error: 0.48.

Table 9. Least squares means (Lsmeans) for b* values of the deep portion of *semimembranosus* steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.

	Day of Storage				
Lighting Type	**0**	**1**	**2**	**3**	**4**
LED	30.75^{ac}	25.64^{ad}	23.27^{ae}	22.27^{aef}	21.33^{af}
FLS	26.52^{bc}	25.50^{ac}	23.06^{ad}	22.54^{ade}	21.35^{ae}

^{ab} Lsmeans within each column having a different superscript letter differ ($P < 0.05$).
^{cf} Lsmeans within each row having a different superscript letter differ ($P < 0.05$).
Standard error: 0.56.

Table 10. Least squares means (Lsmeans) for saturation index values of the superficial portion of *semimembranosus* steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.

	Day of Storage				
Lighting Type	**0**	**1**	**2**	**3**	**4**
LED	45.04^{ac}	41.82^{ad}	36.88^{ae}	36.28^{ae}	36.59^{ae}
FLS	40.57^{bc}	39.71^{bc}	37.85^{ad}	36.90^{ad}	36.31^{ad}

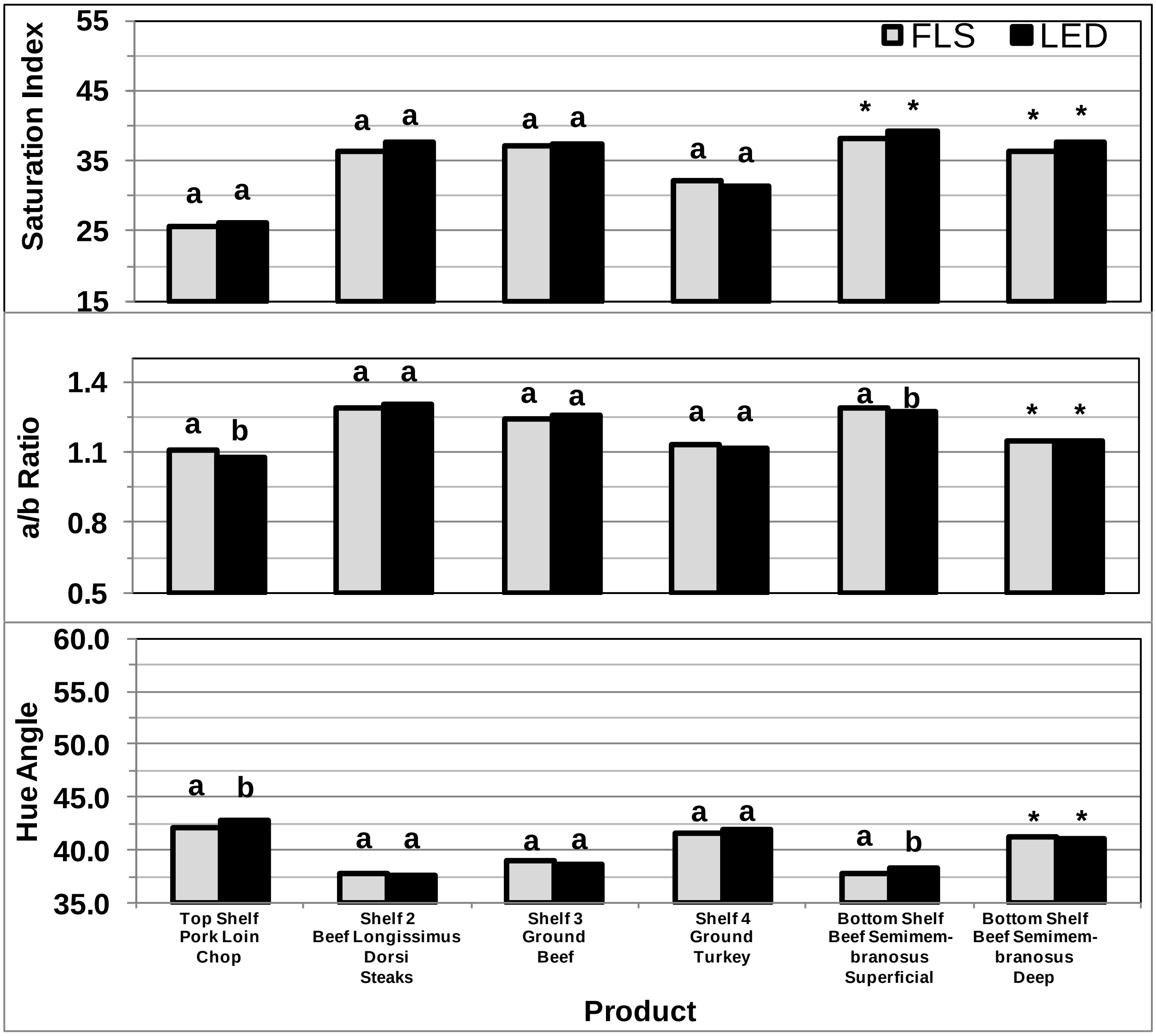
^{ab} Lsmeans within each column having a different superscript letter differ ($P < 0.05$).
^{ce} Lsmeans within each row having a different superscript letter differ ($P < 0.05$).
Standard error: 0.67.

Table 11. Least squares means (Lsmeans) for saturation index values of the deep portion of *semimembranosus* steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.

	Day of Storage				
Lighting Type	**0**	**1**	**2**	**3**	**4**
LED	47.91^{ac}	39.72^{ad}	35.94^{ae}	33.46^{af}	31.33^{ag}
FLS	42.73^{bc}	39.80^{ad}	34.99^{ae}	33.32^{ae}	30.78^{af}

^{ab} Lsmeans within each column having a different superscript letter differ ($P < 0.05$).
^{cg} Lsmeans within each row having a different superscript letter differ ($P < 0.05$).
Standard error: 0.85.

Fig. 3-12. Least squares means (Lsmeans) for saturation index[1], a/b ratio[2] and hue angle[3] instrumental color of five products displayed in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



[ab] Lsmeans within each product having a different superscript letter differ ($P<0.05$).
[1] Saturation index standard error: Pork loin chop=0.22, beef *longissimus dorsi* steak= 0.76, ground beef= 0.59, ground turkey= 0.53, beef *semimembranosus* superficial= 0.30, beef *semimembranosus* deep= 0.38.
[2] a/b ration standard error: Pork loin chop=0.01, beef *longissimus dorsi* steak=0.01, ground beef=0.01, ground turkey=0.02, beef *semimembranosus* superficial=0.01, beef *semimembranosus* deep=0.01.
[3] Hue angle standard error: Pork loin chop=0.25, beef *longissimus dorsi* steak=0.23, ground beef=0.40, ground turkey=0.57, beef *semimembranosus* superficial=0.16, beef *semimembranosus* deep=0.19.
* These products had an interaction between lighting type and day of display.

steaks under FLS lighting had a greater (P<0.05) a/b ratio on d 0 compared to FLS samples on d 0 before becoming similar throughout the rest of display (Table 12).

Pork loin chops and the superficial portion beef *semimembranosus* steaks had higher (P<0.05) hue angles under LED lighting (Fig. 3-12). Beef *longissimus dorsi* steaks, ground beef and ground turkey had higher (P<0.05) hue angle values as display time increased. An interaction between lighting type and day of display existed where deep portion beef *semimembranosus* steaks under LED lighting had greater (P<0.05) hue angle values on d 0 compared to FLS samples before becoming similar throughout the rest of display (Table 13).

Using instrumental color parameters to support the subjective comparison of visual scores can give an indication of shelf life extension (AMSA, 1991). Greater saturation indices and a* values for the deep portion of beef *semimembranosus* steaks under LED lighting were indicative of extended color shelf life, but this was not detected visually by panelists. Conversely, color differences observed by panelists for beef *longissimus dorsi* steaks under LED lighting were not supported by instrumental color measurements. Visual differences were detected for products with greater amounts of myoglobin, and instrumental measurements confirmed differences between samples held under different lighting sources with the beef *semimembranosus* which has the greatest amount of myoglobin (Bodwell & McClain, 1971; King, Shackelford, & Wheeler, 2011). The effect of LED lighting extending fresh meat color life increases with increasing amounts of myoglobin. Discrepancy between the two methods of color evaluation can be attributed to panelists' perception of color under two different lighting sources as opposed to an instrumental measurement using a single light source.

Ground beef packaged with PVC overwrap is a product that typically has a short retail color life due to decreased NADH content (Ledward et al., 1977), areas of low oxygen pressure (Kropf, 1980), and disruption of cell membranes with more exposed surface to oxidation (Govindarajan & Hultin, 1977). An extension of retail display would reduce financial losses for retailers. In this study, ground beef had less visual discoloration (Fig. 3-4) under LED than FLS lighting; however, instrumental measurements did not support (P>0.05) this observation. LED lighting may help minimize visual discoloration of beef *longissimus dorsi* steaks and ground beef even though instrumental data did not support the visual panel observations. A study with 16 trained color panelists conducted at the Lighting Research Center showed a preference for retail dairy products, frozen entrèes, and beverages displayed under LED lighting compared to FLS

Table 12. Least squares means (Lsmeans) for a/b ratio values of the deep portion of *semimembranosus* steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.

	Day of Storage				
Lighting Type	**0**	**1**	**2**	**3**	**4**
LED	1.2^{bc}	1.18^{ad}	1.18^{ad}	1.12^{ae}	1.08^{ae}
FLS	1.26^{ac}	1.20^{ad}	1.14^{ae}	1.09^{af}	1.04^{ag}

^{ab} Lsmeans within each column having a different superscript letter differ (P < 0.05).
^{cg} Lsmeans within each row having a different superscript letter differ (P < 0.05).
Standard error: 0.02

Table 13. Least squares means (Lsmeans) for hue angle values of the deep portion of *semimembranosus* steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.

	Days of Storage				
Lighting Type	**0**	**1**	**2**	**3**	**4**
LED	39.85^{ac}	40.20^{ac}	40.38^{ac}	41.83^{ad}	43.00^{ad}
FLS	38.35^{bc}	39.85^{ad}	41.28^{ae}	42.61^{af}	44.01^{ag}

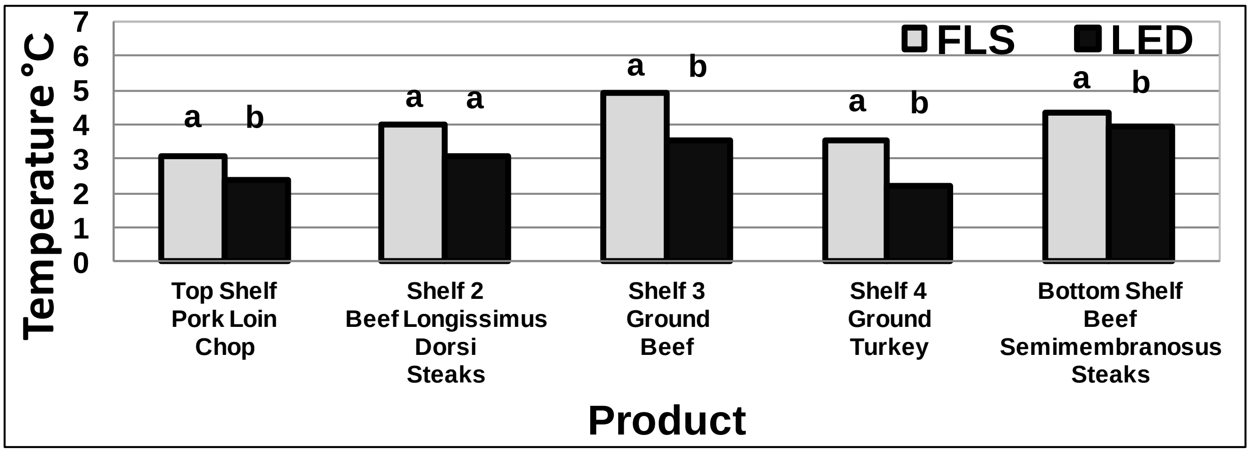
^{ab} Lsmeans within each column having a different superscript letter differ (P < 0.05).
^{cg} Lsmeans within each row having a different superscript letter differ (P < 0.05).
Standard error: 0.43.

lighting (Raghavan & Narendran, 2002). They concluded that a more uniform illuminance spectrum provided by LED lighting was the major reason products displayed under LED were preferred over FLS in retail display cases.

Product Internal Temperature

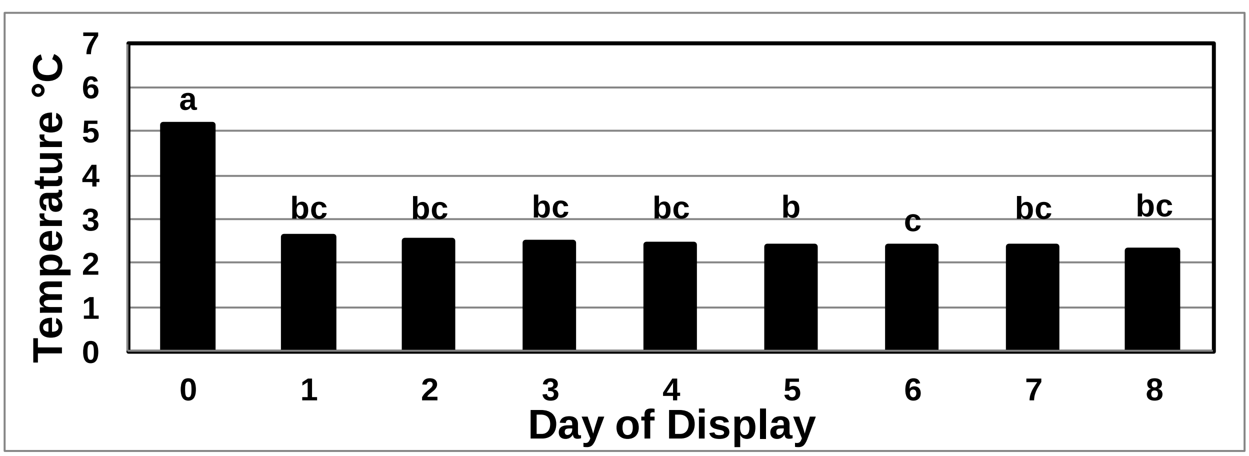
Product internal temperature pooled during display under LED and FLS lighting is shown in Fig. 3-13. Pork loin chops, ground beef, ground turkey and beef *semimembranosus* steaks in the LED case had lower (P<0.05) internal temperatures than under FLS. The internal temperature of beef *longissimus dorsi* steaks was similar (P>0.05) regardless of lighting type. The lack of an internal temperature difference in beef *longissimus dorsi* steaks displayed under LED and FLS lighting may be due to being on display for only 2 days since it had a short visual color life in this study. For pork loin chops, ground turkey and beef *semimembranosus* steaks, internal product temperatures decreased (P<0.05) as days of display increased regardless of lighting type (Figs. 3-14 to 3-16).

Fig. 3-13. Least squares means (Lsmeans) for internal temperature of five products[1] displayed in refrigerated cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



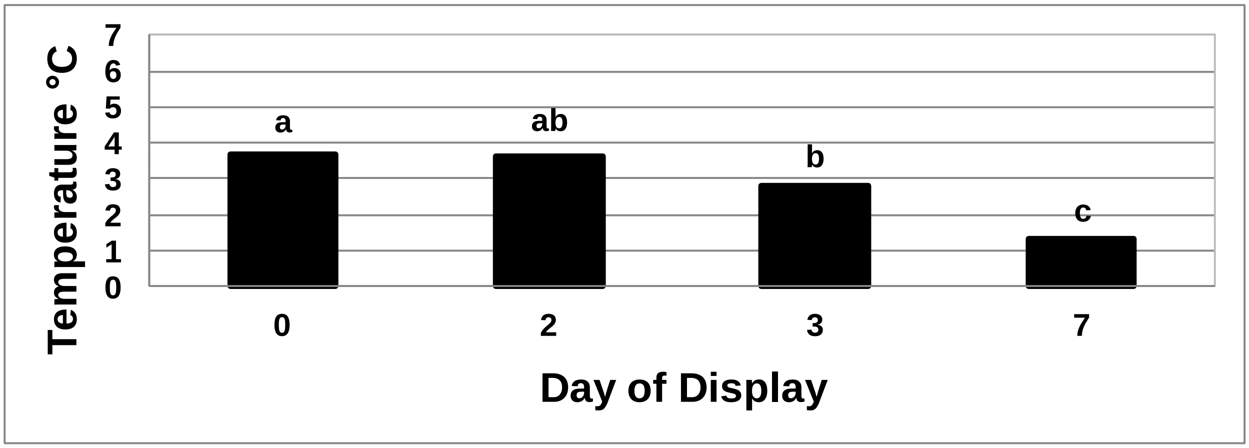
ab Lsmeans within each product having a different superscript letter differ (P<0.05).
1 Standard error: Pork loin chop = 0.04, beef *longissimus dorsi* steak = 0.45, ground beef = 0.45, ground turkey = 0.44, beef *semimembranosus* steak = 0.10.

Fig. 3-14. Least squares means (Lsmeans) for internal temperature of pork loin chops over 8 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



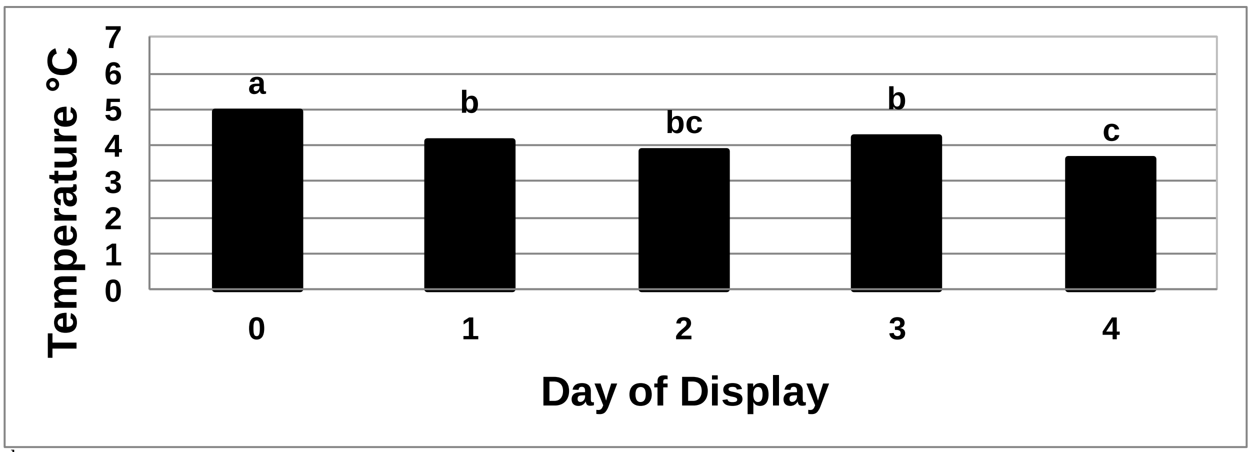
ab Lsmeans with different superscript letters differ (P<0.05). Standard error = 0.09.

Fig. 3-15. Least squares means (Lsmeans) for internal temperature of ground turkey over 7 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



[ab] Lsmeans with different superscript letters differ (P<0.05). Standard error = 0.62.

Fig. 3-16. Least squares means (Lsmeans) for internal temperature of beef *semimembranosus* steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.

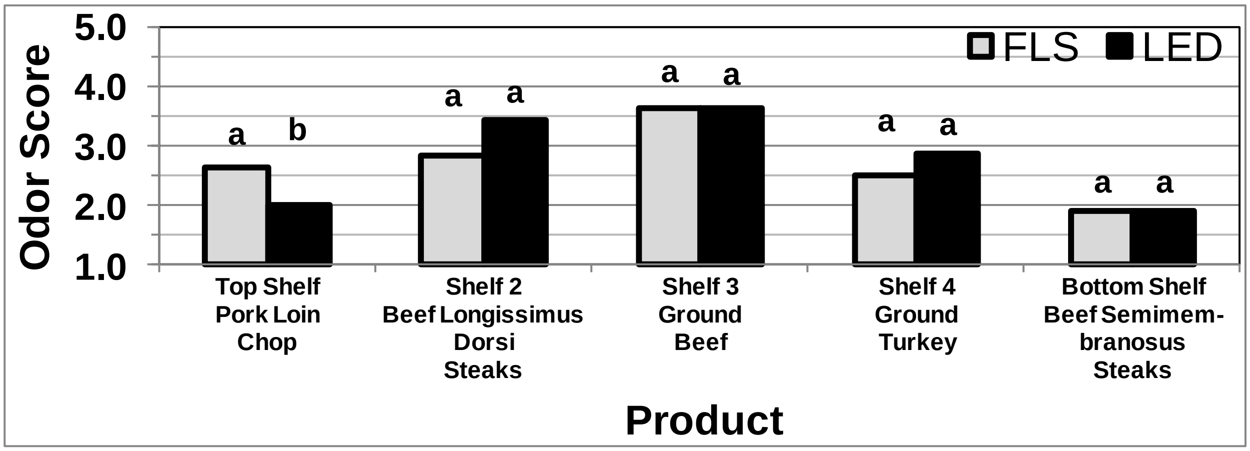


[ab] Lsmeans with different superscript letters differ (P<0.05). Standard error = 0.17.

Odor

All products had no off-odor on d 0 except for the beef *longissimus dorsi* steaks that had a very slight off-odor possibly the result of being packaged for 9 d in the case-ready packaging in a mother bag at the initiation of the study. Pork loin chops displayed under FLS had a higher (P<0.05) subjective off-odor score of 2.6 versus 2.0 for chops under LED (Fig. 3-17). Off-odor scores for each of the remaining four products were similar within product type (P>0.05) regardless of lighting type (Fig. 3-17). Over the duration of the study, only beef *longissimus dorsi* steaks and ground beef had odor scores of 3 equating to small amounts of detectable odor at the end of their color life.

Fig. 3-17. Least squares means (Lsmeans) for subjective odor of five products[1] displayed in refrigerated cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting[2].



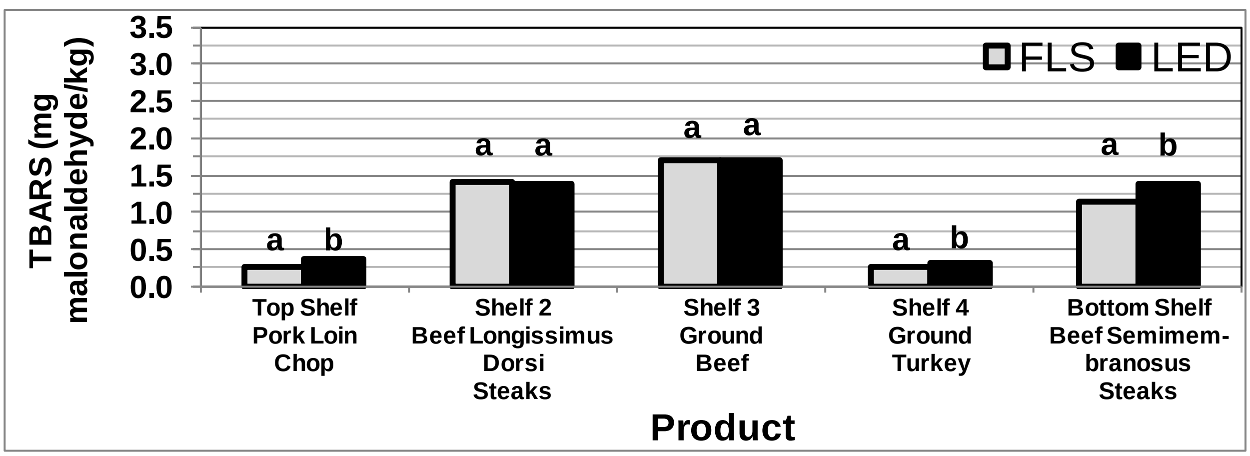
[ab] Lsmeans within each product having a different superscript letter differ (P<0.05).
[1] Standard error: Pork loin chop= 0.17, beef *longissimus dorsi* steak= 0.32, ground beef= 0.24, ground turkey= 0.71, beef *semimembranosus* steak= 0.18.
[2]Odor scale: 1= no off-odor, 3= small off-odor, and 5= extreme off-odor.

Lipid Oxidation – TBARS

Pork loin chops had higher (P<0.05) TBARS values when displayed under LED lighting than FLS lighting; however, the TBARS value remained below the threshold of consumer perceived oxidation of 0.5-1.0 according to Tarladgis, Watts, Younathan, & Dugan (1960) (Fig. 3-18). Beef *semimembranosus* steaks had 0.24 mg malonaldehyde/kg greater (P<0.05) oxidation under LED lighting than FLS (Fig. 3-18). Campo, Nute, Hughes, Enser, Wood, & Richardson (2006) stated that the threshold for rancid flavor overpowering beef flavor in beef loin steaks was 2.28 mg malonaldehyde/kg TBARS value. Green & Cumuze (1981) determined the detectable threshold for rancid flavor in beef was TBARS values between 0.6 and 2.0 mg malonaldehyde/kg. Ground turkey under LED lighting had a higher (P<0.05) TBARS value of 0.31 compared to 0.25 for products displayed under FLS lighting. In addition, there was a day effect (P<0.05) for all five products with higher TBARS values at the end of display compared to d 0, regardless of lighting type (Figs. 3-19 to 3-23).

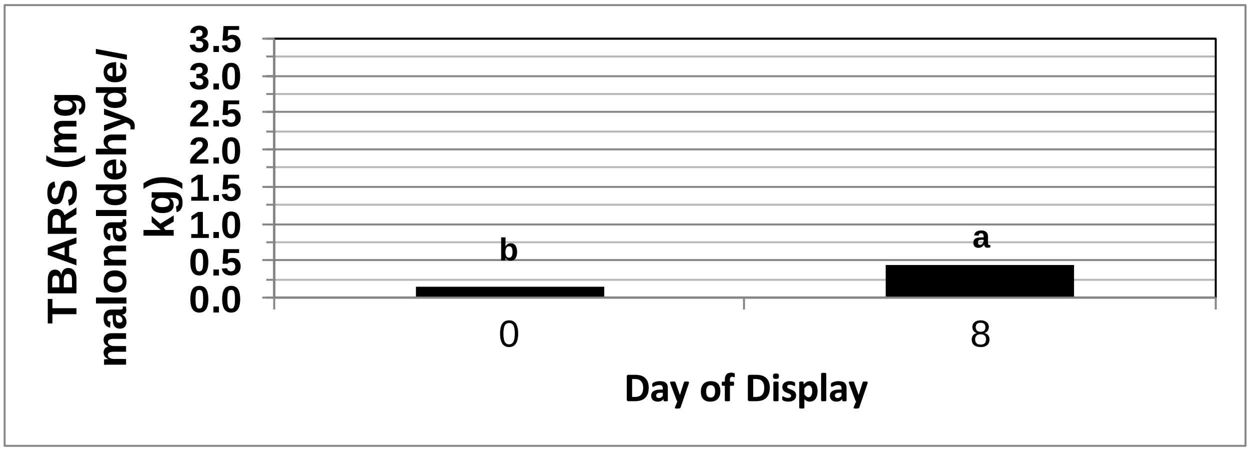
Pork loin chops and ground turkey have greater amounts of unsaturated fatty acids which are more prone to oxidation than saturated fats. Although some products experienced more oxidation under the refrigerated display case temperatures with LED lighting, Betts and Uri (1963) explained that lower temperatures hold lipids in the solid phase and provide more time for radicals to further propagation of oxidation. McWeeney (1968) stated that lipids in the solid phase have faster rates of lipid oxidation than expected. For the beef *semimembranosus* steaks in this study, LED lighting enhanced visual and instrumental color, while TBARS results showed greater oxidation. Further research is needed to explore the mechanisms of lipid oxidation under LED and FLS lighting.

Fig. 3-18. Least squares means (Lsmeans) for oxidative rancidity (TBARS) of five products[1] displayed in refrigerated cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



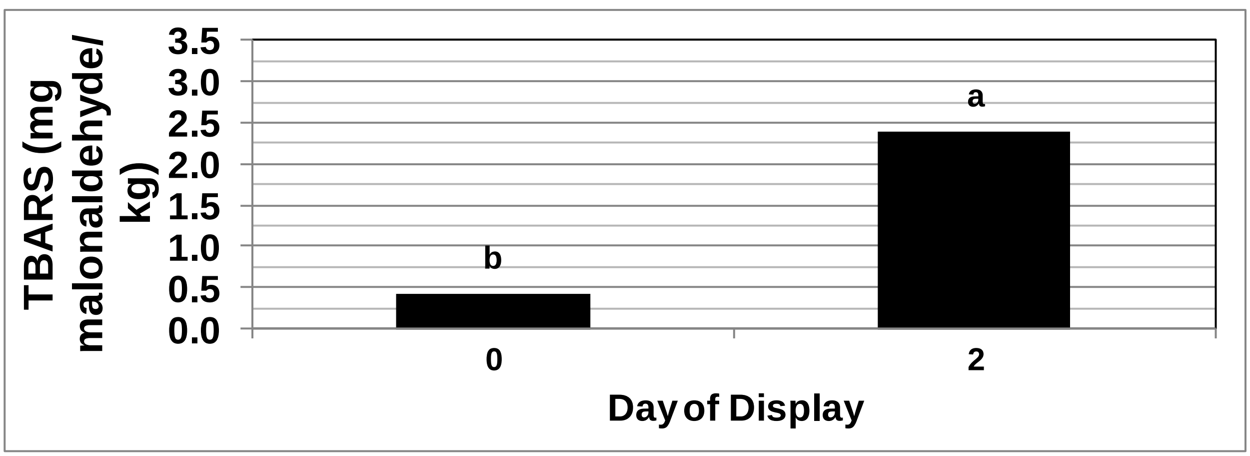
[ab] Lsmeans within each product having a different superscript letter differ (P<0.05).
[1] Standard error: Pork loin chop= 0.03, beef *longissimus dorsi* steak= 0.09, ground beef= 0.06, ground turkey= 0.02, beef *semimembranosus* steak= 0.06.

Fig. 3-19. Least squares means (Lsmeans) for oxidative rancidity (TBARS) of pork loin chops over 8 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



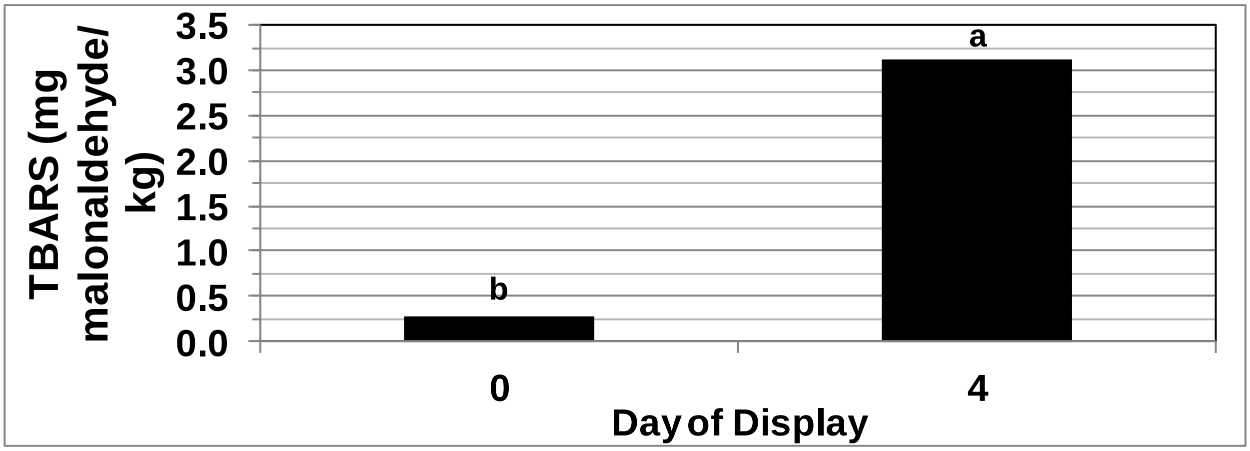
[ab] Lsmeans with a different superscript letter differ (P<0.05). Standard error= 0.03.

Fig. 3-20. Least squares means (Lsmeans) for oxidative rancidity (TBARS) of beef *longissimus dorsi* steaks over 2 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



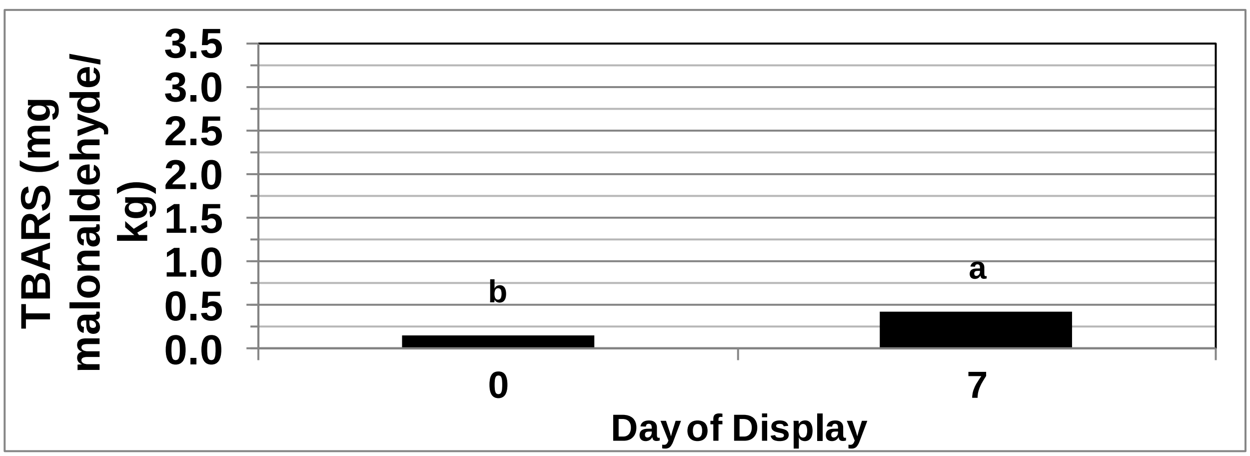
[ab] Lsmeans with a different superscript letter differ (P<0.05). Standard error= 0.09.

Fig. 3-21. Least squares means (Lsmeans) for oxidative rancidity (TBARS) of ground beef over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



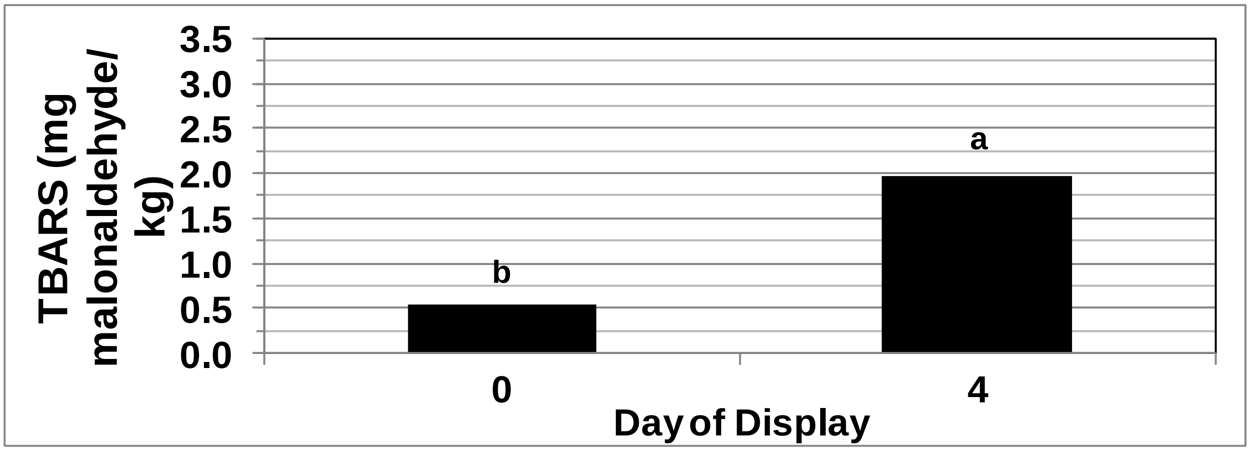
[ab] Lsmeans with a different superscript letter differ ($P<0.05$). Standard error= 0.06.

Fig. 3-22. Least squares means (Lsmeans) for oxidative rancidity (TBARS) of ground turkey over 7 days of refrigerated in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



[ab] Lsmeans with a different superscript letter differ ($P<0.05$). Standard error= 0.02.

Fig. 3-23. Least squares means (Lsmeans) for oxidative rancidity (TBARS) of beef *semimembranosus* steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



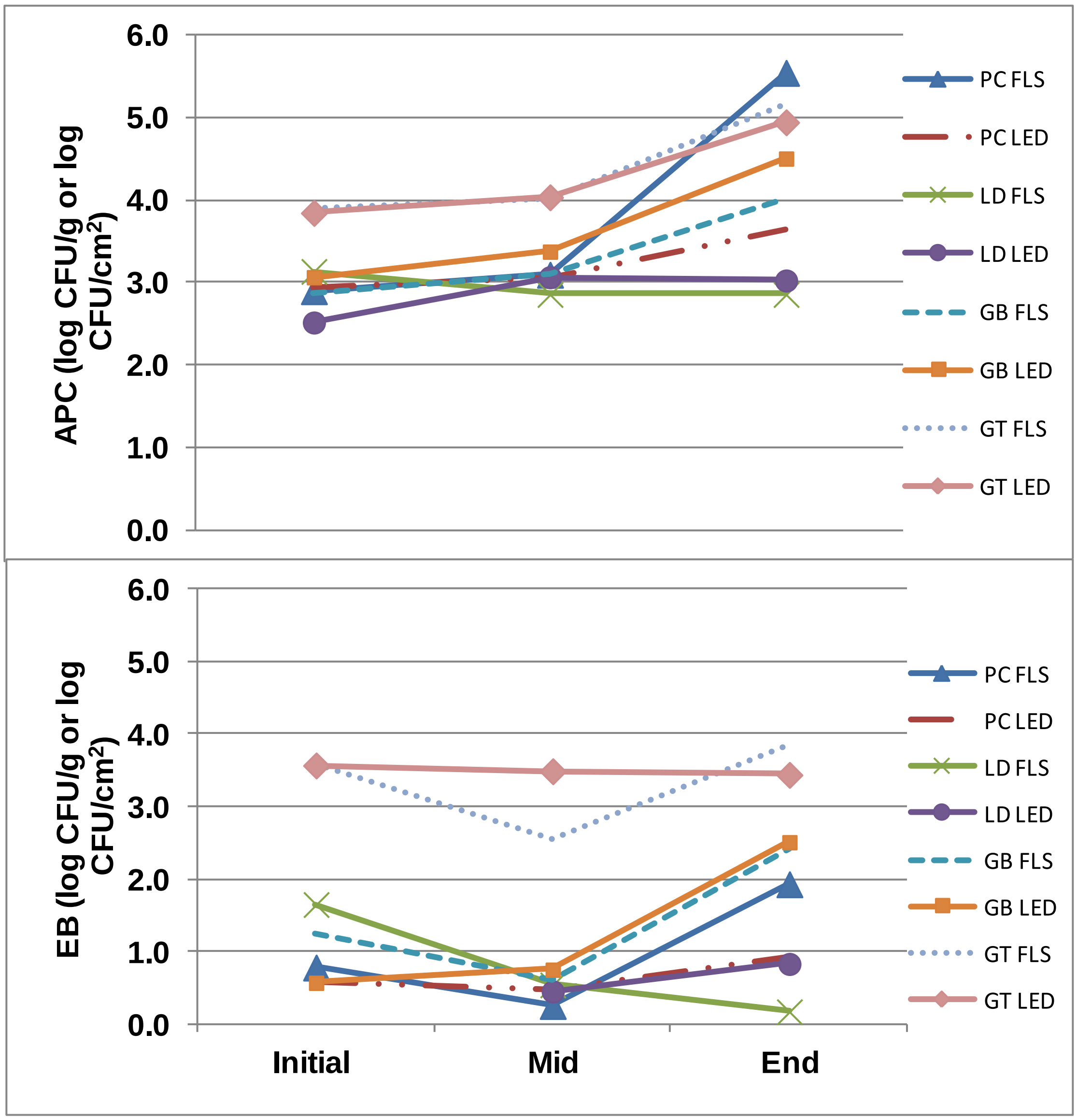
[ab] Lsmeans with a different superscript letter differ (P<0.05). Standard error= 0.06.

Product Microbiology

Aerobic plate count and *Enterobacteriaceae* count populations for each sampling period and product are shown in Fig. 3-24. There were no differences for APC or EB count populations between lighting types for ground beef (Fig. 3-25). There was an interaction (P<0.05) between lighting type and day of display for pork loin chops APC count populations (Table 3). Aerobic plate count populations were greater (P<0.05) by more than 2.50 log CFU/g in pork loin chops under FLS compared to LED at the end of display than on d 0 or at the middle of product color shelf life (Table 14). By the end of display, APC populations in pork loin chops under LED were 1.91 log CFU/g lower (P<0.05) than when displayed under FLS. As expected, APC populations increased (P<0.05) from d 0 to the end of display for pork loin chops, ground beef and ground turkey (Fig. 3-24).

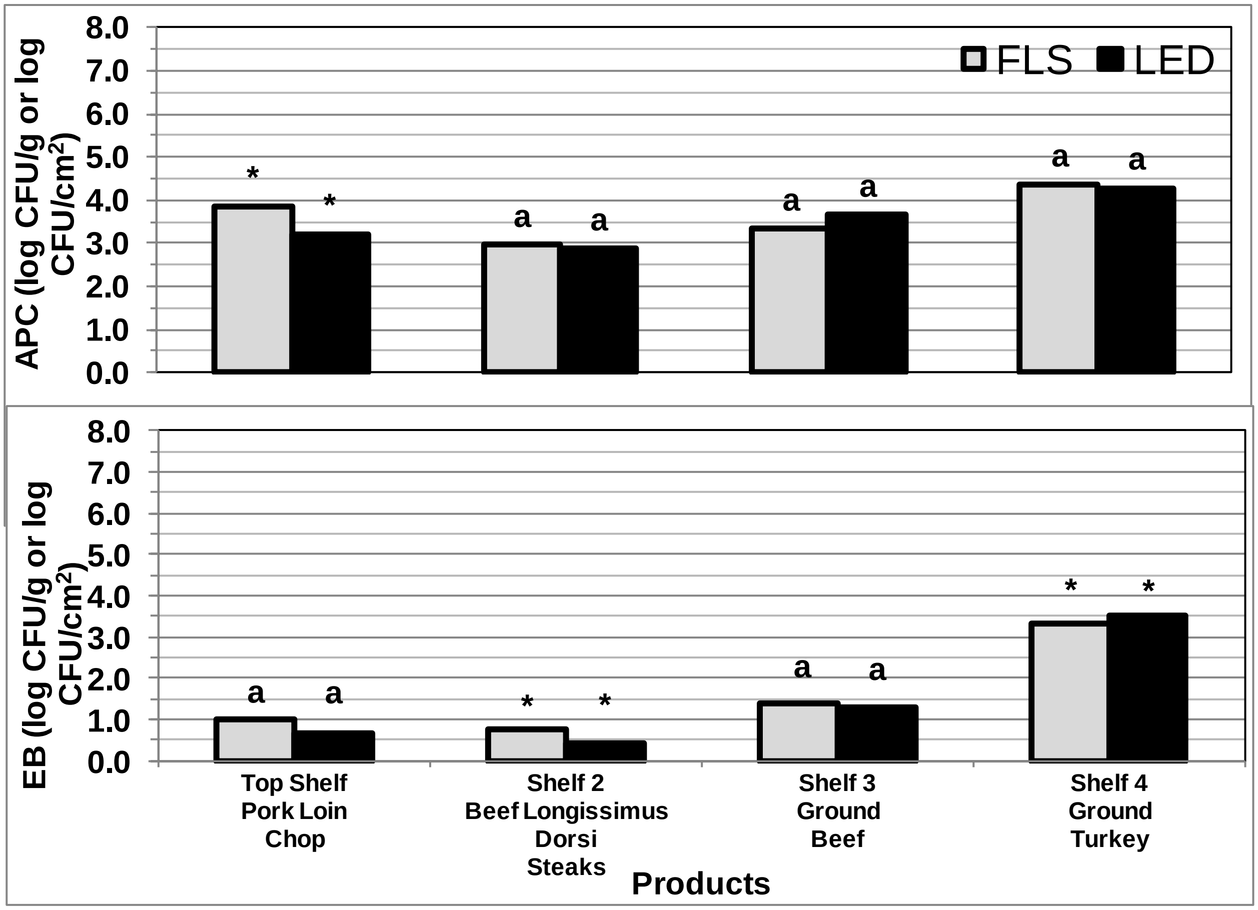
There was a day effect (P<0.05) resulting in EB populations being higher by 0.74 and 1.56 log CFU/g , respectively for pork loin chops and ground beef by the end of display. There was a lighting type by day of display effect (P<0.05) for beef *longissimus dorsi* steak EB populations where products under FLS lighting had lower populations by the end of display than product under LED (Table 15). For ground turkey displayed under FLS, there was a lighting type by day of display effect (P<0.05) resulting in the middle of color display life EB populations to be more than 1.00 log CFU/g lower than d 0 or the end of display populations (Table 16).

Fig. 3-24. Mean populations for aerobic plate count (APC) and *Enterobacteriaceae* (EB) populations across three sampling periods[1] for five products[2] during refrigerated retail display[3] in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



[1]Initial= day 0, Middle= middle of color display life, End= end of color display life.
[2] PC= pork loin chop, LD= beef *longissimus dorsi*, GB= ground beef, GT= ground turkey.
[3] Day of end of color shelf life for each product: PC= 8, LD= 3, GB= 4, GT= 7, SM= 4.

Fig. 3-25. Least squares means (Lsmeans) for aerobic plate count (APC)[1] and *Enterobacteriaceae* (EB)[2] populations across three sampling periods for five products[3] during refrigerated retail display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



[ab] Lsmeans within each product having a different superscript letter differ (P<0.05).
[1] APC standard error: Pork loin chop= 0.18, beef *longissimus dorsi* steak= 0.14 (FLS) and 0.11 (LED), ground beef= 0.17 (FLS) and 0.12 (LED), ground turkey= 0.13.
[2] EB standard error: Pork loin chop= 0.19, beef *longissimus dorsi* steak= 0.22, ground beef= 0.34 (FLS) and 0.31 (LED), ground turkey= 0.69 (FLS) and 0.08 (LED).
[3] Pork loin, ground beef, and ground turkey were measured as log CFU/g; beef *longissimus dorsi* steaks were measured as log CFU/cm^2.
* These products had an interaction between lighting type and day of display.

Table 14. Least squares means (Lsmeans) for Aerobic Plate Count (APC) populations of pork loin chops in refrigerated display cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.

	Days of Storage		
Lighting Type	**Initial**	**Mid**	**End**
LED	2.94^{ac}	3.06^{ac}	3.64^{ac}
FLS	2.90^{ac}	3.10^{ac}	5.55^{bd}

^{ab} Lsmeans within each column having a different superscript letter differ (P < 0.05).
^{cd} Lsmeans within each row having a different superscript letter differ (P < 0.05).
Standard error: 0.32.

Table 15. Least squares means (Lsmeans) for *Enterobacteriaceae* (EB) populations of beef *longissimus dorsi* steaks in refrigerated display cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.

	Day of Storage		
Lighting Type	**Initial**	**Mid**	**End**
LED	-	0.45^{ac}	0.83^{bc}
FLS	1.65^{ac}	0.54^{ac}	0.17^{ac}

^{ab} Lsmeans within each column having a different superscript letter differ (P < 0.05).
^{cd} Lsmeans within each row having a different superscript letter differ (P < 0.05).
Standard error: FLS Initial= 0.51; FLS Mid & End= 0.30; LED Mid & End= 0.30.

Table 16. Least squares means (Lsmeans) for *Enterobacteriaceae* (EB) populations of ground turkey in refrigerated display cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.

	Day of Storage		
Lighting Type	**Initial**	**Mid**	**End**
LED	3.57^{ac}	3.49^{ac}	3.44^{bc}
FLS	3.59^{ac}	2.56^{bd}	3.86^{ac}

^{ab} Lsmeans within each column having a different superscript letter differ (P < 0.05).
^{cd} Lsmeans within each row having a different superscript letter differ (P < 0.05).
Standard error: FLS Initial, Mid, End= 0.12; LED Initial= 0.17; LED Mid & End= 0.12.

CHAPTER 4 - Conclusions

Light emitting diode lighting in fresh meat retail display cases offer benefits in extending color life of pork loin chops, beef *longissimus dorsi* steaks, ground beef, and beef *semimembranosus* steaks. LED lighting extended beef retail cuts color shelf life by up to one day longer than under FLS. In addition to more efficient condenser cycling, the lower operation temperatures of LED lighting promote longer shelf life. Pork loin chops and ground turkey color can be displayed under LED or FLS lighting; however, if product lipid oxidation is a concern, pork loin chops and ground turkey should be displayed under FLS lighting. Light emitting diode lighting in meat retail display cases will save money not only by lowering fixed overhead operational costs but also by extending the fresh meat color life of products with greater amounts of myoglobin compared to FLS lighting. The effect of LED lighting on lipid oxidation should be further examined.

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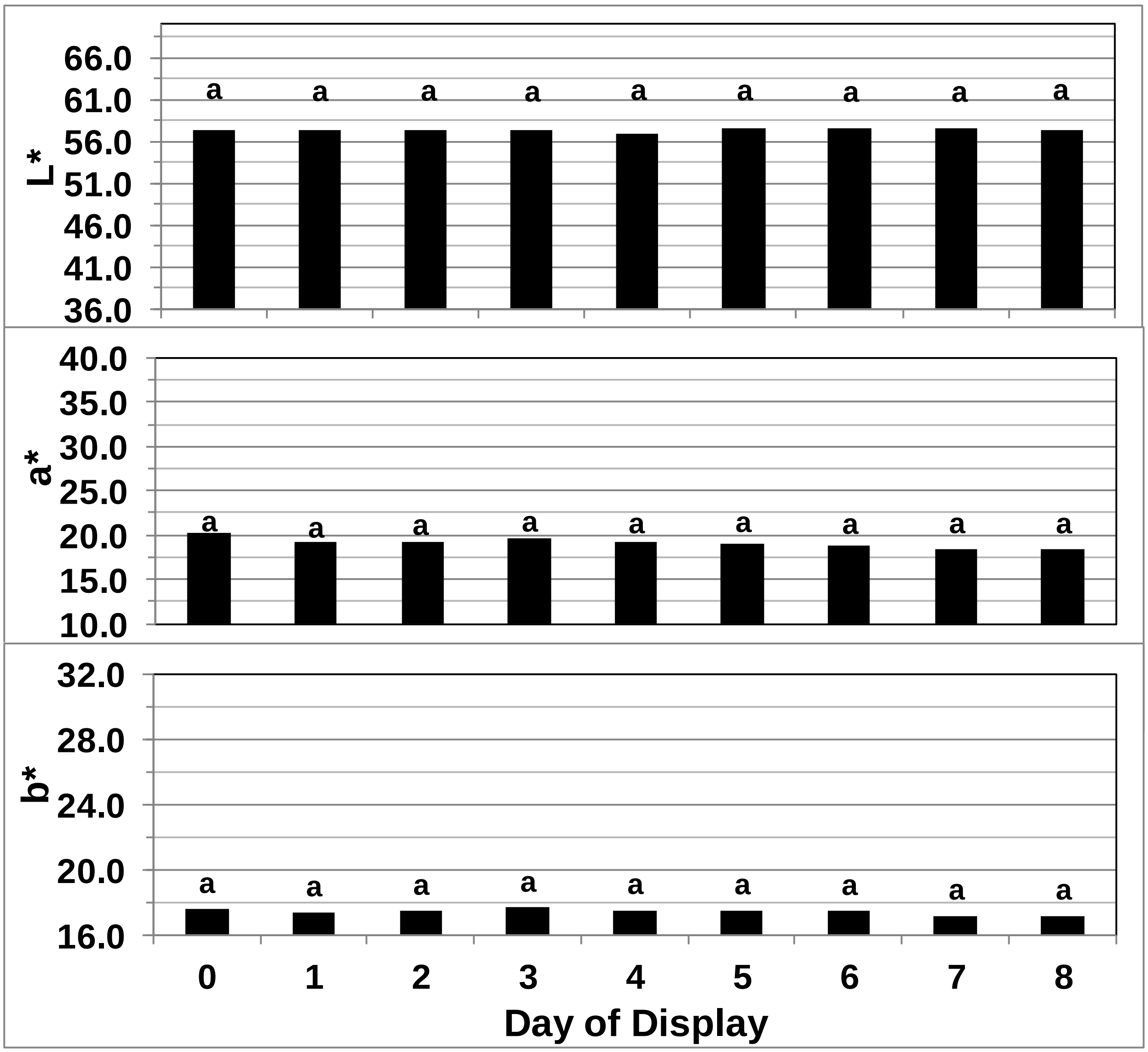
Appendix A - Figures and Tables

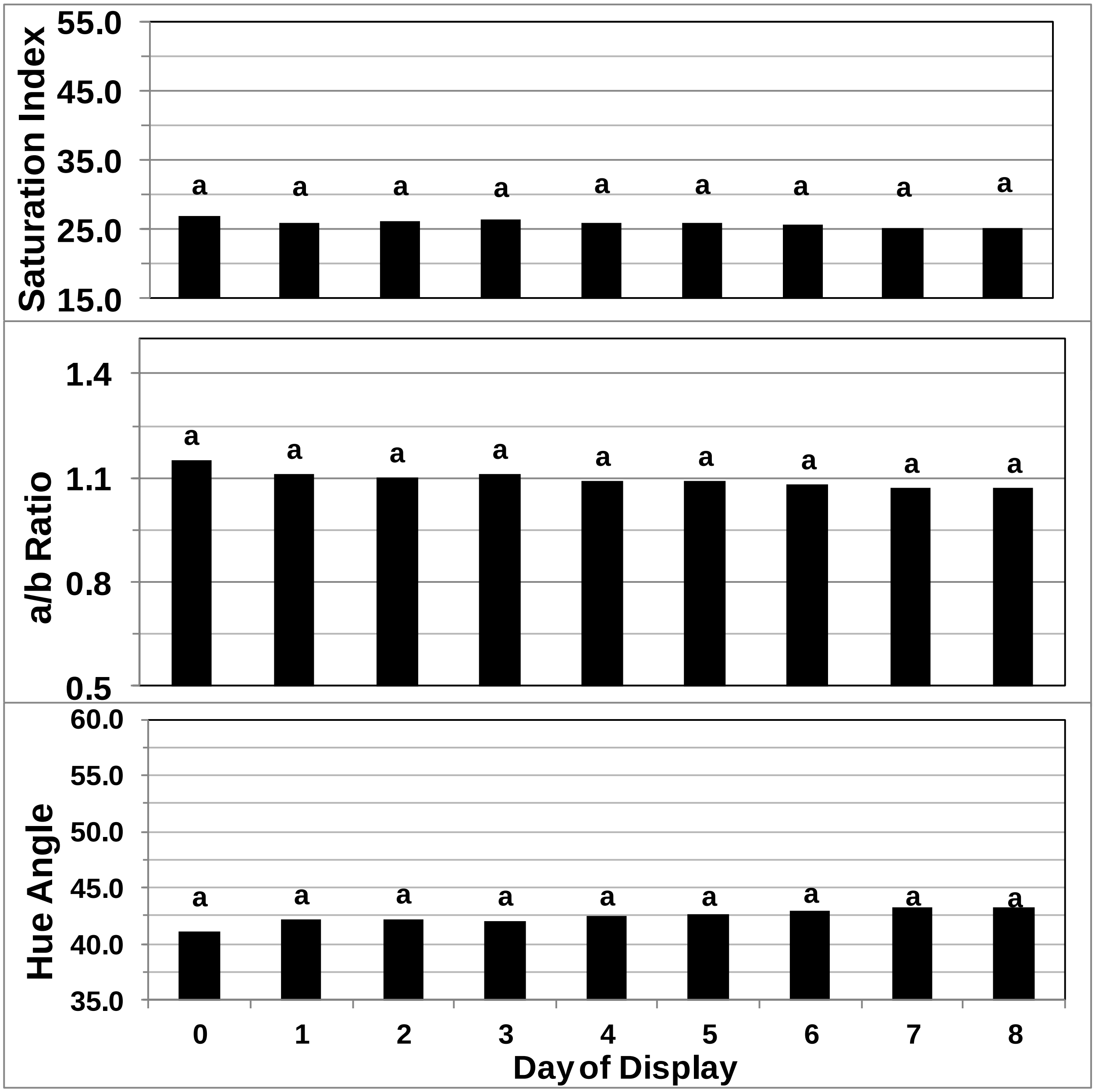
Figures and Tables Within Appendices

Fig. 4-1. Least squares means (Lsmeans) for L*[1], a*[2], & b*[3] instrumental color values of pork loin chops over 8 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



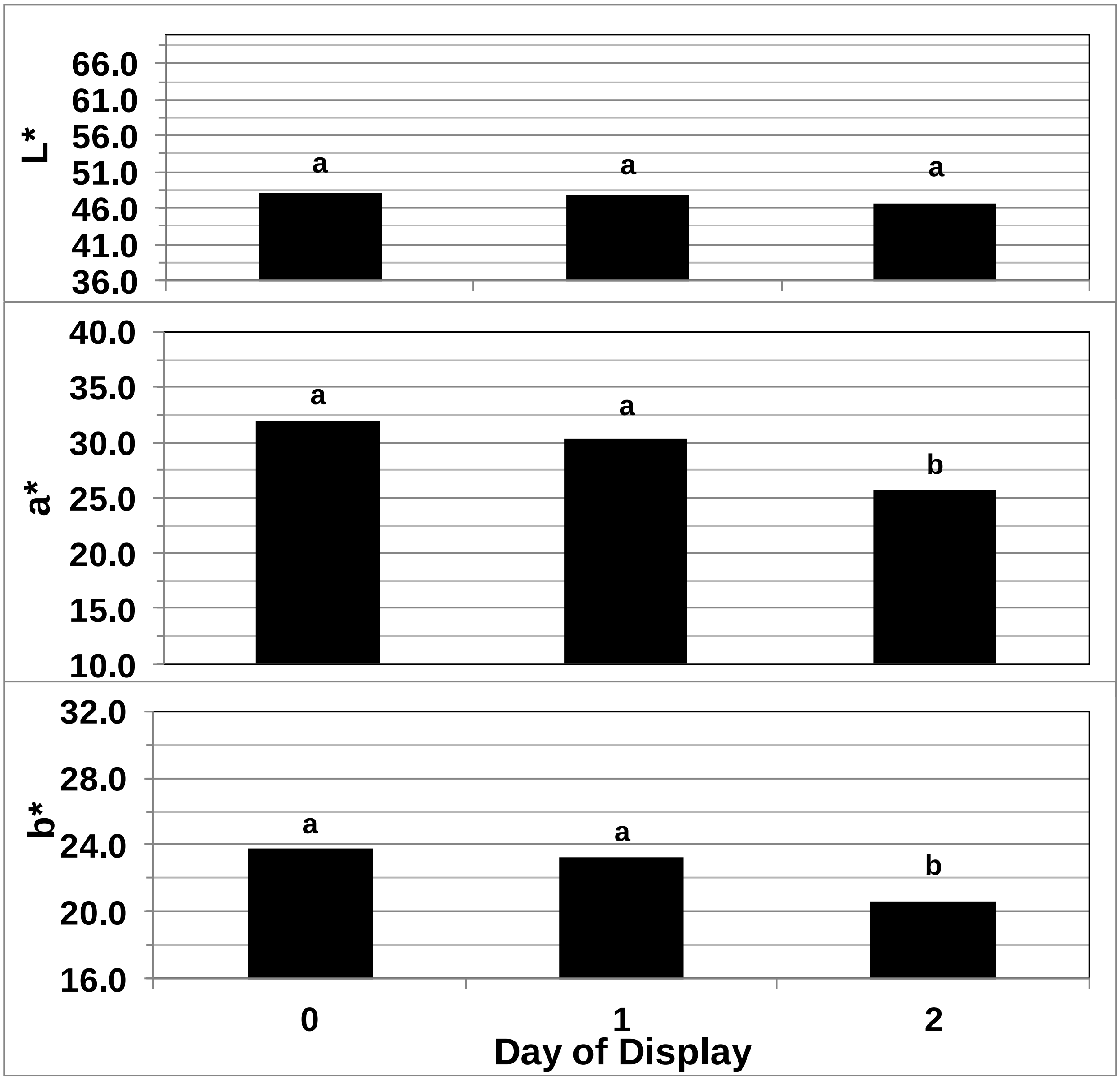
[ab] Lsmeans with different superscript letters differ ($P<0.05$).
[1] L* standard error= 0.65.
[2] a* standard error= 0.42.
[3] b* standard error= 0.10.

Fig. 4-2. Least squares means (Lsmeans) for saturation index[1], a/b ratio[2], & hue angle[3] instrumental color of pork loin chops over 8 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



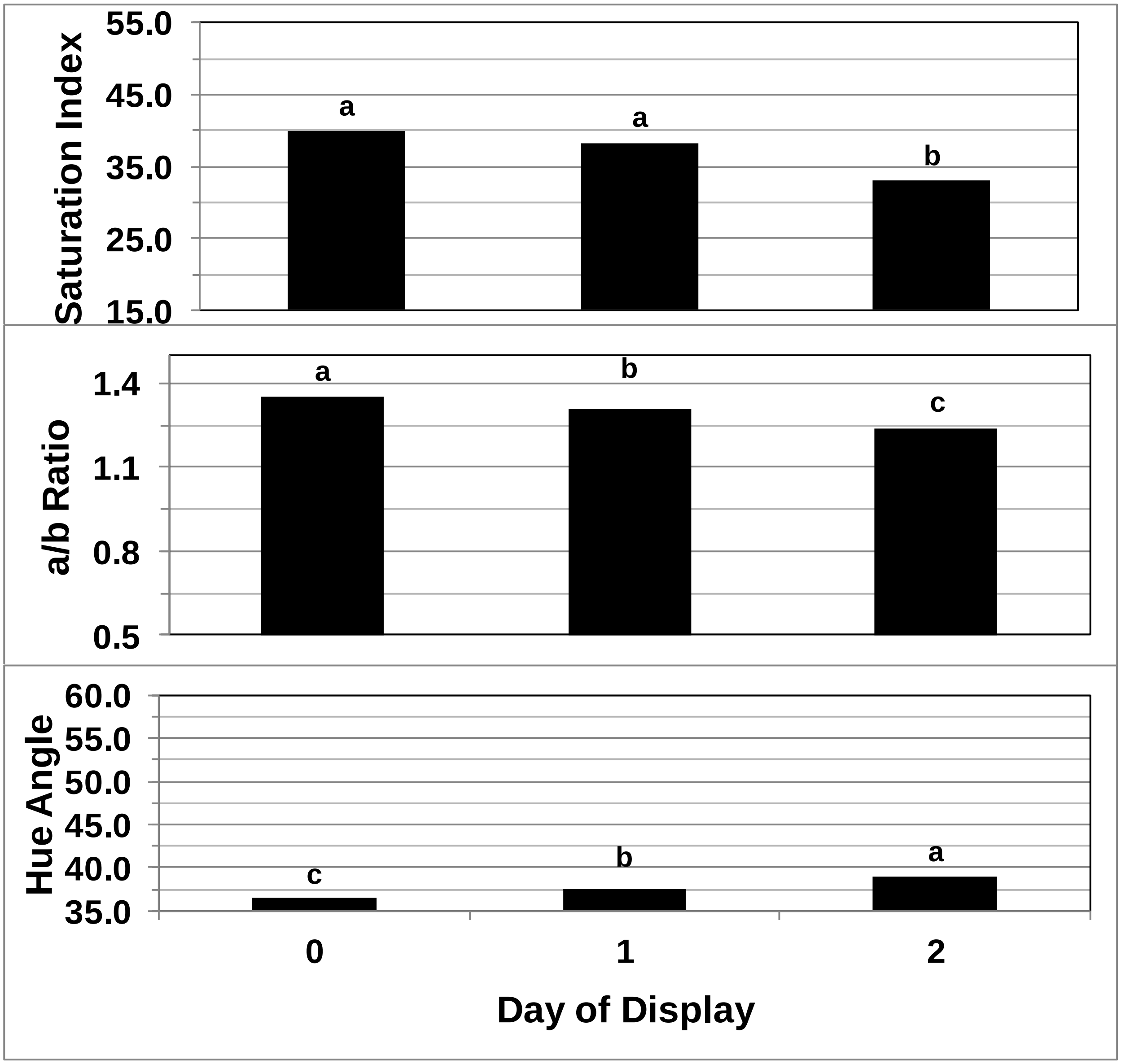
[ab] Lsmeans with different superscript letters differ ($P<0.05$).
[1] Standard error = 0.46.
[2] Standard error = 0.02.
[3] Standard error= 0.53.

Fig. 4-3. Least squares means (Lsmeans) for L*[1], a*[2], & b*[3] instrumental color values of beef *longissimus dorsi* steaks over 2 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



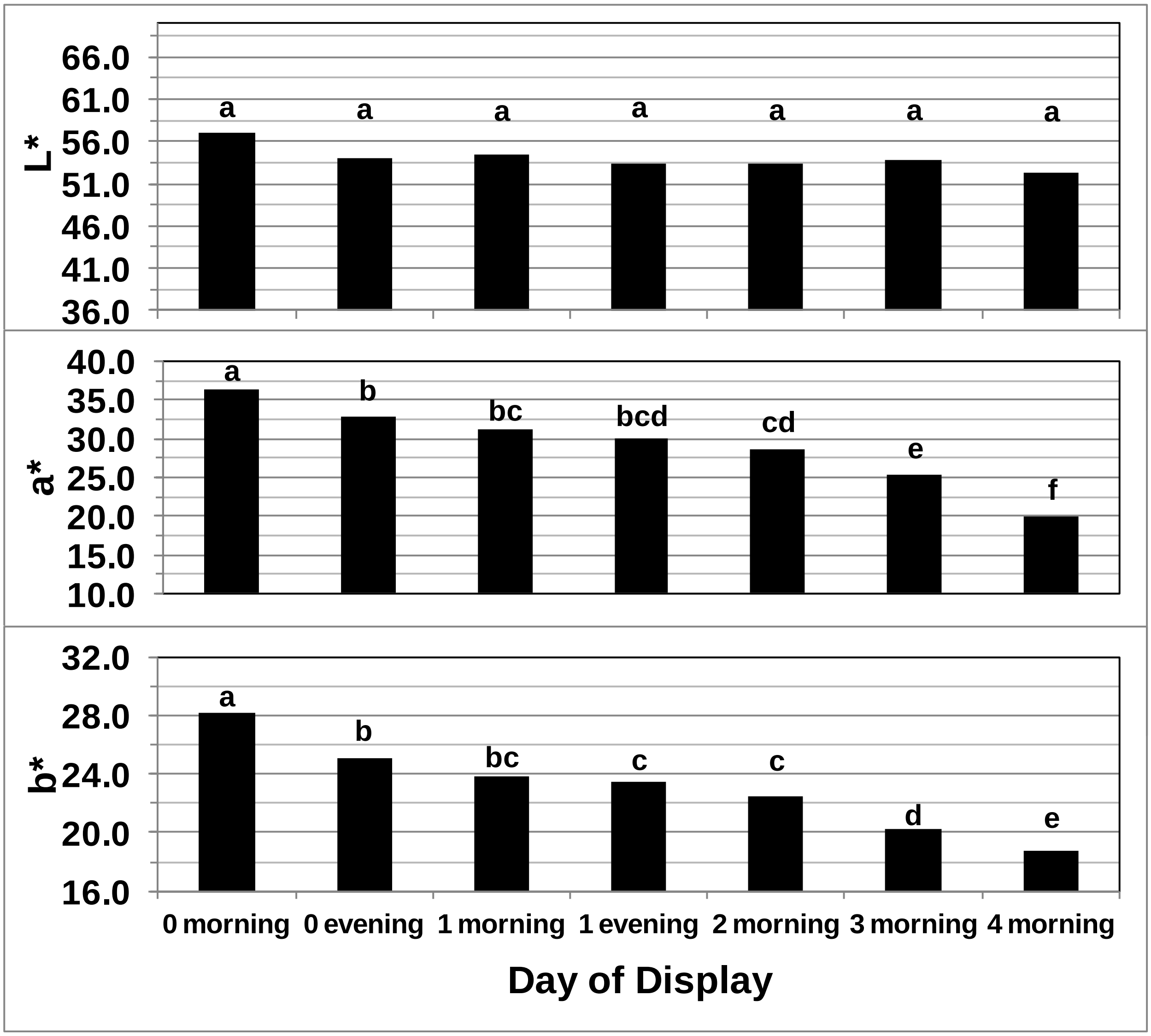
[ab] Lsmeans with different superscript letters differ (P<0.05).
[1] Standard error= 0.57.
[2] Standard error= 0.79.
[3] Standard error= 0.51.

Fig. 4-4. Least squares means (Lsmeans) for saturation index[1], a/b ratio[2], & hue angle[3] instrumental color of beef *longissimus dorsi* steaks over 2 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



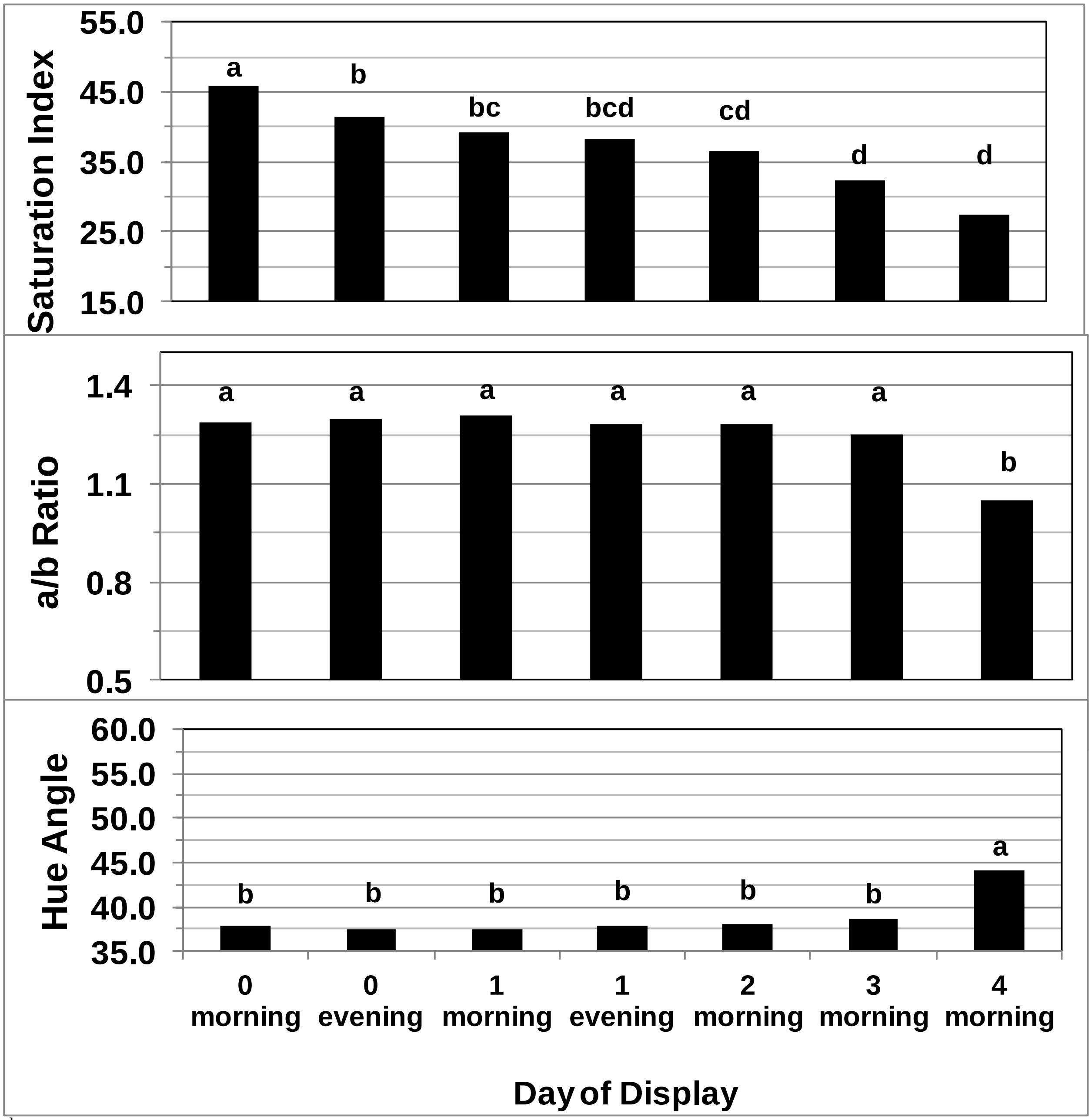
[ab] Lsmeans with different superscript letters differ (P<0.05).
[1] Standard error = 0.93.
[2] Standard error = 0.01.
[3] Standard error= 0.28.

Fig. 4-5. Least squares means (Lsmeans) for L*[1], a*[2], & b*[3] instrumental color values of ground beef over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



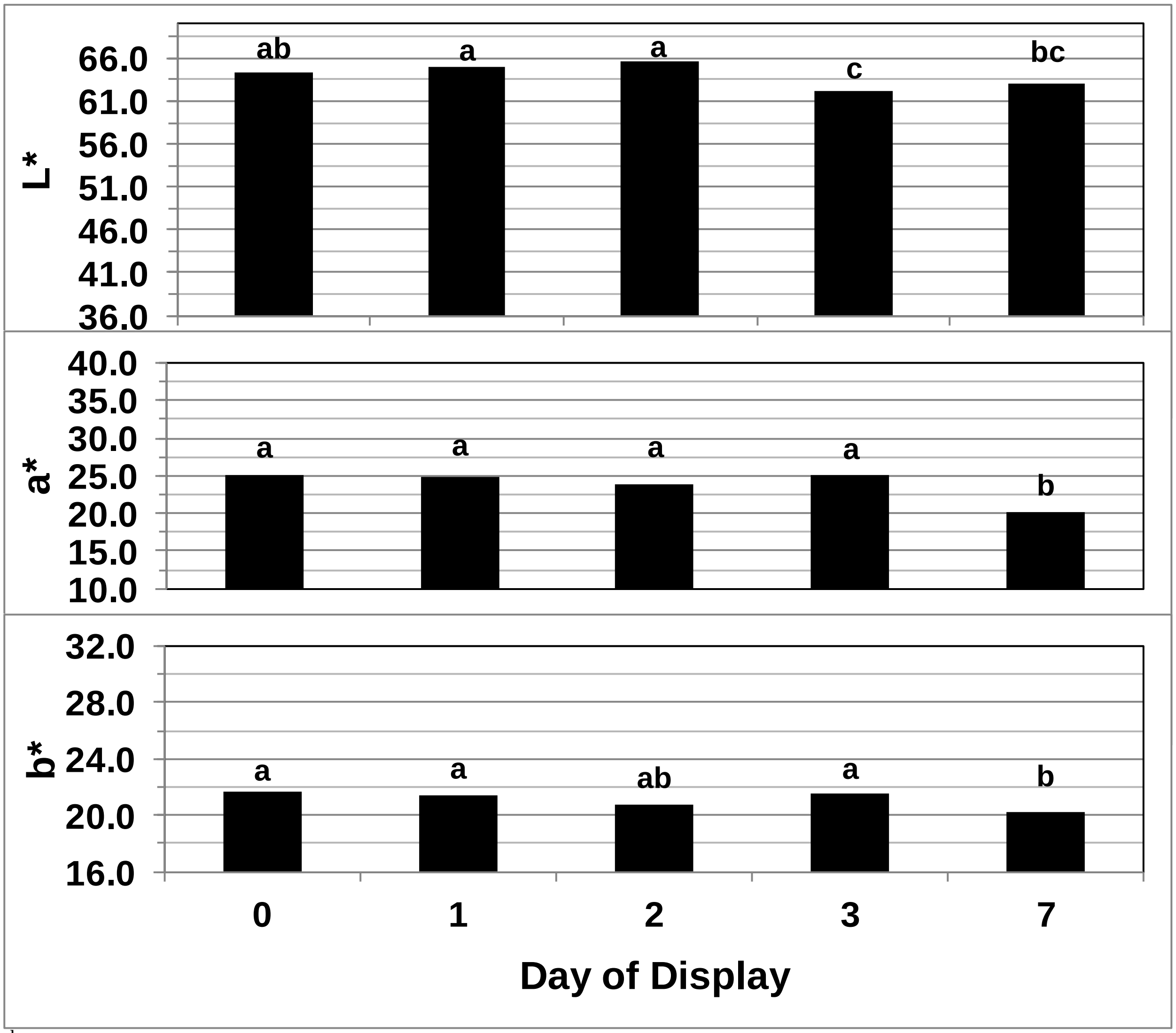
[ab] Lsmeans with different superscript letters differ ($P<0.05$).
[1] L* standard error= 0.94.
[2] a* standard error= 1.02.
[3] b* standard error= 0.57.

Fig. 4-6. Least squares means (Lsmeans) for saturation index[1], a/b ratio[2], & hue angle[3] instrumental color of ground beef over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



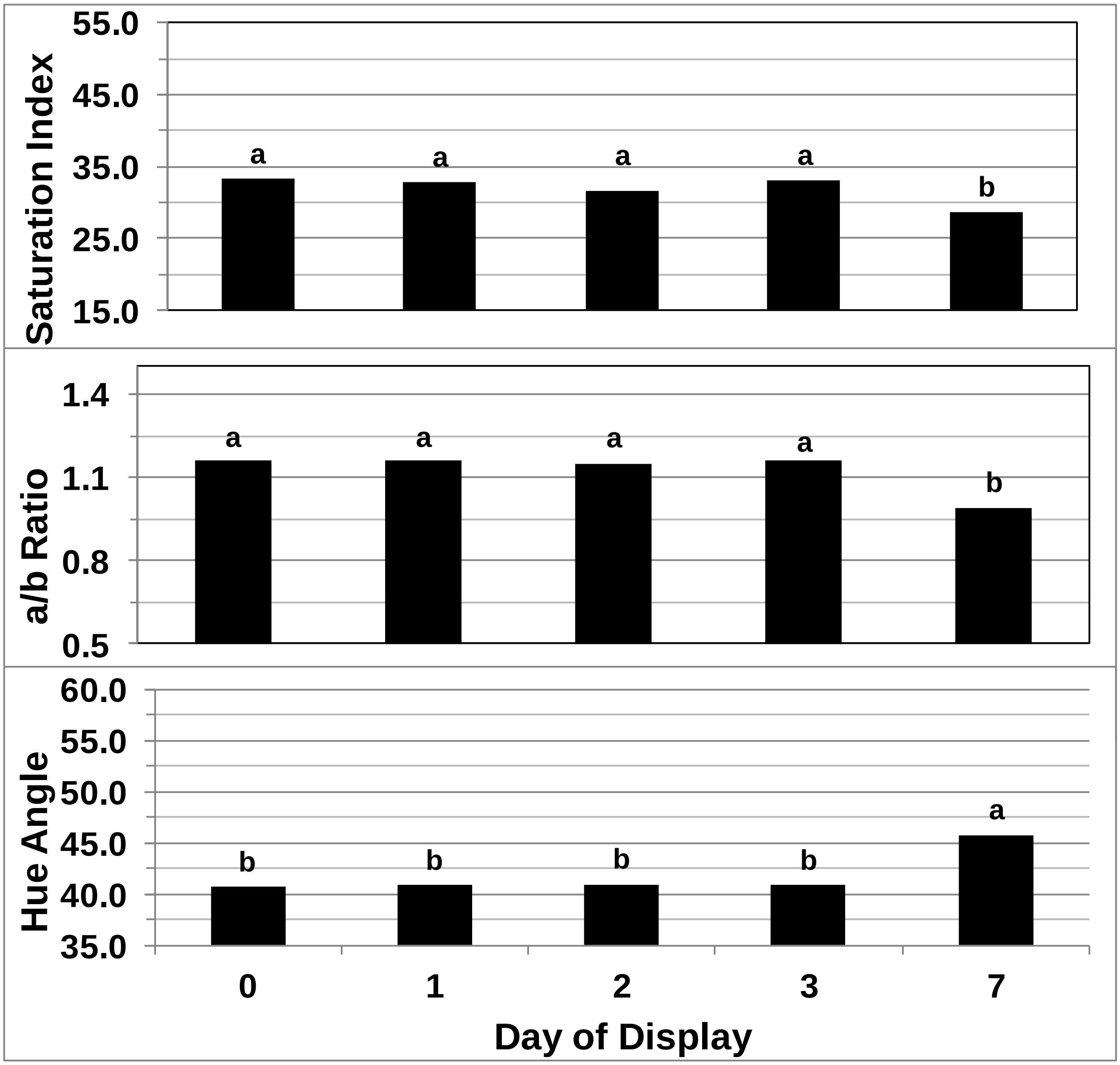
[ab] Lsmeans with different superscript letters differ (P<0.05).
[1] Standard error= 1.11.
[2] Standard error= 0.03.
[3] Standard error= 0.74.

Fig. 4-7. Least squares means (Lsmeans) for L*[1], a*[2], & b*[3] instrumental color values of ground turkey over 7 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



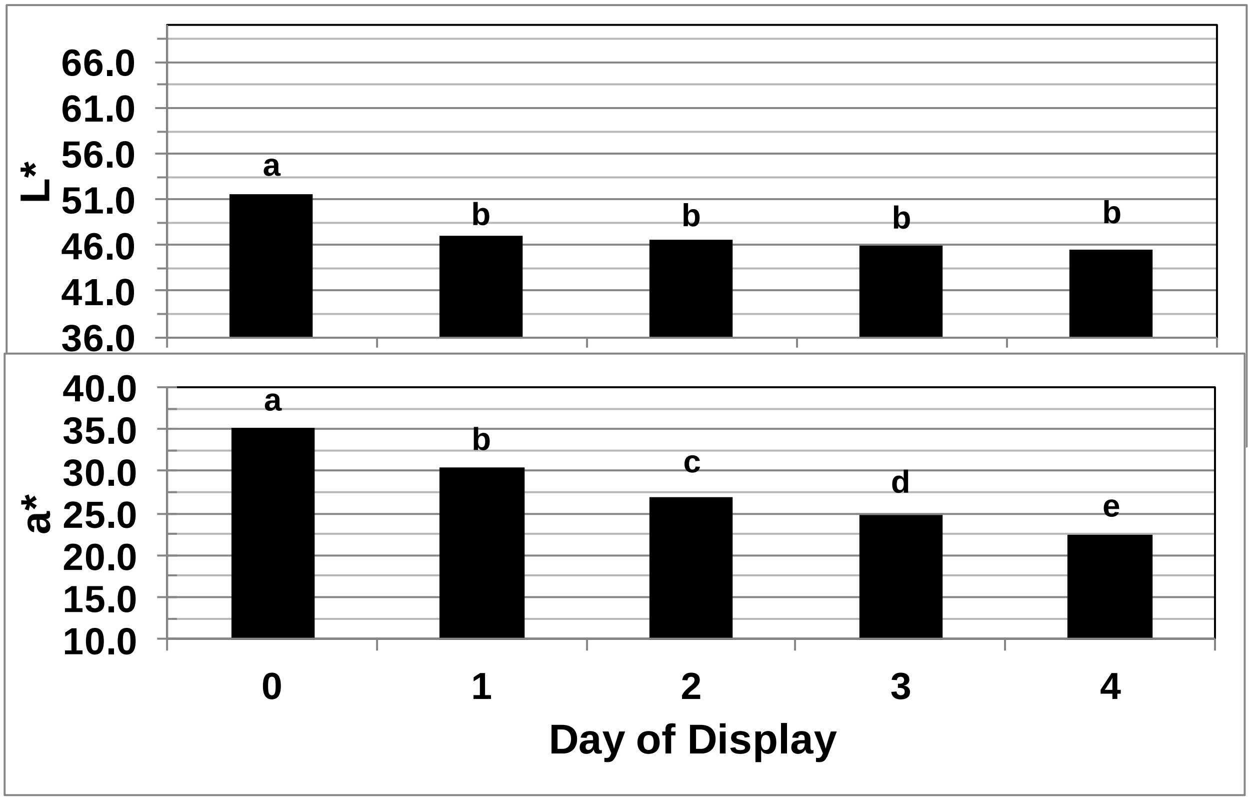
[ab] Lsmeans with different superscript letters differ (P<0.05).
[1] L* standard error= 0.57.
[2] a* standard error= 0.86.
[3] b* standard error= 0.36.

Fig. 4-8. Least squares means (Lsmeans) for saturation index[1], a/b ratio[2], & hue angle[3] instrumental color of ground turkey over 7 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



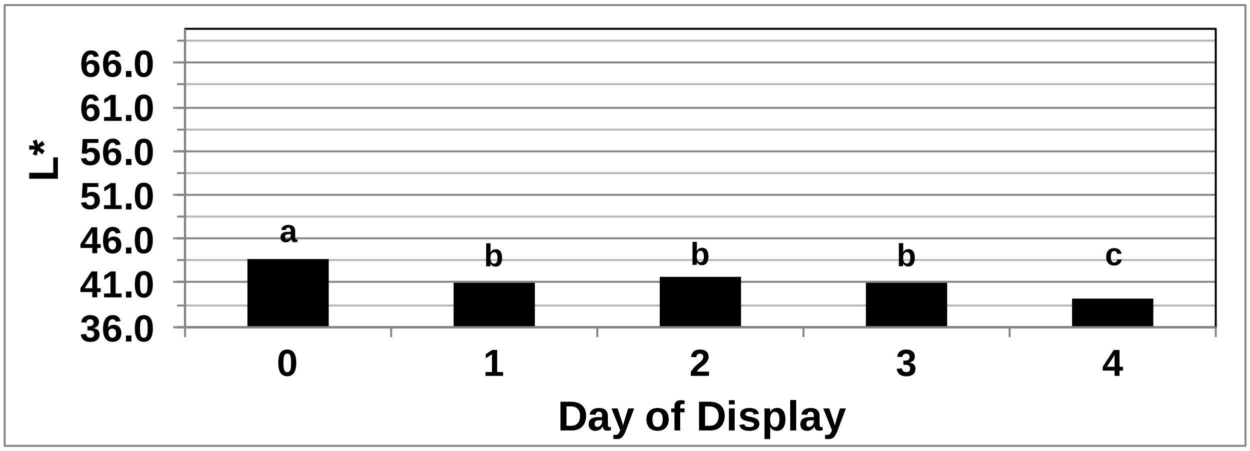
[ab] Lsmeans with different superscript letters differ (P<0.05).
[1] Standard error = 0.83.
[2] Standard error = 0.03.
[3] Standard error = 0.90.

Fig. 4-9. Least squares means (Lsmeans) for L*[1] & a*[2] instrumental color values of beef *semimembranosus* deep portion steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



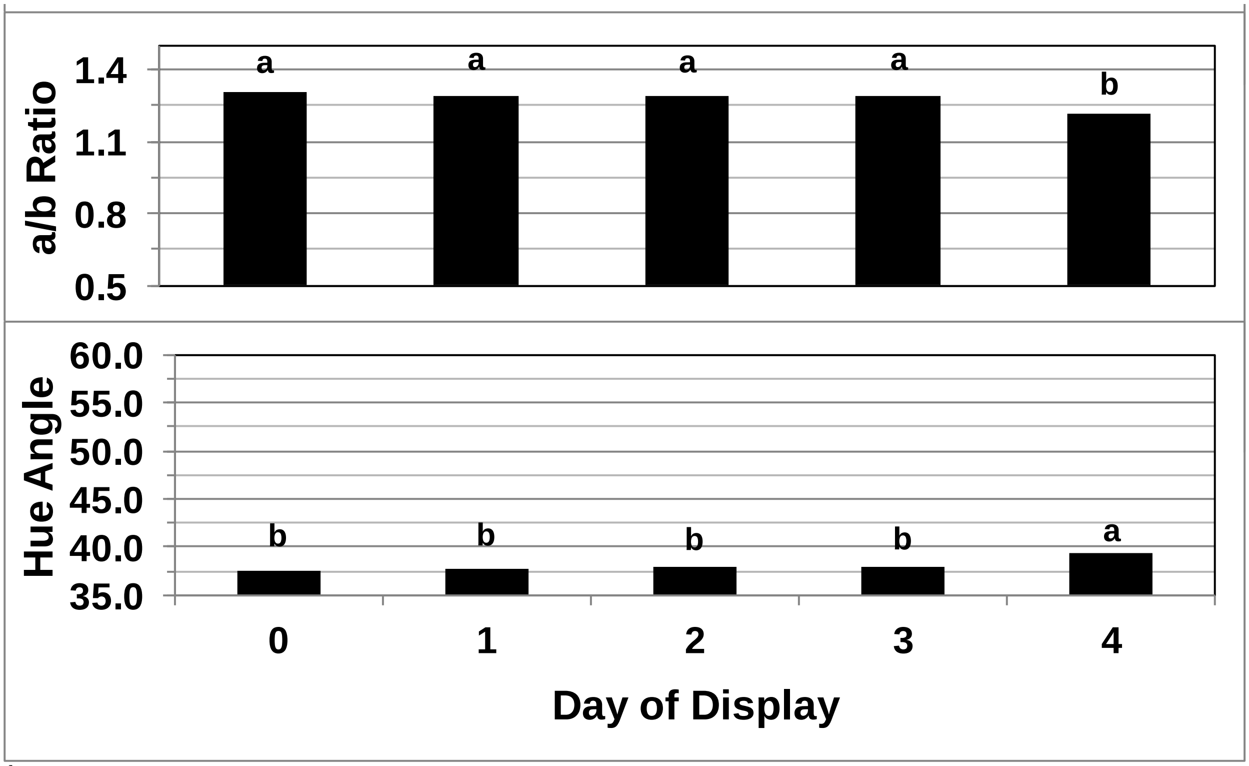
[ab] Lsmeans with different superscript letters differ (P<0.05).
[1] L* standard error = 0.59.
[2] a* standard error = 0.47.
b*, saturated index, a/b ratio, & hue angle all had a significant interaction between lighting type and day of display.

Fig. 4-10. Least squares means (Lsmeans) for L*[1] instrumental color values of beef *semimembranosus* superficial portion steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



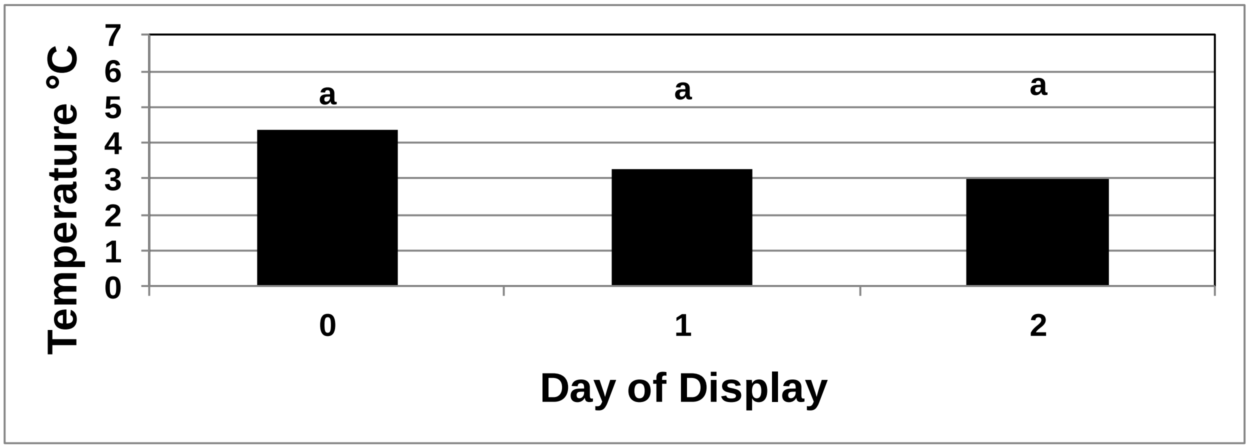
[ab] Lsmeans with different superscript letters differ ($P<0.05$).
[1] L* standard error = 0.57.
a* & b* had a significant interaction between lighting type and day of display.

Fig. 4-11. Least squares means (Lsmeans) for a/b ratio[1] & hue angle[2] instrumental color of beef *semimembranosus* superficial portion steaks over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



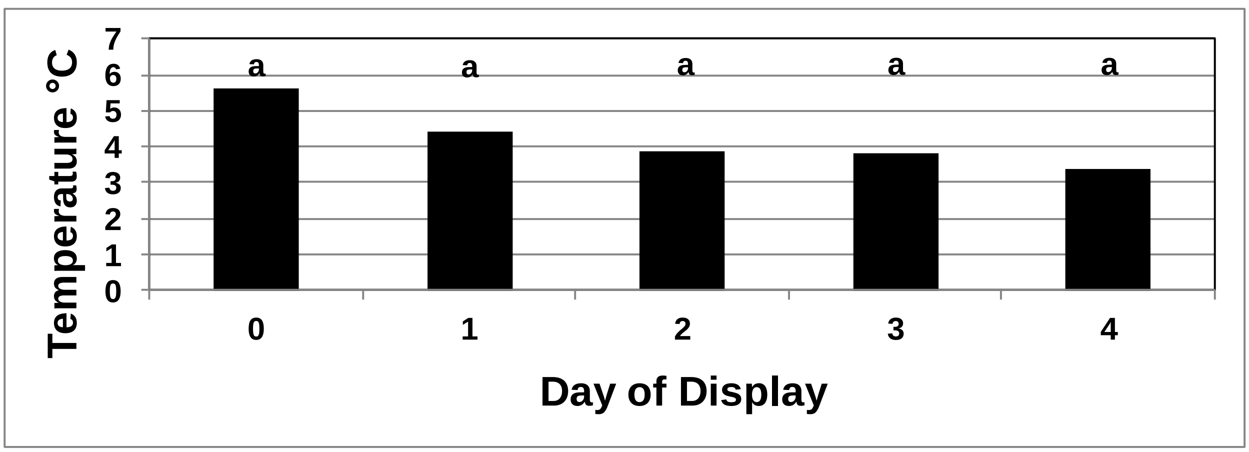
[ab] Lsmeans with different superscript letters differ ($P<0.05$).
[1] Standard error = 0.02.
[2] Standard error = 0.35.
Saturation index had a significant interaction between lighting type and day of display.

Fig. 4-12. Least squares means (Lsmeans) for internal temperature of beef *longissimus dorsi* steaks over 2 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



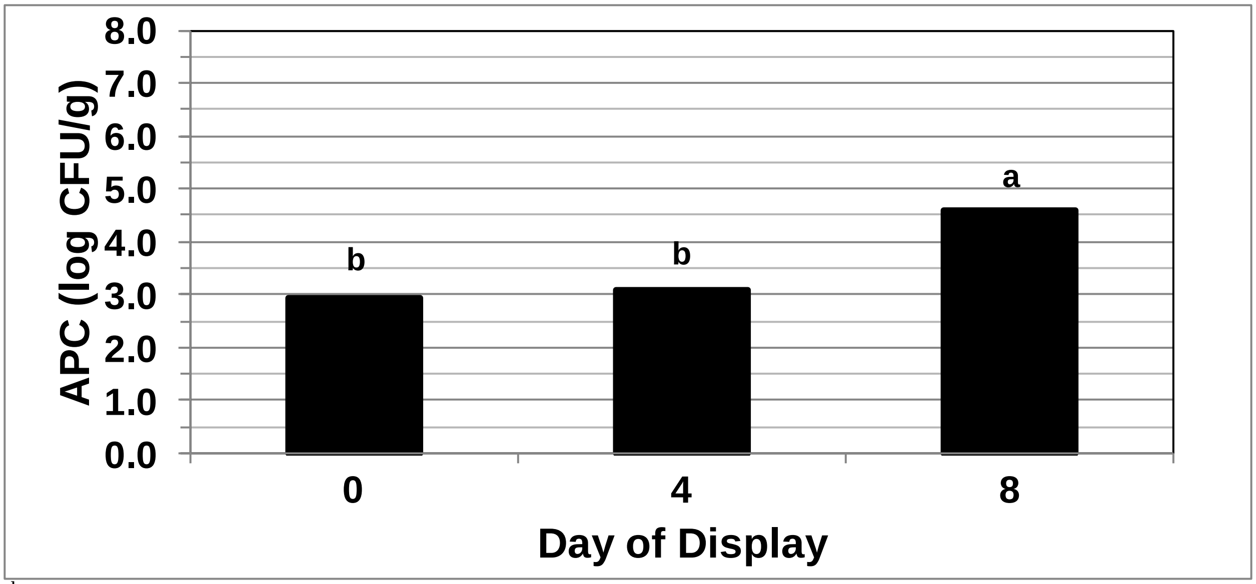
[ab] Lsmeans with different superscript letters differ (P<0.05). Standard error = 0.56.

Fig. 4-13. Least squares means (Lsmeans) for internal temperature of ground beef over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



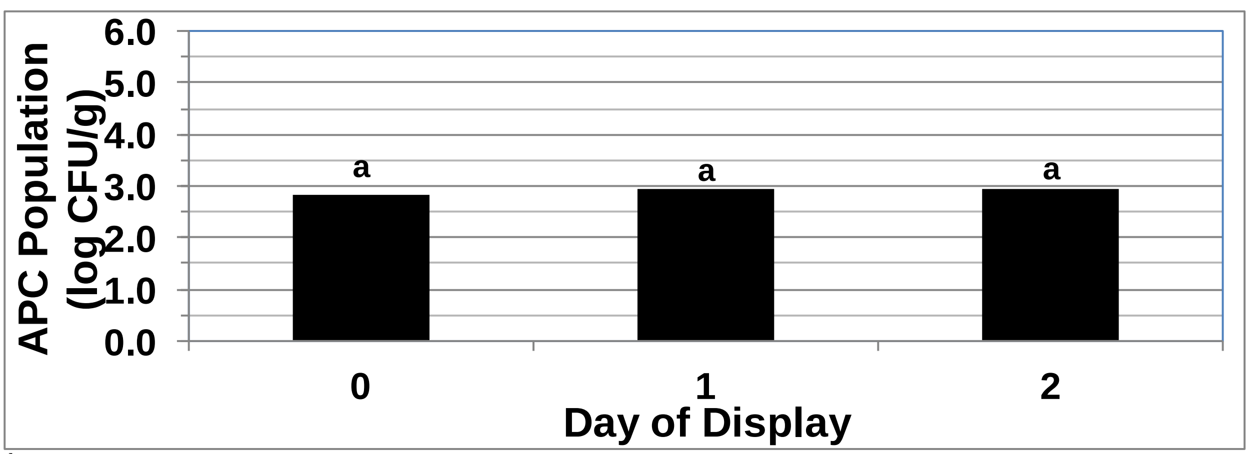
[ab] Lsmeans with different superscript letters differ (P<0.05). Standard error = 0.71.

4-14. Least squares means (Lsmeans) for Aerobic Plate Count (APC) populations of pork loin chops over 8 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



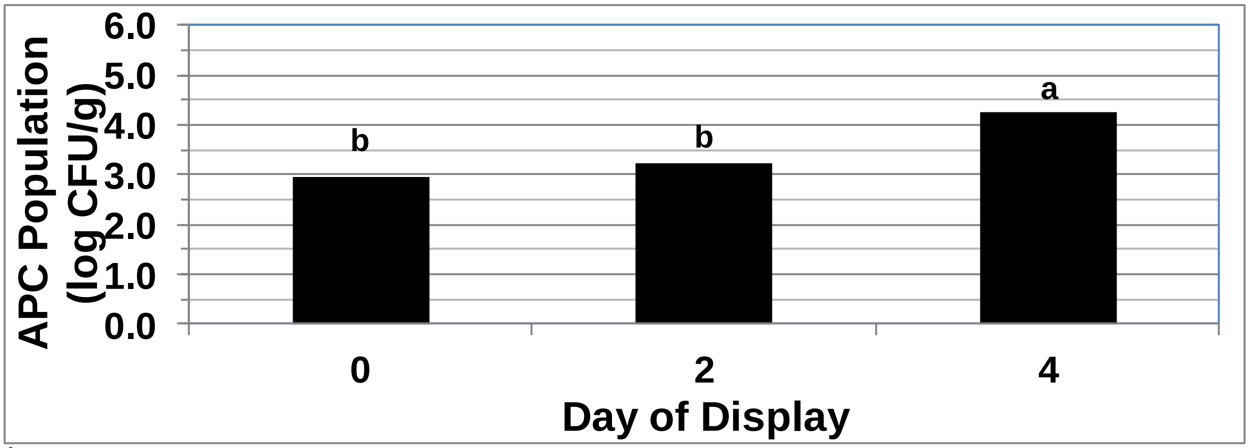
[ab] Lsmeans with a different superscript letter differ (P<0.05). Standard error: 0.22.

Fig. 4-15. Least squares means (Lsmeans) for Aerobic Plate Count (APC) populations of beef *longissimus dorsi* steaks over 2 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



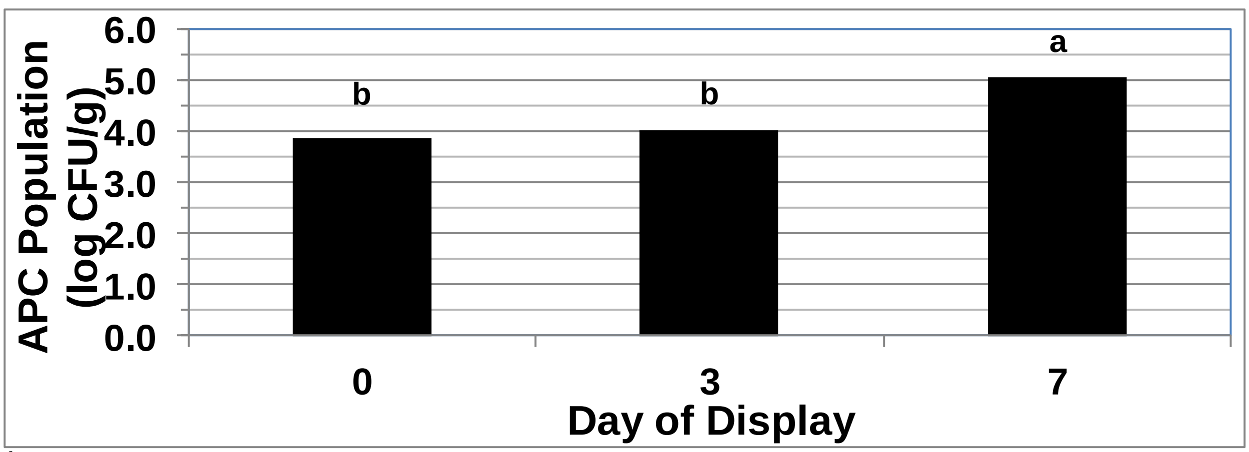
[ab] Lsmeans with a different superscript letter differ (P<0.05). Standard error: Initial= 0.23, Middle= 0.11, End= 0.11.

Fig. 4-16. Least squares means (Lsmeans) for Aerobic Plate Count (APC) populations of ground beef over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



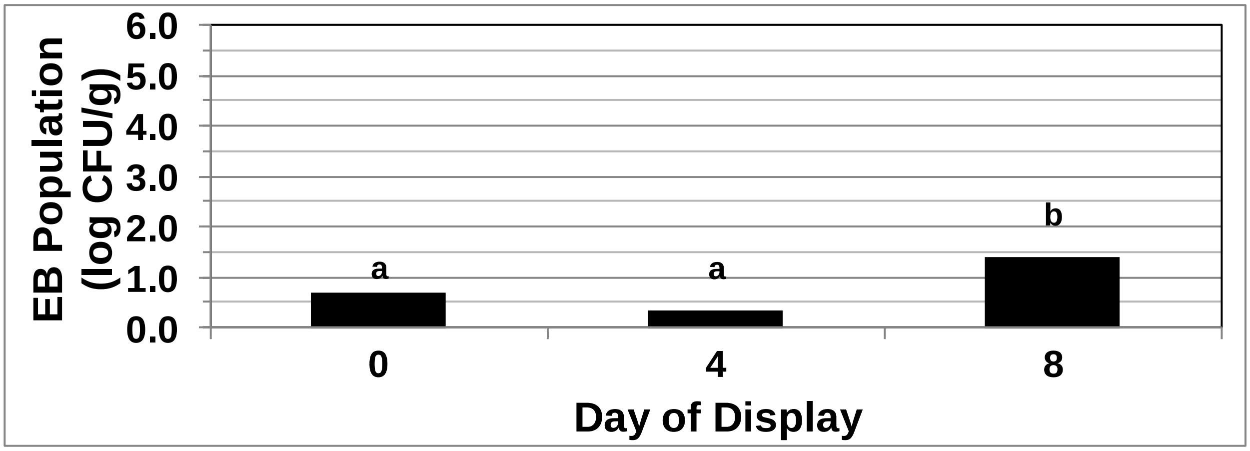
[ab] Lsmeans with a different superscript letter differ ($P<0.05$). Standard error: Initial= 0.16, Middle= 0.15, End= 0.23.

Fig. 4-17. Least squares means (Lsmeans) for Aerobic Plate Count (APC) populations of ground turkey over 7 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



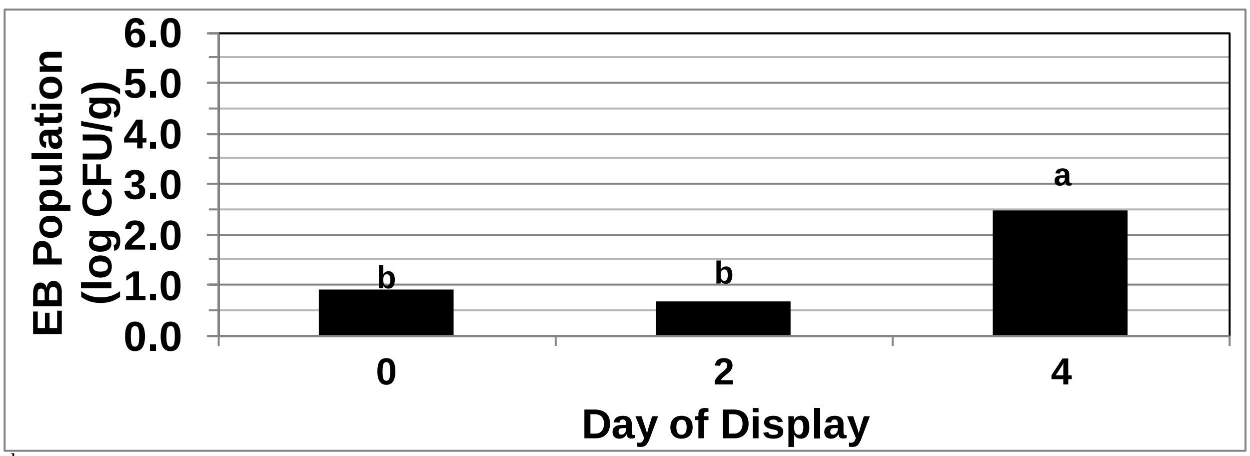
[ab] Lsmeans with a different superscript letter differ ($P<0.05$). Standard error: Initial= 0.16, Middle= 0.16, End= 0.16.

Fig. 4-18. Least squares means (Lsmeans) for *Enterobacteriaceae* (EB) populations of pork loin chops over 8 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



[ab] Lsmeans with a different superscript letter differ (P<0.05). Standard error= 0.79.

Fig. 4-19. Least squares means (Lsmeans) for *Enterobacteriaceae* (EB) populations of ground beef over 4 days of refrigerated display in cases equipped with fluorescent (FLS) or light emitting diode (LED) lighting.



[ab] Lsmeans with a different superscript letter differ (P<0.05). Standard error: Initial= 0.36, Middle= 0.36, End= 0.47.

Appendix B - Case Specifications and Visual Color Analysis

4-20. UV, correlated color temperatures and lumens for fluorescent (FLS) and light emitting diode (LED) lighting.

	FLS Case					Ave. Lux
1, Top shelf	0.0038 Δuv	0.0033 Δuv	0.0033 Δuv	0.0038 Δuv	0.0039 Δuv	
	3174 K	3179 K	3170 K	3180 K	3144 K	
	1760	2278	2042	2238	1702	**2004.0**
2	0.0028 Δuv	0.0025 Δuv	0.0025 Δuv	0.0028 Δuv	0.0031 Δuv	
	3232 K	3248 K	3215 K	3252 K	3210 K	
	1875	2277	2048	2357	1726	**2056.6**
3	0.0026 Δuv	0.0026 Δuv	0.0027 Δuv	0.0033 Δuv	0.0031 Δuv	
	3240 K	3259 K	3251 K	3300 K	3219 K	
	1542	1817	1747	1921	1392	**1683.8**
4	0.0014 Δuv	0.0001 Δuv	0.0012 Δuv	0.0014 Δuv	0.0017 Δuv	
	3276 K	3258 K	3229 K	3295 K	3253 K	
	1724	2276	1821	2298	1653	**1954.4**
5, Bottom	0.0036 Δuv	0.0030 Δuv	0.0028 Δuv	0.0035 Δuv	0.0035 Δuv	
	3389 K	3339 K	3303 K	3362 K	3328 K	
	973	985.8	909	883	836.8	**860.2**
						1711.8

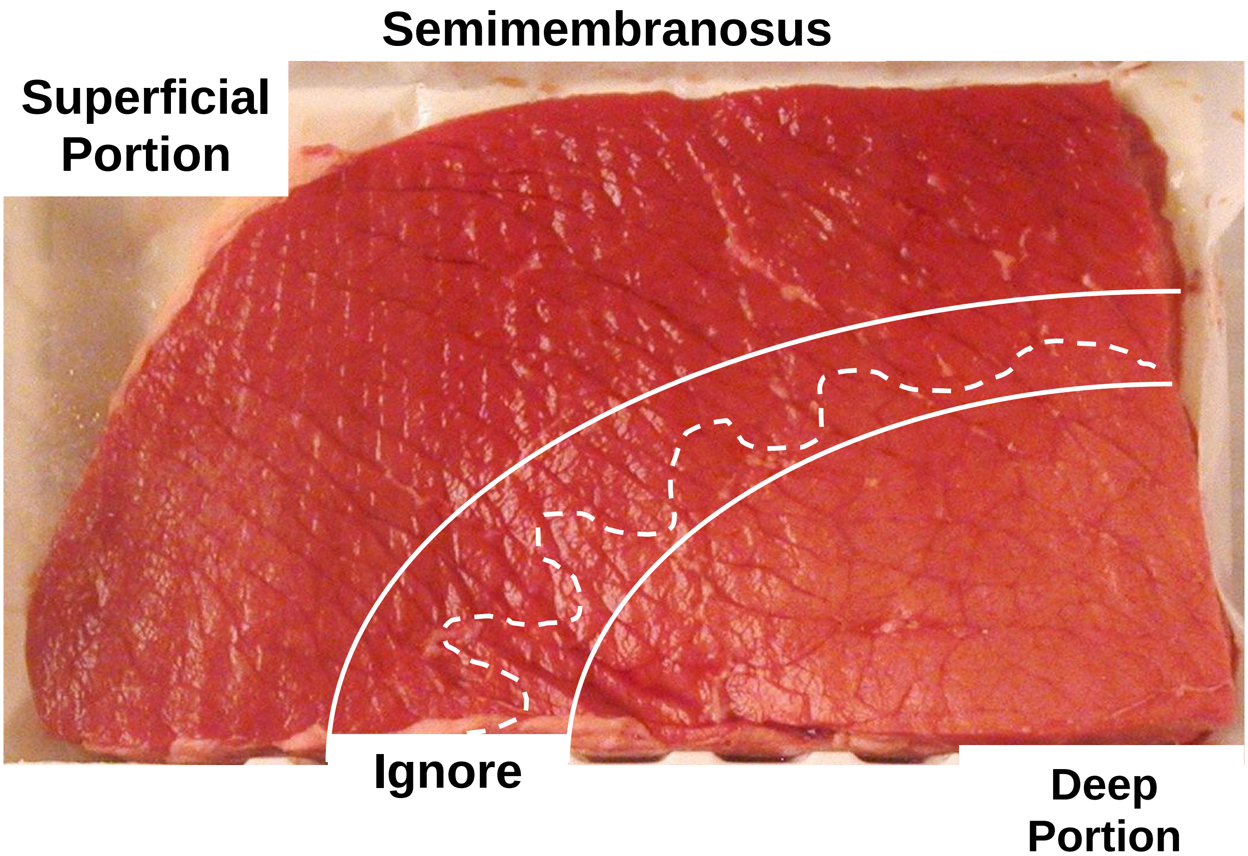
	LED Case					
1, Top Shelf	(-0.0011) Δuv	(-0.0016) Δuv	(-0.0014) Δuv	(-0.0013) Δuv	(-0.0020) Δuv	
	3045 K	3025 K	3026 K	3021 K	2949 K	
	909	1066	1011	1076	803	**973.0**
2	(-0.0001) Δuv	(-0.0003) Δuv	(-0.0005) Δuv	(-0.0005) Δuv	(-0.0003) Δuv	
	2965 K	2934 K	2941 K	2940 K	2888 K	
	1617	2396	1727	2205	1643	**1917.6**
3	(-0.0027) Δuv	(-0.0023) Δuv	(-0.0019) Δuv	(-0.0016) Δuv	(-0.0018) Δuv	
	2994 K	3050 K	3036 K	3077 K	3038 K	
	1867	2549	2194	2896	1968	**2294.8**
4	(-0.0025) Δuv	(-0.0012) Δuv	(-0.0026) Δuv	(-0.0014) Δuv	(-0.0013) Δuv	
	2979 K	2991 K	3029 K	3105 K	3060 K	
	1979	2583	2050	3026	2125	**2352.6**
5, Bottom	0.0050 Δuv	0.0034 Δuv	0.0035 Δuv	0.0042 Δuv	0.0039 Δuv	
	3676 K	3559 K	3551 K	3626 K	3600 K	
	683	559	564	648	542	**599.2**
						1627.4

Fig. 4-21. Five fresh meat products displayed in retail display cases outfitted with fluorescent or light emitting diode lighting. (Photo courtesy of Dr. Melvin Hunt).

Fig. 4-22. Product layout within each display case.

Study Design LED vs. FLS Lighting Comparison in M5X Cases													
Top Shelf 1	Row 2	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC
Shelf 1	Row 1	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC	Pork PVC
Shelf 2	Row 3	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC
Shelf 2	Row 2	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC
Shelf 2	Row 1	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC	LD PVC
Shelf 3	Row 2	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC
Shelf 3	Row 1	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC	GB PVC
Shelf 4	Row 2	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP
Shelf 4	Row 1	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP	GT MAP
Shelf 5	Row 3	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC
Shelf 5	Row 2	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC
Shelf 5	Row 1	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC	SM PVC
		Replicate 1											
		Replicate 2											
		Replicate 3											
		Replicate 4											
		Replicate 5											
		Replicate 6											

Fig. 4-23. Superficial and deep portion of the beef semimembranosus.



Appendix C - Statistical Codes

Product pH

```
Data= pH;
Input product$ ph;
Datalines;

proc mixed;
title 'pH';
class pH product;
model  pH=product/ddfm=kr;
lsmeans product/pdiff;
run;
```

Case Temperatures

```
libname huss 'C:\Documents and Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann';

ods rtf file='C:\Documents and Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann\TempLog.RTF';

    data temp; set huss.templog;
    proc sort; by shelf locat;
    proc mixed;
    class trt locat day shelf;
    model tempf = trt locat shelf trt*locat trt*shelf locat*shelf;
    lsmeans trt locat shelf trt*locat trt*shelf locat*shelf;
    run;
    ods rtf close;
```

Visual Color

```
libname huss 'C:\Documents and Settings\Dallas Johnson\My Documents\DALLAS\HUNTER\Hussmann'
;

ods rtf file='C:\Documents and Settings\Dallas Johnson\My Documents\DALLAS\HUNTER\Hussmann\visual.RTF';

data temp; set huss.Pchpsvisual;
run;
proc mixed;
 title 'Analysis of Pork Chops Visual Color';
 class trt rep day;
 model Avg = trt day trt*day/ddfm=kr;
 random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.Ldstkvisual;
IF DAY='Day3am' THEN DELETE;
run;
proc mixed;
 title 'Analysis of LD STEAKS Visual Color';
 class trt rep day;
 model Avg = trt day trt*day/ddfm=kr;
 random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.Gbeefvisual;
run;
proc mixed;
 title 'Analysis of GROUND BEEF Visual Color';
 class trt rep day;
 model Avg = trt day trt*day/ddfm=kr;
 random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.Gturkvisual;
run;
proc mixed;
 title 'Analysis of Ground Turkey Visual Color';
 class trt rep day;
 model Avg = trt day trt*day/ddfm=kr;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.Smdeepvisual;
run;
proc mixed;
 title 'Analysis of SM Deep Visual Color';
 class trt rep day;
 model Avg = trt day trt*day/ddfm=kr;
 random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.Smsupervisual;
run;
proc mixed;
 title 'Analysis of SM Super Visual Color';
 class trt rep day;
 model Avg = trt day trt*day/ddfm=kr;
 random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run; ODS RTF CLOSE;
```

Instrumental L* Color

```
libname huss 'C:\Documents and
Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann'
;

ods rtf file='C:\Documents and
Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann\
LSTAR.RTF';

        data temp; set huss.LAB_PC;
        run;
        proc mixed;
         title 'Analysis of Pork Chops
LSTAR';
         class trt rep day;
         model LSTAR = trt day
trt*day/ddfm=kr;
         random REP*TRT*DAY;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_LD;
        IF DAY='Day3' THEN DELETE;
        run;
        proc mixed;
         title 'Analysis of LD STEAKS
LSTAR';
         class trt rep day;
         model LSTAR = trt day
trt*day/ddfm=kr;
         random REP*TRT*DAY;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_GB;
        run;
        proc mixed;
         title 'Analysis of GROUND BEEF
LSTAR';
         class trt rep day;
         model LSTAR = trt day
trt*day/ddfm=kr;
         random REP*TRT*DAY;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_GT;
        run;
        proc mixed;
         title 'Analysis of Ground Turkey
LSTAR';
         class trt rep day;
         model LSTAR = trt day
trt*day/ddfm=kr;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_DSM;
        run;
        proc mixed;
         title 'Analysis of DSM LSTAR';
         class trt rep day;
         model LSTAR = trt day
trt*day/ddfm=kr;
         random REP*TRT*DAY;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_SSM;
        run;
        proc mixed;
         title 'Analysis of SSM LSTAR';
         class trt rep day;
         model LSTAR = trt day
trt*day/ddfm=kr;
         random REP*TRT*DAY;
         lsmeans trt|day/pdiff;
         run;
        ODS RTF CLOSE;
```

Instrumental a* Color

```
libname huss 'C:\Documents and Settings\Dallas Johnson\My Documents\DALLAS\HUNTER\Hussmann'
;

ods rtf file='C:\Documents and Settings\Dallas Johnson\My Documents\DALLAS\HUNTER\Hussmann\ASTAR.RTF';

data temp; set huss.LAB_PC;
run;
proc mixed;
 title 'Analysis of Pork Chops ASTAR';
 class trt rep day;
 model ASTAR = trt day trt*day/ddfm=kr;
 random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.LAB_LD;
IF DAY='Day3' THEN DELETE;
run;
proc mixed;
title 'Analysis of LD STEAKS ASTAR';
class trt rep day;
model ASTAR = trt day trt*day/ddfm=kr;
random REP*TRT*DAY;
lsmeans trt|day/pdiff;
 run;
data temp; set huss.LAB_GB;
run;
proc mixed;
 title 'Analysis of GROUND BEEF ASTAR';
 class trt rep day;
 model ASTAR = trt day trt*day/ddfm=kr;
 random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.LAB_GT;
run;
proc mixed;
 title 'Analysis of Ground Turkey ASTAR';
 class trt rep day;
 model ASTAR = trt day trt*day/ddfm=kr;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.LAB_DSM;
run;
proc mixed;
 title 'Analysis of DSM ASTAR';
 class trt rep day;
 model ASTAR = trt day trt*day/ddfm=kr;
 random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.LAB_SSM;
run;
proc mixed;
 title 'Analysis of SSM ASTAR';
 class trt rep day;
 model ASTAR = trt day trt*day/ddfm=kr;
 random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run;
ODS RTF CLOSE;
```

Instrumental b* Color

```
libname huss 'C:\Documents and Settings\Dallas Johnson\My Documents\DALLAS\HUNTER\Hussmann'
;

ods rtf file='C:\Documents and Settings\Dallas Johnson\My Documents\DALLAS\HUNTER\Hussmann\BSTAR.RTF';

data temp; set huss.LAB_PC;
run;
proc mixed;
title 'Analysis of Pork Chops BSTAR';
class trt rep day;
model BSTAR = trt day trt*day/ddfm=kr;
random REP*TRT*DAY;
lsmeans trt|day/pdiff;
run;
data temp; set huss.LAB_LD;
IF DAY='Day3' THEN DELETE;
run;
proc mixed;
title 'Analysis of LD STEAKS BSTAR';
class trt rep day;
model BSTAR = trt day trt*day/ddfm=kr;
random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.LAB_GB;
run;
proc mixed;
 title 'Analysis of GROUND BEEF BSTAR';
 class trt rep day;
 model BSTAR = trt day trt*day/ddfm=kr;
 random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.LAB_GT;
run;
proc mixed;
 title 'Analysis of Ground Turkey BSTAR';
 class trt rep day;
 model BSTAR = trt day trt*day/ddfm=kr;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.LAB_DSM;
run;
proc mixed;
 title 'Analysis of DSM BSTAR';
 class trt rep day;
 model BSTAR = trt day trt*day/ddfm=kr;
 random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run;
data temp; set huss.LAB_SSM;
run;
proc mixed;
 title 'Analysis of SSM BSTAR';
 class trt rep day;
 model BSTAR = trt day trt*day/ddfm=kr;
 random REP*TRT*DAY;
 lsmeans trt|day/pdiff;
 run;
ODS RTF CLOSE;
```

Instrumental Saturation Index

```
libname huss 'C:\Documents and
Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann'
ods rtf file='C:\Documents and
Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann\
SATINDX.RTF';
        data temp; set huss.LAB_PC;
        SATINDX =
SQRT(ASTAR*ASTAR+BSTAR*BSTAR)
;
        run;
        proc mixed;
         title 'Analysis of Pork Chops
SATINDX';
         class trt rep day;
         model SATINDX = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_LD;
        SATINDX =
SQRT(ASTAR*ASTAR+BSTAR*BSTAR)
;
        IF DAY='Day3' THEN DELETE;
        run;
        proc mixed;
         title 'Analysis of LD STEAKS
SATINDX';
         class trt rep day;
         model SATINDX = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_GB;
        SATINDX =
SQRT(ASTAR*ASTAR+BSTAR*BSTAR)
;
        IF DAY='Day3' THEN DELETE;
        run;
        proc mixed;
         title 'Analysis of GROUND BEEF
SATINDX';
         class trt rep day;
         model SATINDX = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_GT;
        SATINDX =
SQRT(ASTAR*ASTAR+BSTAR*BSTAR)
;
        run;
        proc mixed;
         title 'Analysis of Ground Turkey
SATINDX';
         class trt rep day;
         model SATINDX = trt day
trt*day/ddfm=kr;
         random rep;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_DSM;
        SATINDX =
SQRT(ASTAR*ASTAR+BSTAR*BSTAR)
;
        run;
        proc mixed;
         title 'Analysis of DSM SATINDX';
         class trt rep day;
         model SATINDX = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_SSM;
        SATINDX =
SQRT(ASTAR*ASTAR+BSTAR*BSTAR)
        run;
        proc mixed;
         title 'Analysis of SSM SATINDX';
         class trt rep day;
```

```
model SATINDX = trt day
trt*day/ddfm=kr;
random rep*trt*day;
lsmeans trt|day/pdiff;
run;
ODS RTF CLOSE;
```

Instrumental a/b Ratio

```
libname huss 'C:\Documents and
Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann'
;


ods rtf file='C:\Documents and
Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann\
ABRATIO.RTF';


        data temp; set huss.LAB_PC;
        ABRatio = ASTAR/BSTAR;
        run;
        proc mixed;
         title 'Analysis of Pork Chops A/B
RATIO';
         class trt rep day;
         model ABRATIO = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_LD;
        IF DAY='Day3' THEN DELETE;
        ABRatio = ASTAR/BSTAR;
        run;
        proc mixed;
         title 'Analysis of LD STEAKS A/B
RATIO';
         class trt rep day;
         model ABRATIO = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_GB;
        ABRatio = ASTAR/BSTAR;
        IF DAY='Day3' THEN DELETE;
        run;
        proc mixed;
         title 'Analysis of GROUND BEEF
A/B RATIO';
         class trt rep day;
         model ABRATIO = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_GT;
        ABRatio = ASTAR/BSTAR;
        run;
        proc mixed;
         title 'Analysis of Ground Turkey
A/B RATIO';
         class trt rep day;
         model ABRATIO = trt day
trt*day/ddfm=kr;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_DSM;
        ABRatio = ASTAR/BSTAR;
        run;
        proc mixed;
         title 'Analysis of DSM A/B RATIO';
         class trt rep day;
         model ABRATIO = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
        lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_SSM;
        ABRatio = ASTAR/BSTAR;
        run;
        proc mixed;
         title 'Analysis of SSM A/B RATIO';
         class trt rep day;
         model ABRATIO = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run; ODS RTF CLOSE;
```

Instrumental Hue Angle

```
libname huss 'C:\Documents and
Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann'
;
ods rtf file='C:\Documents and
Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann\
HUEANGLE.RTF';
        data temp; set huss.LAB_PC;
        HUEANGLE=ATAN(BSTAR/AST
AR)*180/3.14159;
        run;
        proc mixed;
         title 'Analysis of Pork Chops HUE
ANGLE';
         class trt rep day;
         model HUEANGLE = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_LD;
        HUEANGLE=ATAN(BSTAR/AST
AR)*180/3.14159;
        IF DAY='Day3' THEN DELETE;
        run;
        proc mixed;
         title 'Analysis of LD STEAKS HUE
ANGLE';
         class trt rep day;
         model HUEANGLE = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_GB;
        HUEANGLE=ATAN(BSTAR/AST
AR)*180/3.14159;
        run;
        proc mixed;
         title 'Analysis of GROUND BEEF
HUE ANGLE';
         class trt rep day;
         model HUEANGLE = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_GT;
        HUEANGLE=ATAN(BSTAR/AST
AR)*180/3.14159;
        run;
        proc mixed;
         title 'Analysis of Ground Turkey
HUE ANGLE';
         class trt rep day;
         model HUEANGLE = trt day
trt*day/ddfm=kr;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_DSM;
        HUEANGLE=ATAN(BSTAR/AST
AR)*180/3.14159;
        run;
        proc mixed;
         title 'Analysis of DSM HUE
ANGLE';
         class trt rep day;
         model HUEANGLE = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.LAB_SSM;
        HUEANGLE=ATAN(BSTAR/AST
AR)*180/3.14159;
        run;
        proc mixed;
         title 'Analysis of SSM HUE
ANGLE';
         class trt rep day;
         model HUEANGLE = trt day
trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
```

```
ODS RTF CLOSE;
```

Product Internal Temperatures

```
libname huss 'C:\Documents and
Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann'
;


ods rtf file='C:\Documents and
Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann\
INTTEMP.RTF';


        data temp; set huss.Pchpsinttemp;
run;
        proc mixed;
         title 'Analysis of Pork Chops
Internal Temperature';
         class trt rep day;
         model tempf = trt day
trt*day/ddfm=kr;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.ldstkinttemp;
        if day = 'Day3' then delete; run;
        proc mixed;
         title 'Analysis of LD Steaks Internal
Temperature';
         class trt rep day;
         model tempf = trt day
trt*day/ddfm=kr;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.Gbeefinttemp;
run;
        proc mixed;
         title 'Analysis of Ground Beef
Internal Temperature';
         class trt rep day;
         model tempf = trt day
trt*day/ddfm=kr;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.gturkinttemp;
run;
        proc mixed;
         title 'Analysis of Ground Turkey
Internal Temperature';
         class trt rep day;
         model tempf = trt day
trt*day/ddfm=kr;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.SMstkinttemp;
run;
        proc mixed;
         title 'Analysis of SM Steaks Internal
Temperature';
         class trt rep day;
         model tempf = trt day
trt*day/ddfm=kr;
         lsmeans trt|day/pdiff;
         run;
        ODS RTF CLOSE;
```

Odor

```
libname huss 'C:\Documents and Settings\Dallas Johnson\My Documents\DALLAS\HUNTER\Hussmann'
ods rtf file='C:\Documents and Settings\Dallas Johnson\My Documents\DALLAS\HUNTER\Hussmann\ODOR.RTF';

data temp; set huss.PchpsOdor; run;
proc mixed;   Where Day='End';
 title 'Analysis of Pork Chops Odor';
 class trt;
 model Odor = trt/ddfm=kr;
 lsmeans trt/pdiff;
 run;
data temp; set huss.GbeefOdor; run;
proc mixed;   Where Day='End';
 title 'Analysis of Ground Beef Odor';
 class trt;
 model Odor = trt/ddfm=kr;
 lsmeans trt/pdiff;
 run;
data temp; set huss.gturkOdor; run;
proc mixed;   Where Day='End';
 title 'Analysis of Ground Turkey Odor';
 class trt;
 model Odor = trt/ddfm=kr;
 lsmeans trt/pdiff;
 run;
data temp; set huss.ldstkOdor;
if day = 'Day3' then delete; run;
proc mixed;   Where Day='End';
 class trt;
 model Odor = trt/ddfm=kr;
 lsmeans trt/pdiff;
 run;
data temp; set huss.SMstkOdor; run;
proc mixed;   Where Day='End';
 title 'Analysis of SM Steaks Odor';
 class trt;
 model Odor = trt/ddfm=kr;
 lsmeans trt/pdiff;
 run;
ods rtf close;
```

Lipid Oxidation-TBARS

```
libname huss 'C:\Documents and
Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann'
;

ods rtf file='C:\Documents and
Settings\Dallas Johnson\My
Documents\DALLAS\HUNTER\Hussmann\
tbars.RTF';

        data temp; set huss.Pchpstbars; run;
        proc mixed;
         title 'Analysis of Pork Chops tbars';
         class trt;
         model tbars = trt/ddfm=kr;
         lsmeans trt/pdiff;
         run;
        data temp; set huss.Gbeeftbars; run;
        proc mixed;
         title 'Analysis of Ground Beef
tbars';
         class trt;
         model tbars = trt/ddfm=kr;
         lsmeans trt/pdiff;
         run;
        data temp; set huss.gturktbars; run;
        proc mixed;
         title 'Analysis of Ground Turkey
tbars';
         class trt;
         model tbars = trt/ddfm=kr;
         lsmeans trt/pdiff;
         run;
        data temp; set huss.ldstktbars;
        if day = 'Day3' then delete; run;
        proc mixed;
         class trt;
         model tbars = trt/ddfm=kr;
         lsmeans trt/pdiff;
         run;
        data temp; set huss.SMstktbars; run;
        proc mixed;
        title 'Analysis of SM Steaks tbars';
         class trt;
         model tbars = trt/ddfm=kr;
         lsmeans trt/pdiff;
         run;
        ods rtf close;
```

Product Microbiology

```
libname huss 'C:\Documents and Settings\Dallas Johnson\My Documents\DALLAS\HUNTER\Hussmann'
ods rtf file='C:\Documents and Settings\Dallas Johnson\My Documents\DALLAS\HUNTER\Hussmann\MICRO.RTF';
        data temp; set huss.Micro_PC;
        if D='Init' then Day = 1;
        if D='MID' then Day=2;
        if D='END' then Day=3;
        drop D;
        run;
        PROC SORT; BY MICRO;
        proc mixed;     BY MICRO;
         title 'Analysis of Pork Chops Micro';
         class trt rep day;
         model AVGLOG = trt day trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.Micro_LD;
        if D='Init' then Day = 1;
        if D='MID' then Day=2;
        if D='END' then Day=3;
        drop D;
        run;
        PROC SORT; BY MICRO;
        proc mixed;     BY MICRO;
        title 'Analysis of LD STEAKS Micro';
         class trt rep day;
         model AVGLOG = trt day trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.Micro_GB;
        if D='Init' then Day = 1;
        if D='MID' then Day=2;
        if D='END' then Day=3;
        drop D;
        run;
        PROC SORT; BY MICRO;
        proc mixed;     BY MICRO;
         title 'Analysis of GROUND BEEF Micro';
         class trt rep day;
         model AVGLOG = trt day trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.Micro_GT;
        if D='Init' then Day = 1;
        if D='MID' then Day=2;
        if D='END' then Day=3;
        drop D;
        run;
        PROC SORT; BY MICRO;
        proc mixed;     BY MICRO;
         title 'Analysis of Ground Turkey Micro';
         class trt rep day;
         model AVGLOG = trt day trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        data temp; set huss.Micro_SM;
        if D='Init' then Day = 1;
        if D='MID' then Day=2;
        if D='END' then delete;
        drop D;
        run;
        PROC SORT; BY MICRO;
        proc mixed;     BY MICRO;
         title 'Analysis of SM Micro';
         class trt rep day;
         model AVGLOG = trt day trt*day/ddfm=kr;
         random rep*trt*day;
         lsmeans trt|day/pdiff;
         run;
        ods rtf close;
```

Appendix D - Visual Color Scales

HUSSMANN – CARGILL – KSU
Retail Display Lighting Study

Pork Chops
FLS and LED Display Cases

NAME: ______________________ DATE: ________ Time: _______

Color Scale: To characterize retail color shelf-life

1 = Very bright reddish pink
2 = Bright reddish pink
3 = Dull reddish pink
4 = Slightly grayish pink
5 = Grayish pink
6 = Slightly tannish gray
7 = Moderately tannish gray
8 = Tan to brown

****Score to half-point increments*****

____Display Case	
Package ID	**Color Score**

HUSSMANN – CARGILL – KSU
Retail Display Lighting Study

Beef *Longissimus dorsi* Steaks
FLS and LED Cases

NAME: ______________________ DATE: ________ Time: _______

Odor Scale: To characterize retail color shelf-life

1 = Very bright red
2 = Bright red
3 = Dull red
4 = Slightly dark red
5 = Moderately dark red
6 = Dark red to tannish red
7 = Dark reddish tan
8 = Tan to brown

*****Score to half-point increments*****

____Display Case	
Package ID	**Color Score**

HUSSMANN – CARGILL – KSU
Retail Display Lighting Study

Ground Beef
FLS and LED Display Cases

NAME: ________________________ DATE: _________ Time: ________

Color Scale: To characterize retail color shelf-life

1 = Very bright
2 = Bright red
3 = Dull red
4 = Slightly dark red
5 = Moderately dark red
6 = Dark red to tannish red
7 = Dark reddish tan
8 = Tan to brown

*****Score to half-point increments*****

_____ Display Case	
Package ID	**Color Score**

HUSSMANN – CARGILL – KSU
Retail Display Lighting Study

Ground Turkey
FLS and LED Display Cases

NAME: ______________________ DATE: ________ Time: _______

Color Scale: To characterize retail color shelf-life

1 = Very bright reddish pink
2 = Bright reddish pink
3 = Dull reddish pink
4 = Slightly grayish pink
5 = Grayish pink
6 = Slightly tannish gray
7 = Moderately tannish gray
8 = Tan to brown

*****Score to half-point increments*****

____Display Case	
Package ID	**Color Score**

HUSSMAN – CARGILL – KSU
Retail Display Lighting Study

Beef *Semimembranosus* Steaks
FLS and LED Cases

NAME: ______________________ DATE: ________ Time: _______

Color Scale: To characterize retail color display shelf-life

Superficial Portion

1 = Very bright red
2 = Bright red
3 = Dull red
4 = Slightly dark red
5 = Moderately dark red
6 = Dark red to tannish red
7 = Dark reddish tan
8 = Tan to brown

Deep Portion

1 = Very bright pinkish red
2 = Bright pinkish red
3 = Dull pinkish red
4 = Slightly dark pinkish red
5 = Moderately dark pinkish red
6 = Dark pinkish red to tannish pink
7 = Dark pinkish tan
8 = Tan to brown

*****Score to half-point increments*****

____ Display Case		
Package ID	**Superficial Color Score**	**Deep Color Score**