Determination of consumer color and discoloration thresholds for purchase of retail ground beef

by

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Abstract

The objective of this study was to identify the threshold for color and discoloration for consumers to purchase ground beef in a simulated retail display and to determine the best objective measurement to predict consumer purchase intent. This study was designed in two phases, with Phase 1 requiring consumers to evaluate ground beef samples of multiple days of display simultaneously, and Phase 2 having consumers evaluate samples of only a single day of display. Our models showed that each of the objective measures evaluated were predictors ($P < 0.05$) of consumer purchasing intent. All logistic regression equations ($P < 0.01$) had high R^2 values of 0.48 – 0.86 (Phase 1) and 0.26 – 0.65 (Phase 1), and correctly classified 78.1 – 90.1% (Phase 1) and 70.5 – 84.0% (Phase 2) of samples as would / would not purchase. Linear regression equations predicting consumer overall appearance ratings with objective measures also resulted in significant ($P < 0.01$) models, with R^2 values of 0.57 – 0.93 and 0.35 – 0.54. The a^* values of 21.6, 24.6, 28.3, and 30.5 (Phase 1) and 20.7, 26.2, 31.7, and 35.4 (Phase 2) correspond with consumers being 50, 75, 90, and 95% likely to purchase the product at full price. However, if the product was discounted, the values were 17.9, 21.4, 25.0, and 27.4 (Phase 1) and 17.7, 22.7, 27.7, and 31.1 (Phase 2). The percentage of metmyoglobin values of 40.1, 33.6, 27.1, and 22.7 (Phase 1) and 37.8, 28.7, 19.5, and 13.3 (Phase 2) correspond with consumers being 50, 75, 90, and 95% likely to purchase the product at full price and 47.8, 40.5, 33.2, and 28.2 (Phase 1) and 45.2, 36.0, 26.9, and 20.6 (Phase 2) if the product was discounted. The models generated from this study provide the ability to predict consumer willingness to purchase ground beef, and provide ground beef producers an indication of potential consumer purchasing behaviors based upon objective values that are easy to measure.

Key words: oxymyoglobin, metmyoglobin, consumer, sensory, color, ground beef

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Dedication

This thesis is dedicated to my parents, Dave and Myra. I can’t put into words how much I love and appreciate you both. Thank you for leading by example, and teaching me the value of hard work and following my dreams. You truly shaped me into the person I am today. I am forever grateful for you.

Chapter 1 - Review of literature

Ground beef has expanded its market share in the United States throughout recent decades (Schulz, 2021). The consumer discrimination of discolored ground beef results in 2.55% of beef being discarded at the retail level (Ramanathan, 2022). Furthermore, this discarded beef is equivalent to 780,000 head of cattle going to waste in the United States alone (Ramanathan, 2022). However, the impact of ground beef color on consumer purchase intent is not fully understood. Therefore, it is the objective of this review to discuss the impact of ground beef on the United States meat industry, factors affecting ground beef color, and the influence of ground beef color on consumer purchasing decisions.

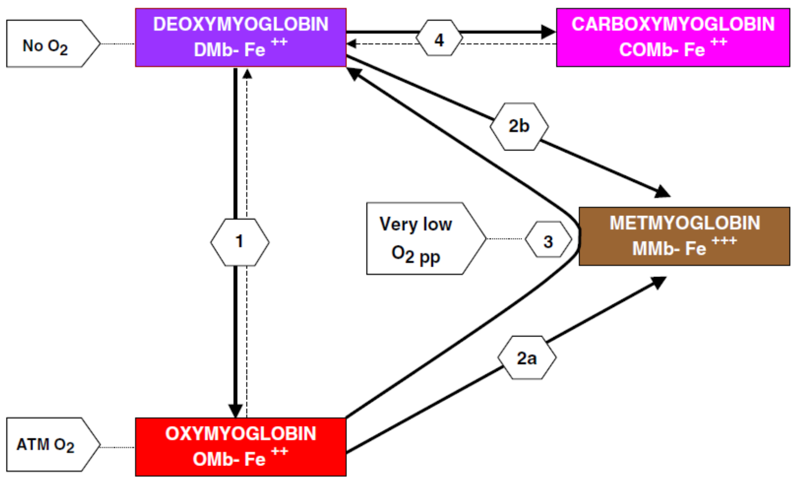
Ground beef

The United States Code of Federal Regulations defines ground beef as, "chopped fresh and/or frozen beef" (FSIS, 2022). In recent years, the product has taken on a new definition to many United States consumers. Ground beef products have a new reputation as a versatile, convenient, and low-priced staple in the diets of modern consumers (Speer et al., 2015). In 2020, United States customers consumed 22 pounds of ground beef per capita (Schulz, 2021). With ground beef consumption accounting for more than 46% of total retail beef consumption (Schulz, 2021), this growing market demand for an item once considered to be an industry by-product should not be overlooked. Although the United States has shifted to a "ground beef nation" (Close, 2014), there are many unknowns regarding consumer purchasing intent of ground beef products in the retail setting.

Meat color

Consumers often use discoloration as an indicator of meat freshness and wholesomeness when making meat purchasing decisions (Mancini and Hunt, 2005). Therefore, it is essential to understand the principles and mechanisms of meat color.

The main protein involved in dictating meat color is myoglobin, and there are four forms of this molecule primarily responsible for these effects: deoxymyoglobin, oxymyoglobin, metmyoglobin, and carboxymyoglobin (Faustman and Cassens, 1990; Mancini and Hunt, 2005; Suman and Joseph, 2013; Faustman and Suman, 2017). The form of myoglobin is dependent on the ligand existing at the 6^{th} coordination site, as well as the valence state of iron in the molecule (Giddings, 1977). Deoxymyoglobin is associated with a purplish-red color, due to the lack of oxygen present in the muscle tissue, and it contains an empty 6^{th} coordination site with iron in the ferrous state (Fe^{2+}) (Faustman and Cassens, 1990; Mancini and Hunt, 2005; Suman and Joseph, 2013; Faustman and Suman, 2017). Meat in the fully oxygenated state, or oxymyoglobin, is known for its bright red color. Oxymyoglobin possesses a diatomic oxygen connected to the 6^{th} coordination site in addition to the ferrous iron (Fe^{2+}) (Faustman and Cassens, 1990; Mancini and Hunt, 2005; Suman and Joseph, 2013; Faustman and Suman, 2017). A more stable bright color occurs when meat enters the carboxymyoglobin state. Carboxymyoglobin takes place when the 6^{th} coordination site is occupied by carbon monoxide and in an oxygen-less environment (Faustman and Cassens, 1990; Mancini and Hunt, 2005; Suman and Joseph, 2013; Faustman and Suman, 2017). Finally, metmyoglobin is a fully oxygenated state in which meat is a tan to brown color with water in the 6^{th} coordination site (Faustman and Cassens, 1990; Mancini and Hunt, 2005; Suman and Joseph, 2013; Faustman and Suman, 2017). Myoglobin is capable of shifting between these states in fresh meat through the process of four different reactions (Figure 1.1) dependent on variables such as oxygen level, pH, time, temperature, and competition for oxygen by the mitochondria (Faustman and Cassens, 1990; Mancini and Hunt, 2005; Suman and Joseph, 2013; Faustman and Suman, 2017).



Rx 1 (Oxygenation): DMb + O_2 → OMb

Rx 2a (Oxidation): OMb + [oxygen consumption or low O_2 partial pressure] – e^- → MMb

Rx 2b (Oxidation): [DMb – hydroxyl ion – Hydrogen ion complex]+ O_2 → MMb + O_2^-

Rx 3 (Reduction): MMb + Oxygen consumption + metmyoglobin reducing activty → DMb

Rx 4 (CarboxyMb): DMb + carbon monoxide → COMb

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

In the first reaction, deoxymyoglobin shifts to oxymyoglobin (Faustman and Cassens, 1990; Mancini and Hunt, 2005; Suman and Joseph, 2013; Faustman and Suman, 2017). Deoxymyoglobin occurs in the absence of oxygen, and is often associated with muscle tissue directly after a cut is made or meat in a vacuum package. As oxygenation occurs, the meat shifts to the oxymyoglobin state. This process is often referred to as “bloom.” Oxymyoglobin will permeate below the surface of meat as the amount of oxygen the product is exposed to increases.

Oxymyoglobin changes to metmyoglobin in the second reaction due to the oxidation of the ferrous (Fe^{2+}) iron in oxymyoglobin to a ferric (Fe^{3+}) state (Faustman and Cassens, 1990;

Mancini and Hunt, 2005; Suman and Joseph, 2013; Faustman and Suman, 2017). Due to the laws of thermodynamics, this reaction is unlikely to occur under aerobic conditions. Alternatively, another version of the second reaction can occur when deoxymyoglobin is in the same ferrous (Fe^{2+}) iron state is oxidized to the ferric (Fe^{3+}) iron state of metmyoglobin. Although this reaction most commonly takes place, the visual interpretation of these changes is challenging as the product shifts in color from bright red directly to brown without displaying the purple-red color often associated with deoxymyoglobin. This is attributed to the deoxymyoglobin color development being overpowered by the distinct colors of the oxymyoglobin and metmyoglobin states (Faustman and Cassens, 1990; Mancini and Hunt, 2005; Suman and Joseph, 2013; Faustman and Suman, 2017).

The third reaction results in the transition of meat from the oxymyoglobin state to deoxymyoglobin via the metmyoglobin state (Faustman and Cassens, 1990; Mancini and Hunt, 2005; Suman and Joseph, 2013; Faustman and Suman, 2017). Since the first reaction is not reversible, the reduction of metmyoglobin must take place to reestablish the ferrous (Fe^{2+}) state of myoglobin. This reaction can be challenging as it is dependent on the limited oxygen scavenging, reducing enzymes, and NADH pool in postmortem muscle. The final reaction is the formation of carboxymyoglobin from deoxymyoglobin through the addition of carbon monoxide to the 6^{th} coordination site.

Physics of color

Color is defined as, “the appearance something has as the result of reflected light (Cambridge, 2022).” Therefore, a proper understanding of the physics of color and light is paramount to study of meat color. Color is interpreted from wavelengths of light reflected off an object (Boynton, 1990; UVM, 2010; AMSA, 2012; O'Connor, 2021). These wavelengths of light are responsible for development of color (Figure 1.2). For example, the wavelengths of 650 – 700 nm are responsible for red color, while the wavelengths of 455 – 490 are responsible for blue color (AMSA, 2012). When light reaches an object, such as meat, some wavelengths are absorbed by the object and not reflected back to the observer. The wavelengths which are not absorbed by the object are utilized to determine the color (Boynton, 1990; UVM, 2010; AMSA, 2012). There are two main modes in which color can be detected and interpreted: the human eye or objective instrumental device (AMSA, 2012).

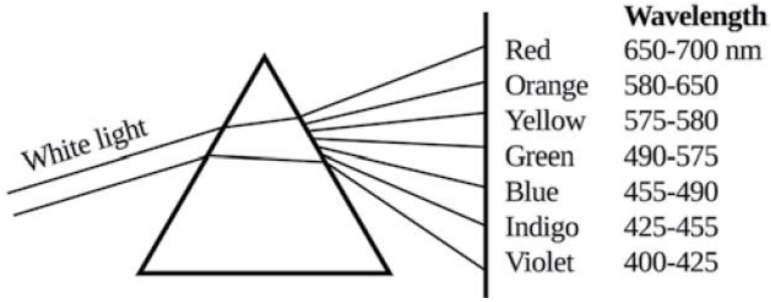


Figure 1.2. White light split into its components by a prism, and the corresponding wavelength to each visual light color (AMSA, 2012)

Human color perception

When visual light reaches the eye, the retina is responsible for capturing the wavelengths (Boynton, 1990; AMSA, 2012). The retina utilizes rods and cones to detect light and determine color. The rods react only to the spectrum of light from black to white, including gray. Alternatively, the cones have the ability to capture color on the red, blue, and green spectra (AMSA, 2012). The cones and rods work together to assimilate the wavelengths for color development. The optic nerve disseminates this information to the brain via the optic nerve, where it is then interpreted (AMSA, 2012).

Visual color analysis

There are two types of visual color analysis which may occur: consumer panels and trained sensory panels. Consumer panels are composed of untrained individuals, and used to determine willingness to purchase and acceptability (Mancini and Ramanathan, 2020). Consumer panels require a large number of individuals, and are not appropriate to evaluate meat color characteristics. Contrastingly, trained sensory panels are a tool to describe and quantify color characteristics consisting of a much smaller number of individuals trained to use color scales and objectively evaluate meat products, but are not suitable to provide information regarding preferences (Mancini and Ramanathan, 2020). Although in some instances utilizing one of the panel types may be adequate, it is often necessary to conduct both types of panels to evaluate the research question at hand (AMSA, 2012).

Instrumental color analysis

Instrumental meat color measurement is an essential aspect of meat color research, as it provides a truly objective way to measure data in comparison to visual color panels. There are two main options for collecting instrumental color data: colorimeters and spectrophotometers. Colorimeters are slightly limited due to only measuring tristimulus values, also known as CIE *L**, *a**, and *b** (Figure 1.3) (AMSA, 2012). The unique combinations of these factors correlate to specific colors, since *L** measures the spectrum of white to black, *a** measures the spectrum of green to red, and the *b** measures the spectrum of blue to yellow (AMSA, 2012; Mancini and Ramanathan, 2020). These tristimulus values can also be used to calculate important variables, such as hue angle and chroma (AMSA, 2012; Mancini and Ramanathan, 2020).

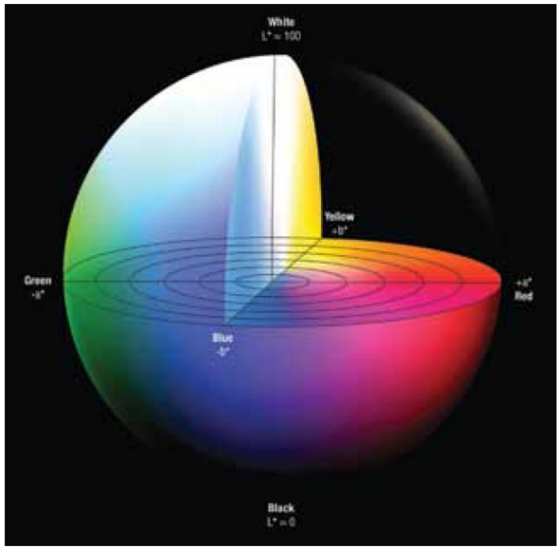


Figure 1.3. Representation of color solid for CIE L*a*b* color space (AMSA, 2012)

Spectrophotometers have the ability to gather more data due to their complexity. These instruments collect spectral data in addition to the tristimulus values (AMSA, 2012). This spectral data is crucial for many meat color studies, because it can be used to quantify myoglobin forms present on the surface of the product through a calculation process (Mancini and Hunt, 2005; AMSA, 2012; Mancini and Ramanathan, 2020).

There are many aspects of instrumental color measurement which must be monitored and reported to ensure consistency and replication. Illuminant selection is an integral part of a meat color research study. There are three illuminants commonly utilized: A, C, and D_{65} (AMSA, 2012). Illuminant A is more popular among meat scientists, as it has the ability to distinguish minute differences in redness among samples in comparison to C and D_{65} (AMSA, 2012).

There are two primary options for the degree of observer: 2º and 10º (AMSA, 2012). The 10º observer remains dominant among meat scientists due to its capacity to collect a larger area of the scanned sample (AMSA, 2012).

The aperture is the opening in which light enters the instrument for measurement to take place, and aperture size is another major consideration when conducting meat color research

(AMSA, 2012). The largest aperture size which allows for multiple measurements of the same sample with no crossover should be used. Aperture sizes should not be adjusted within a study, as this will directly affect tristimulus values. Tristimulus CIE *L**, *a**, *b** values will decrease with decreased aperture sizes (AMSA, 2012).

Impact of lipid oxidation on meat discoloration

Although meat color is not an accurate indicator of lipid oxidation, there is an interaction between meat discoloration and lipid oxidation (Greene, 1969; Faustman et al., 2010; Mancini and Ramanathan, 2020). Lipid oxidation is a series of reactions taking place within meat products which results in a significant decline in quality (Gray and Pearson, 1994). The process often results in a rancid flavor deemed unacceptable by consumers (White et al., 1988). Lipid oxidation has the ability to reduce color stability by creating an environment in which myoglobin is more susceptible to oxidation by inactivating enzymes involved in the reduction of metmyoglobin (Mancini and Ramanathan, 2020). Therefore, discolored meat may also have a negative off-flavor or off-odor due to lipid oxidation.

Greene (1969) documented the parallel increase in discoloration and lipid oxidation of meat products. Greene utilized beef top round steaks which were made into ground beef, and combined with antioxidants, as designated by experimental design (Greene, 1969). The samples were then designated to storage in packaging known to be oxygen impermeable or highly oxygen permeable. A spectrophotometer was utilized to determine the amount of metmyoglobin present in the samples, and thiobarbituric acid (TBA) test was conducted to determine the amount of lipid oxidation present in the samples. Finally, a trained sensory panel evaluated the samples for rancid odors. Results from this study established a connection between lipid oxidation and rancid beef off-odors, as detected by the trained sensory panel. Moreover, they found the odor remained after cooking occurred which makes the prevention of lipid oxidation crucial for meat quality considerations. The anaerobic packaging was effective at preventing metmyoglobin formation, lipid oxidation, and rancid off-odors (Greene, 1969). However, the addition of antioxidants to the ground beef samples deemed the anaerobic packaging needless. Although this study did not identify the mechanisms which allow lipid oxidation to reduce color stability, it set the foundation for later work to build from.

Zakrys et al. (2008) reported that meat discoloration is intensified by the process of lipid oxidation. This study evaluated quality factors in beef *longissimus* dorsi steaks stored in modified atmosphere packaging under 0%, 10%, 20%, 50%, and 80% oxygen (Zakrys et al., 2008). Objective color analysis was conducted on each measurement day, and L^*, a^*, and b^* values were collected. Furthermore, lipid oxidation, oxymyoglobin, and protein oxidation were measured along with trained sensory panels held every three days throughout the twelve-day period of the study. Results from this study found that changes in meat discoloration, specifically the percentage of oxymyoglobin and a^*, appear to be induced by lipid oxidation and highly correlated with TBARS (Zakrys et al., 2008). A strong correlation was found between TBARS data and percentage of oxymyoglobin with $r2$ values > 0.89. This aligned with the results for a^*, which showed a negative correlation with days meaning the red color within samples decreased over time.

A study conducted by Mitacek et al. (2019) evaluated the influence of mitochondria and myoglobin function on beef color. These researchers utilized beef *longissimus lumborum* muscles assigned to 3, 7, 14, 21, or 28 day aging period, and evaluated the mitochondrial, metabolite, and biochemical profiles along with surface color of each aging period after six days of display (Mitacek et al., 2019). Results from this study indicate that muscle oxygen consumption, mitochondrial protein content, and antioxidant capacity all decreased as aging time increased. Moreover, they found that metabolites integral to the TCA cycle, such as fumaric acid, fructose, and creatinine decreased as aging time increased. Finally, this study showed that NADH levels decreased as aging time increased, but NADH-dependent reductase activity was not affected. Mitacek et al. (2019) concluded that an increase in mitochondrial damage, depletion of metabolites responsible for NADH regeneration, and an increase in oxidative stress decreased color stability in wet-aged beef (Mitacek et al., 2019). Therefore, the authors recommended the implementation of strategies to minimize lipid oxidation, along with minimizing mitochondrial damage, to increase beef shelf-life.

Impact of bacteria on meat discoloration

Although meat color is not precise indicator of microbiological safety, some meat discoloration can occur with high bacterial counts. At 6 log CFU/mL, slight amounts of visible meat discoloration develop (Chan et al., 1998; Ramanathan et al., 2021). However at 7 log CFU/mL or greater, there is a reduction in bright cherry-red color and presence of off-odors (Chan et al., 1998). Moreover, it typically takes six days of aerobic storage to achieve bacterial levels of 6 log CFU/mL (Faustman and Cassens, 1990). Therefore, it is unlikely that beef would reach bacterial counts necessary to cause discoloration, as it is typically marketed well before this point (Faustman and Cassens, 1990).

The foundational study regarding the impact of bacteria on meat discoloration was done by Butler et al. in 1953. The objective of this study was to evaluate the effect of bacteria on the discoloration of boneless *longissimus dorsi* beef steaks (Butler et al., 1953). The steaks were inoculated with *pseudomonas sp.*, then wrapped and cellophane and stored under refrigerated temperatures. Bacterial counts and objective color measurements were obtained after each day of display (d0 – d18). A spectrophotometer was utilized to determine *L**, *a**, and *b** values, as well as spectral data. Values for hue, value, and chroma were then calculated from the *L**, *a**, and *b** values. A single value for the index of fading was determined from the combination of hue, value, and chroma. Moreover, metmyoglobin percentage was determined from spectral data and extraction. Results from this study found that the main cause of beef steak discoloration was the formation of metmyoglobin, with the greatest rate of metmyoglobin formation taking place during the logarithmic microbial growth phase (Butler et al., 1953). Finally, Butler et al. (1953) concluded that the shelf life of beef steaks was extended when the initial bacterial contamination was lowest.

A study conducted by Robach and Costilow (1961) evaluated the effect of bacterial inoculation on the rate of pigment oxidation. The surface of beef steaks was inoculated with many different bacterial species known for their spoilage effects, including *Pseudomonas fluorescens*, *Pseudomonas aeruginosa*, *Pseudomonas geniculate*, *Achromobacter liquefaciens*, *Flavobacterium rhenanus*, *Lactobacillus plantarum*, and *Saccharomyces cerevisiae* (Robach and Costilow, 1961). The steaks were incubated, and color analysis was conducted as previously described by Butler et al. (1953). The authors concluded that all the microorganisms, except *Lactobacillus plantarum*, impacted the surface meat color in the same manner. These bacteria caused the surface pigment of the steaks to change from the beginning red (oxymyoglobin) to brown (metmyoglobin) with increased microbial counts, then end with a purple pigment (deoxymyoglobin) when counts were at the highest. Due to its status as an anaerobic microorganism, *Lactobacillus plantarum* did not cause any discoloration. Overall, this study found that meat in the oxymyoglobin state is associated with low bacterial counts, increased bacterial counts cause meat to enter the metmyoglobin state, and meat with the highest bacterial load will be found in the deoxymyoglobin state (Robach and Costilow, 1961).

Renerre and Montel (1986) conducted a study focused on the effects of *Lactobacillus* spp. on meat color. Semimembranosus and *longissimus dorsi* steaks were inoculated with strains of *Lactobacillus*, and then stored in vacuum packaging for 3, 6, or 9 days as designated by the experimental design. Steaks were then removed from vacuum packaging and placed in PVC overwrap packaging to be displayed in a simulated retail display, followed by color analysis utilizing a spectrophotometer. Values for *L**, *a**, and *b** were collected, as well as spectral data. Following color analysis, steaks underwent microbiological analysis to determine microbial counts of the *Lactobacillus* species. Most of the relationships evaluated in this study did not result in statistical significant results. However, the study did conclude that increased levels of *Lactobacillus* spp. led to a decrease in *a** values of the beef steaks (Renerre and Montel, 1986).

Impact of packaging on meat discoloration

Meat packaging must fulfill a variety of functions, including product protection, convenience, information communication, and product containment (Ramanathan et al., 2021). However, shelf life is directly dependent on meat packaging (Figure 1.4) due to its influence on microbial growth, lipid oxidation, and discoloration. Packaging types are classified as aerobic, anaerobic, or modified atmosphere. Each packaging type can be adapted to fit the needs of the meat industry, depending on the preferences of specific markets.

Packaging	Shelf-life (days)
PVC—ground beef	2–3
PVC—intact-steak	5–7
HiOx-MAP—ground beef	6–8
HiOx-MAP—intact-steak	10–12
CO-MAP—ground beef	21–28
CO-MAP—intact-steak	28–35
Vacuum packaging	40–50
Nitrite-embedded packaging	30

Figure 1.4. Shelf life of beef in various forms of packaging (Ramanathan et al., 2021)

Nassau et al (2012) found that vacuum skin packaging increased the color stability of fresh beef. The study compared the effects of overwrapping packaging, modified atmosphere packaging, vacuum skin packaging, and modified atmosphere vacuum skin packaging in *longissimus lumborum* steaks. On each of the eighteen days of display, a color space analysis for red, green, and blue parameters was conducted, as well as a trained sensory panel for retail appearance, lean color, and percentage surface discoloration. Although the modified atmosphere vacuum skin packaging resulted in the most desirable color over the first four days of retail display, it is only suitable for short-term retail display as it became the least desirable at the conclusion of the study (Nassau et al., 2012). Throughout the entirety of the study, vacuum skin packaging presented the greatest amount of color stability. Unfortunately, vacuum skin packaging also results in product with a purple color, which is not favored by consumers in the United States.

Suman et al. (2010) evaluated the lipid oxidation and color stability of ground beef stored in modified atmosphere packaging. Ground beef patties were assigned to four packaging systems: vacuum packaging, high-oxygen modified atmosphere packaging (80% O_2 + 20%

CO_2), CO modified atmosphere packaging (0.4% CO + 19.6% CO_2 + 80% N_2), or aerobic packaging (Suman et al., 2010). Packaged samples were stored for six days, with lipid oxidation measured on days one and three. Instrumental color evaluation was conducted on each day of the study utilizing a colorimeter to capture CIE *L**, *a**, and *b** values. The lipid oxidation measurements taken on day one resulted in vacuum packaging having significantly lower TBARS than all other packaging types, with similar results occurring on day three measurements. As expected, patties packaged in vacuum packaging presented lower *a** values on days one through five, when compared to day one. Moreover, the CO modified atmosphere packaging presented an increase in *a** values after day three, with no differences detected in the first portion of the study. The aerobic packaging and high-oxygen modified atmosphere packaging both resulted in an initial increase in *a** value, with a subsequent decrease occurring after day three.

Active antioxidants films are a component of food packaging which release an antioxidant substance in a selective and controlled manner from the packaging to food it is contacting, and can be a tool to increase beef shelf life. Junior et al. (2015) evaluated the effectiveness of citric acid as an antioxidant in a biodegradable active film. Ground beef was packaged in the active antioxidant film or control film, as designated by experimental design, and stored under refrigeration for ten days. A thiobarbituric acid (TBA) test was conducted on days 0, 2, 4, 6, 8, and 10 to determine the amount of lipid oxidation present in the samples. Furthermore, instrumental color evaluation was conducted on days 0, 2, 4, 6, 8, and 10 of the study utilizing a colorimeter to capture CIE *L**, *a**, and *b** values. Results from this study showed that the ground beef samples packaged in the active antioxidant film packaging had significantly lower TBARS values, than their control counterparts from day two through the end of the study (Junior et al., 2015). Additionally, the study found the product stored in the active antioxidant film packaging maintained a higher *a** value throughout the duration of the study. However, no significant differences were found between the treatments for *L** and *b** (Junior et al., 2015).

Consumer perceptions regarding meat color

Consumers favor beef products emitting a bright, cherry-red color (Carpenter et al., 2001; Killinger et al., 2004), and discolored beef products must be marked down in price due to consumer's decreased willingness to pay (Smith et al., 2000; Grebitus et al., 2013). These circumstances lead to an estimated loss of $3.73 billion to the beef industry annually (Ramanathan, 2022). Therefore, consumer perceptions regarding meat color must be understood to prevent waste and fully capitalize on this segment of the beef industry.

Several studies have attempted to quantify meat discoloration and its relation to consumer acceptance and willingness to pay utilizing online surveys. In an online survey measuring the impact of discoloration on consumer willingness to pay for beef steaks and ground beef, Feuz (2020) found that consumers would require extreme discounts for beef containing 25% discoloration. This study utilized steaks and ground beef, which were packaged in a PVC overwrap and placed in a coffin style case to naturally discolor. The steaks stayed in the case for eight days, while the ground beef only needed five days in the case to fully discolor. Then, photographs of the same product were taken daily to capture each phase of discoloration. Additionally, a spectrophotometer was utilized daily to collect spectral data for the calculation of percentage metmyoglobin. The online survey was completed by 2,598 respondents, who were screened for their computer monitor display and eyesight in the first section of the survey. Respondents were provided photos of three steaks at different levels of manipulated darkness, and asked to identify the darkest. A similar question was asked pertaining to ground beef, except respondents were asked to identify the lightest. Although this question was intended for screening and many consumers answered incorrectly at some point, all consumers were retained to complete the rest of the survey. In the next section, a set of thirteen questions regarding the steak or ground beef products was randomly chosen. Each question contained three beef products at different discoloration levels with orthogonal prices associated with each. Consumers were asked to indicated which product they would purchase. Two types of discoloration were used: coverage and intensity. Coverage refers to the percentage of the surface which was discolored, and was achieved naturally by being placed in the case. Intensity refers to the darkness of the discoloration, and was achieved by manipulating the images in a photo editing software. The third section of the survey consisted of a cheap talk script intending to reduce potential hypothetical bias. Finally in the fourth section of the survey, respondents received the other set of thirteen questions they did not receive in section two to indicate the products in which they would purchase. The responses were then utilized in willingness to pay equations to generate consumer willingness to pay estimates. This resulted in consumers requiring willingness-to-pay discounts of $4.13 for discolored ground beef with 25% of its surface area discolored. Ground beef which was 50%, 75%, and 100% discolored required a discount of $7.15, $12.50, and $16.50, respectively. These results were not accompanied by recommendations regarding objective measurements which could be used to predict consumer acceptability (Feuz et al., 2020). However, this study did establish some discount strategies to encourage the quick sale of discolored beef.

Hood and Riordan (1973) utilized round steaks at varying levels of discoloration to evaluate consumer purchasing habits in a grocery store setting in Dublin, Ireland. The in-store trial observed consumers as they made purchasing decisions unknowing to the study which was taking place. Spectral data was collected and K/S value ratios at 572/525 were used to determine the percentage of metmyoglobin present in the steaks, with the discoloration in the study spanning 5% to 33%. The data collected was then used to generate a linear regression model ($y = 45.5 – 0.56x$) to predict the likelihood of consumer purchase at different stages of discoloration. The study discovered the ratio of sales in Dublin supermarkets of discolored beef to bright red beef is approximately 1:2 when 20% metmyoglobin was present in beef round steaks. Additionally, the study found a linear relationship between metmyoglobin content and the proportion of total sales of discolored beef. Shoppers in the study increasingly discriminated against discolored beef when bright red beef and discolored beef were displayed consecutively. Although a linear regression model was generated, the authors did not provide any thresholds for consumer acceptability. The study concluded metmyoglobin played an important role in determining consumer reaction to meat color, which gave a special significance to the pigment analytical technique of color evaluation (Hood and Riordan, 1973).

In a preliminary study utilizing an online consumer survey format, Holman et al. (2016) used images of beef *m. longissimus lumborum* steaks to determine consumer acceptability. Ten steaks with a range of *L**, *a**, and *b** were selected from a large database of *m. longissimus lumborum* photos. At the time of imaging, the color attributes of each steak were measured with a colorimeter/spectrophotometer (Illuminant D_{65}, 25 mm aperture, 10° observer) which obtained *L**, *a**, *b**, as well as spectral data. The images were taken using a standardized approach, and no image editing, processing, or manipulation was implemented. An online survey was created in which respondents were asked to evaluate the acceptability of the beef color using a 10-point scale. This study reported a lower and upper limit to *b** (13.0 and 22.0, respectively) as an accurate predictor of consumer acceptance, and *a** was not found to be meaningful ($P > 0.05$) (Holman et al., 2016). Although objective measurements were collected, no models were presented for the beef industry to predict consumer acceptance of beef products at differing degrees of discoloration.

Contradictory to their previous study, Holman et al. (2017) found *a** to be an important indicator of consumer beef color acceptability using the same imaging technique previously discussed. In this study, they used eighty images with a range of *L**, *a**, and *b** from the large database of *m. longissimus lumborum* photos. Respondents were directed to their select true color and the highest screen resolution settings available on their device. Differing from their previous study, consumers were asked to evaluate the steaks on a 6-level interval scale with each respondent receiving only eleven samples in their survey. They determined the threshold for acceptable (average rank > 3.5) beef to be an *a** value >12.5, but no prediction models were presented (Holman et al., 2017). However, a true comparison cannot be made between studies using illuminants D_{65} and A (AMSA, 2012). The greatest discrepancy among all studies discussed revolves around inaccuracies among computer monitors presenting variation in discoloration intensity, as admitted by Feuz et al. (2020).

Najar-Villarreal et al. (2021) conducted a meta-analysis of sixteen papers from peer-reviewed journals to establish thresholds for the shelf-life of beef *longissimus lumborum* and *psoas major* steaks. The search for articles included only studies which measured *a** value and conducted trained sensory panels to evaluate discoloration (Najar-Villarreal et al., 2021). Only studies which measured *a** valued using a spectrophotometer with illuminant A were included. Moreover, trained sensory panel scores for *longissimus lumborum* were standardized to be on an 8-point line scale, while *psoas major* steaks were standardized to be on a 5-point line scale. This meta-analysis resulted in in an upper and lower limit to *a** value of 24.07 and 20.24, respectively, for *longissimus lumborum* steaks, and 23.75 and 20.99, respectively for *psoas major* steaks. It is noteworthy to include that this study used trained sensory panels to determine product acceptability which is not in accordance with the AMSA Color Guidelines (AMSA, 2012) that state consumer sensory panels are the only suitable way to determine acceptability thresholds. Moreover, the author chose an arbitrary point within line scales, as opposed to panelists answering a yes/no question regarding acceptability.

Impact of meat discoloration on retail waste

It is well-known that the global population is set to reach a new high within the next decade (UN, 2015). With this increase in population comes an increase in demand for food products, with an emphasis in animal food products. The demand for meat is estimated to reach 255,877 metric tons by 2027 (Ramanathan et al., 2021), and limiting meat waste is an imperative aspect of the challenge to meet the needs of providing affordable and nutritious animal proteins. With top meat consumption countries, including the United States, New Zealand, Canada, and Australia, wasting up to 22% of meat and poultry annually, it is crucial to understand the processes which affect meat color so strategies to reduce meat waste can be established (Ramanathan et al., 2021).

A study conducted by Ramanathan et al. (2022) determined the economic and natural resource losses occurring as a direct result of meat discoloration. To accomplish this objective, they collected data from two national retail grocery chains and one regional retail grocery chain regarding the total beef sales, total beef discarded, and discounted sales values at each location. This data generated an equation to establish the number of beef animals wasted in that time period. (Animals wasted = total amount of beef discarded / 249.7 kg) Furthermore, the equations reported by Asem-Hiablie et al. (2019) were used to calculate the energy and water consumed from this data (Asem-Hiablie, 2019). (Loss of energy = discarded meat amount × energy footprint) (Loss of water = discarded meat amount × water footprint) A CO_2 equivalent was used along with the Global Warming Potential Index to measure the CO_2 emissions produced in this time period. Finally, an equation to calculate the resources which could be saved from a 1% decrease in meat discoloration was created using all of the factors discussed. (Energy saved = reduced discarded meat amount × energy footprint) (Water saved = reduced discarded meat amount × water footprint) (Reduced CO_2e = reduced discarded meat amount × Global Warming Potential Index) This study found that the retail grocery chains involved sold 525,093,617 kilograms of beef, while discarding 13,486,928 kilograms or 2.55% (Ramanathan, 2022). Additionally, researchers found 11.07% of the product was sold at a discounted price with the discount per kilogram being $1.41 (Figure 1.5). Perhaps the most impactful message from this study is the determination that a 1% decrease in discarded beef due to discoloration would save 23.95 billion liters of water, 96.88 billion megaJoule of energy, and 0.40 million tons of CO_2 emissions (Ramanathan, 2022).

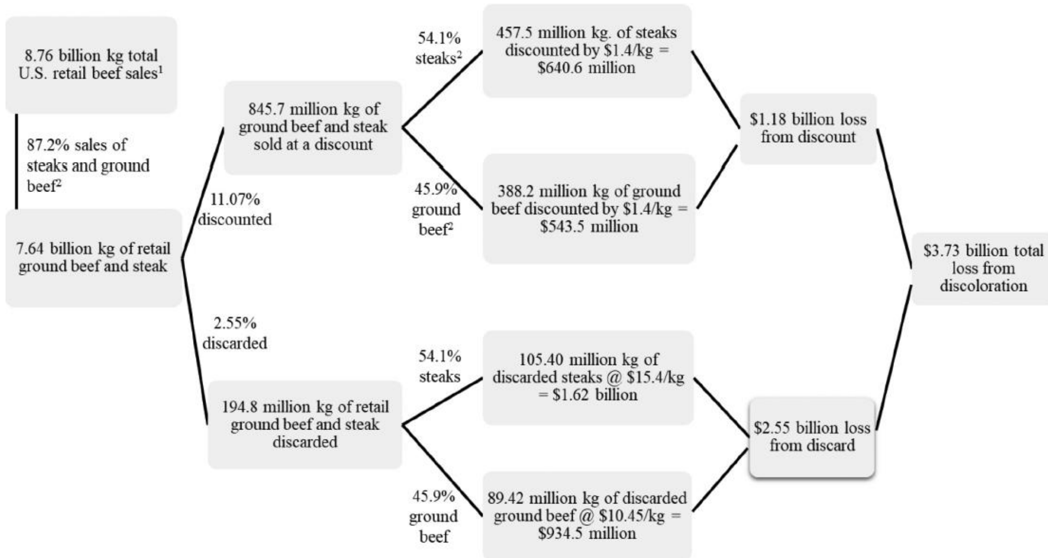


Figure 1.5. Estimated economic and natural resources losses due to discoloration in the United States (Ramanathan, 2022).

Conclusion

As the demand for ground beef from U. S. consumers continues to rise, the meat industry must work to increase efficiency and sustainability within the market. Meat color has the potential to become a valuable tool to reach this goal, as consumers consider it the primary indictor of beef shelf-life (Mancini and Hunt, 2005). As the thresholds surrounding consumer beef color acceptability are better understood, the meat industry can decrease waste and increase profits. A decrease in discarded beef due to discoloration as small as 1% would save 23.95 billion liters of water, 96.88 billion megaJoule of energy, and 0.40 million tons of CO_2 emissions (Ramanathan, 2022).

Chapter 2 - Determination of consumer color and discoloration thresholds for purchase of retail ground beef

Introduction

Once considered a by-product of beef production, ground beef has evolved into a versatile, convenient, and low-priced staple in the diet of U.S. consumers (Speer et al., 2015). The United States population consumed 22 pounds of ground beef per capita in 2020, accounting for more than 46% of total United States retail beef consumption (Schulz, 2021). This demand has shifted ground beef from industry by-product to an increasingly valuable segment of the meat industry (Speer et al., 2015). Although the United States has shifted to a "ground beef nation" (Close, 2014), there are many unknowns regarding consumer purchasing intent of ground beef products in the retail setting.

Meat color is primarily controlled by the myoglobin protein (Faustman and Cassens, 1990; Mancini and Hunt, 2005; Suman and Joseph, 2013; Faustman and Suman, 2017). The form of myoglobin determining the ultimate color is dependent on the ligand existing at the 6^{th} coordination site, as well as the valence state of iron in the molecule (Giddings, 1977). Oxymyoglobin, the form associated with red color, and metmyoglobin, the form associated with a discolored brown color, are of particular importance for ground beef retailing (Faustman and Cassens, 1990; Mancini and Hunt, 2005; Suman and Joseph, 2013; Faustman and Suman, 2017) as ground beef discoloration leads to an estimated loss of $3.73 billion to the beef industry annually (Ramanathan, 2022).

Meat color is an extensively researched area, but only limited research exists evaluating consumer perceptions. Meat shelf life ends primarily when consumers are no longer willing to purchase a product. Several studies have attempted to identify the relationship between meat discoloration and consumer acceptance and willingness to pay, first in an in-store trial (Hood and Riordan, 1973), then utilizing online surveys (Holman et al., 2016; Holman et al., 2017; Feuz et al., 2020; Najar-Villarreal et al., 2021). However, the results of these studies are limited and do not provide a comprehensive understanding of the consumer perceptions of ground beef. Previous work is dated (Hood and Riordan, 1973), utilized color measurement settings non-conforming to AMSA Guidelines (Holman et al., 2016; Holman et al., 2017), or used an online format in which samples may not have been uniformly presented (Holman et al., 2016; Holman et al., 2017; Feuz et al., 2020) Furthermore, many options exist to measure meat color, but it is unknown which objective measurements are best suited for this data as past studies have only presented models considering one or two objective measurements (Hood and Riordan, 1973; Holman et al., 2016; Holman et al., 2017; Feuz et al., 2020; Najar-Villarreal et al., 2021)

Therefore, the objective of this study was to model the relationship between consumer color perception, willingness to purchase, and ground beef redness and discoloration measured through objective means and to establish limits at which consumer purchase intent is greatly diminished.

Materials and methods

The Kansas State University (**KSU**) Institutional Review Board approved all procedures for use of human subjects in the sensory panel evaluations used in this study (IRB 7740.7, February 2021).

Sample collection

This study was designed in two phases, with Phase 1 requiring consumers to evaluate ground beef samples of multiple days of display simultaneously, and Phase 2 having consumers evaluate samples of only a single day of display. Phase 1 took place in November 2021 and

Phase 2 took place in September 2021. The week prior to each phase of the study, 180 – 454 g ground beef packages (80% lean) were obtained from Cargill Meat Solutions in Wichita, KS, and transported under refrigerated temperatures (2 - 4°C) to the KSU Meat Laboratory. Packages were randomly assigned to one of ten days of retail display (**d0** – **d9**), with d0 representing the day samples were placed in the case. All packages were stored in their mother-bag (Tri Gas, 69.6% N, 30% CO_2, 0.4% CO), under refrigeration (2 - 4°C), in the absence of light until scheduled display in the retail case.

On the designated day, ground beef packages were displayed in random order in three coffin-style cases (model DMF8; Tyler Refrigeration Corp., Niles, MI) at 2 – 4°C under continuous fluorescent lights (32 W Del-Warm White 3,000 K; Phillips Lighting Company, Somerset NJ) averaging a 2,143 ± 113 lx emission case-wide. Each case was divided into three sections separated with distinct barriers. Samples entered the case in the afternoon on each day, with trained sensory panels taking place an hour later, and consumer sensory panels following two hours after samples entered the case. The cases were programmed to defrost twice per day, and never reach a temperature above 10°C. For Phase 1, samples within each section represented each day of retail display (d0 – d9) and the entire range of discoloration from extremely fresh (d0) to extremely discolored (d9). For Phase 2, samples within each section represented only one day of retail display, with consumers evaluating entire case of a single day (d0 – d9). Samples were rotated within their designated case section every 24 h to ensure equal distribution of light upon the packages.

Consumer sensory panel evaluation

For both phases of the study, consumer sensory panelists (*N* = 216) were recruited from Manhattan, KS, and surrounding communities, and monetarily compensated for their involvement. For Phase 1 of the study, each consumer evaluated 20 samples, consisting of 2 samples from each day of display. For Phase 2 of the study, consumers evaluated 20 ground beef samples from a single day of display (d0 – d9). Consumers assessed the overall appearance and desirability of each sample on a 100-point continuous line scale with descriptive anchors at 0, 50, and 100. The scale anchor of 0 corresponded to extremely undesirable, 50 neither desirable nor undesirable, and 100 extremely desirable. Furthermore, consumers responded to a yes/no question related to whether or not they would purchase the sample if it was full-priced at retail. If a "no" response was recorded, then the survey was directed to have consumers respond to a yes/no question related to whether or not they would purchase the product if it was discounted at retail. The consumer panelists were provided an electronic tablet (Model 5709 HP Stream 7; Hewlett-Packard, Palo Alto, CA) to record their responses utilizing a digital survey (Qualtrics Software, Provo, UT).

Trained sensory panel evaluation

For both phases of the study, a trained descriptive panel evaluated each sample for redness and percentage discoloration using 100-point continuous line scales prior to consumer evaluation. Trained sensory panelists were trained according to the American Meat Science Association (**AMSA**) meat color measurement guidelines (AMSA, 2012). Panelists were trained leading up to the panels with scales visually anchored at the end points shown in Figure 2.1. as previously described by Van Bibber-Krueger et al, (2020). Prior to the beginning of the study, each panelist was subjected to the Farnsworth – Munsell 100 Hue Color Vision Test (Munsell Color X-Rite, Grand Rapids, MI) to screen for color blindness. Trained sensory panelists were trained to evaluate overall redness through the use of five ground beef packages in the retail display case serving as anchors, with 0 corresponding to packages with an extremely dark red color, 50 slightly dark red, and 100 describing packages with a bright, cherry red color (Figure 2.1). Panelists were trained to assess percentage discoloration through the use of photos of five ground beef packages representing differing levels of discoloration, along with multiple ground beef packages available for evaluation in the retail case. The photos serving as anchors represented ground beef packages at 0%, 50%, and 100% discoloration (Figure 2.1). For each day, a varying number of panelists (*n* = 8 - 17) visually evaluated 180 samples in a randomized order. The trained sensory panelists were given an electronic tablet (Model 5709 HP Stream 7; Hewlett-Packard, Palo Alto, CA) to record their responses utilizing a digital survey (Qualtrics Software, Provo, UT).

Objective color measurements

Prior to each panel for both phases, within a 2-h period before consumer evaluation, *L**, *a**, and *b** values were collected utilizing a Hunter Lab Miniscan spectrophotometer (Illuminant A, 2.54 cm aperture, 10° observer, Hunter Lab Associates Laboratory, Reston, VA) using methods outlined by the AMSA Color Guidelines (AMSA, 2012). Three scans were taken from the surface of the ground beef sample package, and the readings were averaged. Spectral data was also recorded for the calculation of hue angle, chroma, percent oxymyoglobin, and percent metmyoglobin according to the AMSA (AMSA, 2012).

pH

On d0 of each phase, pH measurements of 8 ground beef packages were obtained using a Mettler Toldeo pH meter calibrated according to the manufacturer's specification, as previously described by Hammond et al., 2022. Five g of each sample in duplicate were weighed into 100 ml beakers, and 50 ml of Milli Q water was added to each beaker. Each sample was then mechanically homogenized (Homogenizer 850; Fisher Scientific International, Hampton, NH) and the pH of each sample was then measured and recorded.

Microbiological analysis

For both phases of the study, microbiological analysis was conducted on d0 and d9, with aerobic plate counts (**APC**) measured on 8 ground beef packages per day of analyses. Upon arrival at the laboratory, 10 g samples of ground beef were weighed and stomached with 90 ml of buffered peptone water (**BPW**). Serial dilutions were produced for each sample using BPW. Duplicate Aerobic Count (**AC**) Petrifilms™ were plated with 1 ml of each dilution. The AC Petrifilms™ were then incubated at 35 ± 1°C for 48 hours. Aerobic counts were determined according to the manufacturer's protocol to confirm the ground beef utilized in this study was within the typical range, and differences were not due to microbial contamination.

Statistical analysis

The statistical analyses were performed using the procedures of SAS (SAS Inst. Inc., Cary, NC), with α set at 0.05. Logistic regression models were calculated for the probability of a sample being identified as "would purchase" for both full-priced and discounted responses by consumer sensory panelists using PROG LOGISTIC. The PROC REG program was utilized to determine the simple linear regressions for consumer overall appearance ratings. PROC CORR was used to calculate Pearson correlation coefficients for sensory and objective measures.

Results

Demographics

Demographic information regarding the consumer panelists who participated in both phases of the study can be found in Table 2. Due to an additional day of sampling, Phase 2 had a larger number of participants than Phase 1. An additional day of evaluation was added due to the increased number of samples available and case scheduling. Phase 1 had mostly an even split of females and males (51.4% vs 48.6%), while Phase 2 had a higher number of males than females (62.9% vs 37.1%). In both phases, the majority of consumers (57.9% and 63.9%) resided in one or two person households, with more than a third being married. Phase 1 had 47.2% of consumers over the age of 30, while Phase 2 reported 42.8% in the same age bracket. Caucasian consumers represented the highest ethnic origin in both phases (89.8% and 87.4%), with the majority making more than $50,000 per year (54.2% and 50.0%). The population was educated with college and post college graduates comprising 51.8% and 55.1% of the population in Phase1 and Phase 2, respectively. Consumers in this study reported regular beef consumption at a rate of 1 to 3 times weekly in 59.7% of people in Phase 1, and 59.4% of people in Phase 2. The top purchasing motivators in both phases was “lean/fat ratio,” “price,” and “color” (Table 2.1).

Logistic regression equations

The average pH of the ground beef product in Phase 1 was 6.01 with a standard deviation of 0.05, and in Phase 2 was 6.07 with a standard deviation of 0.07. The microbiological analysis resulted in a 3 log CFU/g increase in average aerobic plate counts between d 0 and d 9 for both phases of the study.

A summary of the minimums, maximums, and variation for all independent variables evaluated in both phases of the study are provided in Table 2.2. Due to the study objectives, a large range within the variables was created and measured within both phases. Such a range was required for the calculation of robust statistical models for the prediction of consumer purchase intent and sensory ratings.

Tables 2.3 and 2.4 present the logistic regression equations calculated for the prediction of consumer sensory panel purchase intent of retail ground beef for Phases 1 and 2. The objective measurements evaluated during the study were utilized to create logistic regression models to predict the likelihood a consumer would respond as “yes” or “would purchase” to the full-priced and discounted survey questions. Overall, the models showed that each of the objective measurements evaluated were predictors of consumer purchasing intent, and all of the logistic regression equations were predictive ($P < 0.01$) of consumer purchase intent. Phase 1 presented models with high R^2 values ($R^2 > 0.48$; most models with $R^2 > 0.78$). Furthermore, the models generated from Phase 1 correctly classified more than 78% of samples as would / would not purchase, with the majority of the models correctly classifying more than 87% of samples. Phase 2 presented effective models with R^2 values of 0.26 – 0.65 (most models with $R^2 > 0.40$), and correctly classified more than 70% of samples as would / would not purchase.

In Phase 1, *a** value was among the best objective measurements evaluated with R^2 values of 0.83 and 0.79 for full-priced and discounted models, respectively (Figure 2.2). Calculated metmyoglobin percentage (Figure 2.3) was determined from spectral data, and resulted in high R^2 values of 0.81 in full-priced models and 0.78 in discounted models. Also in Phase 1, trained sensory panel discoloration was a noteworthy predictor with R^2 values of 0.81 in the full-priced model, and 0.78 in the discounted model (Figure 2.4). Trained sensory panel redness scores were also good predictors ($R^2 > 0.77$) in Phase 1.

Phase 2 presented similar results among the objectives measurements. Values for *a** continued to be the strongest measurement with R^2 values of 0.42 for both full-priced and discounted models (Figure 2.5). Calculated metmyoglobin percentage (Figure 2.6) also resulted in strong R^2 values of 0.41 and 0.40 for full-priced and discounted models, respectively. The trained sensory panel discoloration score models (Figure 2.7) had R^2 values of 0.39 in the full-priced models and 0.38 in the discounted models. Overall, the Phase 2 models accounted for less variation among the variables than the Phase 1 models

Consumer likeliness to purchase thresholds were also generated from the logistic regression equations for each phase of the study (Tables 2.5 and 2.6). Common threshold values for the likeliness for a consumer to purchase (50, 75, 90, and 95% likely) were identified based on the values of the independent variables measured. In Phase 1, the model showed a^* values (Figure 2.1) of 21.6, 24.6, 28.3, and 30.5, related to a 50, 75, 90, and 95% likelihood of consumers purchasing the product at full price. If the product was discounted, then the values shifted substantially to 17.9, 21.4, 25.0, and 27.4 for the corresponding 50, 75, 90, and 95% likelihood thresholds for purchase. The trained sensory panel discoloration scores (Figure 2.4), which were a measure of the percentage of metmyoglobin (brown color) on the surface of the product, provided insight regarding the amount of discoloration present on product that would still result in a consumer to purchase. For consumers to be 50, 75, and 90% likely to purchase the product, the percentage of discoloration was determined to be 37.8, 19.5, and 1.1% in Phase 1. Discounted product again shifted these values, with consumers willing to purchase product with a greater amount of discoloration if discounted, with the models showing discoloration percentages of 64.0, 42.0, 20.1, and 5.2 corresponding with 50, 75, 90, and 95% likely to purchase.

Phase 2 likeliness to purchase threshold values are summarized in Table 2.6. In this phase, a^* values of 20.7, 26.2, 31.7, 35.4 corresponded with 50, 75, 90, and 95% likely to purchase, respectively. Similar to Phase 1, consumers indicated a willingness to purchase ground beef with lower a^* values (Figure 2.5), with values of 17.7, 22.7, 27.7, and 31.1 resulting in 50, 75, 90, and 95% likely to purchase if the product was discounted. Phase 2 resulted in a higher percentage of discoloration accepted by consumers. In this phase, trained sensory panel discoloration values (Figure 2.7) of 40.3 and 12.8% correspond to 50 and 75% likely to purchase. Meanwhile, trained sensory panel discoloration values of 79.0, 42.4, and 5.8% correspond with consumers being 50, 75, and 90% likely to purchase the if the product was discounted.

Pearson correlation coefficients

Pearson correlation coefficients were calculated utilizing the objective measurements collected in both phases of the study (Table 2.7). All of the variables were related ($P < 0.01$), with many highly correlated ($r > 0.90$). In Phase 1, trained sensory panel redness and consumer appearance scores were closely related to a^* values ($r > 0.96$), with Phase 2 also showing a close relationship between trained panel redness scores and a^* values ($r = 0.90$). However, the relationship between consumer appearance score and a^* value in Phase 2 was weaker ($r = 0.71$).

In Phase 1, consumer overall appearance presented a strong relationship to almost all of the objective measurements ($r > 0.93$ for all but L^*). However, the relationship was not as strong in Phase 2 ($r = 0.64$ to 0.74). The relationship between consumer overall appearance score and all other objective measurements was the strongest in both phases, but differed between the two phases due to the differences in design among them.

The trained sensory panel discoloration score resulted in a very strong relationship ($r = 0.98$) with the calculated metmyoglobin score in Phase 1. While the results in Phase 2 were similarly high ($r = 0.93$) indicating the trained sensory panel discoloration scores were an accurate indicator of the percentage of metmyoglobin on the surface of the ground beef product.

Hue angle also showed potential as an objective measurement to assess discoloration, with strong relationships reported between almost all other measurements ($r > 0.91$ for all but L^*) in Phase 1. Although slightly lower values were reported in Phase 2, the relationship between hue angle and all other measurements was still strong ($r > 0.71$, most $r > 0.93$).

Linear regression equations

Linear regression equations predicting consumer overall appearance ratings with objective measures also resulted in significant ($P < 0.01$) models, with R^2 values of 0.57 to 0.93 in Phase 1 (Table 2.8) and R^2 values of 0.35 to 0.54 in Phase 2 (Table 2.9). Therefore, these models were able to account for a large amount of variation within the consumer overall appearance scores. The strongest relationships include a^* (Figure 2.8) and calculated metmyoglobin percentage (Figure 2.9) in their prediction of consumer willingness to purchase.

The linear regression equations for a^* resulted in a robust R^2 values of 0.92 and 0.50 for Phases 1 and 2, respectively (Figure 2.8). This linear regression equation generated in Phase 1 accounted for 92% of the variation within the data points collected. Moreover, Figure 2.8 demonstrates that as a^* (sample redness) increases there is a linear increase in consumer overall appearance ratings.

The linear regression equations for calculated metmyoglobin percentage presented strong R^2 values of 0.92 and 0.54 for Phases 1 and 2, respectively (Figure 2.9). The linear regression equation generated in Phase 1 accounted for 92% of the variation within the data points collected. Figure 2.9 demonstrates that as the calculated metmyoglobin percentage increases (sample brownness), there is an equivalent decrease in consumer overall appearance ratings.

Finally, Figure 2.10 presents the linear regression for predicting trained sensory panel discoloration scores based upon calculated metmyoglobin percentage. The linear regression equations for both phases of the study were almost identical. (Phase 1, trained sensory panel discoloration score = − 61.8 + 2.6(calculated percentage metmyoglobin)) (Phase 2, trained sensory panel discoloration score = − 65.0 + 2.6(calculated percentage metmyoglobin)) This indicates the trained sensory panel's discoloration scores were not impacted by the varied methods between Phase 1 and Phase 2 of the study. This is evidenced by R^2 values of 0.96 and 0.87 for Phase 1 and Phase 2, respectively.

Discussion

Ground beef color

Consumers in this study reported "Lean/fat ratio", "price", and "color" as the most important motivators when purchasing ground beef at the retail level. Recent studies involving customer purchasing motivators also reported "color" to be among the top three purchasing motivators (Olson et al., 2019; Prill et al., 2019; Davis, 2021; Harr, 2021; Farmer, 2022). Lucherk et al. (2017) reported fresh beef steak color was of more importance to female consumers and Californian consumers, while it was less important to consumers categorized as "heavy beef eaters" (Lucherk et al., 2017). Pohlman (2017) found ground beef color, fat, and price to be significantly more important than the product label (Pohlman, 2017). Ramanathan et al. (2022) reported 2.55% of beef is discarded at the retail level due to discoloration. Furthermore, these authors reported a 1% decrease in discarded beef due to discoloration would save 23.95 billion liters of water, 96.88 billion megaJoule of energy, and 0.40 million tons of CO_2 emissions (Ramanathan, 2022). However, Ramanathan et al. (2022) did not provide any data regarding the point in which beef products becomes unacceptable to consumers leading to this wastage. The consumer purchasing motivators reported in recent work, along with the results from Ramanathan et al. (2022) illustrate the importance of determining the point in which beef reaches an unacceptable state at retail to consumers.

Impact of color on consumer perceptions of ground beef

Several studies have attempted to evaluate the impact of meat discoloration on consumer purchasing intent, but results have been limited and inconsistent. The first study with this objective was Hood and Riordan (1973), which established a linear regression model (proportion of discolored meat in total sales = 45.5 – 0.56*level of metmyoglobin in discolored meat) to predict the likelihood of consumer purchase at different levels of metmyoglobin in beef steak products. The linear regression equations from the current work differed greatly. Hood and Riordan (1973) reported that for every 0.56 increase in the level of metmyoglobin in discolored beef, there was a corresponding decrease in the proportion of sales. Meanwhile, our study found the slope of the model to be much steeper with 1.94 or 1.37 increase in the percentage of metmyoglobin to result in a corresponding decrease of one point in consumer sensory panel liking scores. There are many factors which could cause these differences. Hood and Riordan (1973) did not include the entire range of metmyoglobin discoloration (0 – 100%), and only included samples with 5 – 33% discoloration due to the in-store trial nature of the study. The current work was able to include the entire range of discoloration for consumer consideration, and therefore more precisely identify the points in which consumers found ground beef products to be unacceptable. It is also noteworthy to highlight that Hood and Riordan (1973) was conducted over fifty years ago, and consumer preferences may have shifted over time.

In a more recent study, a preliminary trial utilizing an online survey format, Holman et al. (2016) reported an upper and lower limit to b^* (13.0 and 22.0, respectively) as an accurate predictor of consumer acceptance of beef steaks while not finding a^* to be meaningful. This contrasts the current work, likely due to the small sample size used in the previously mentioned study (N = 10) (Holman et al., 2016). The current work found b^* was among the poorest for predicting consumer sensory panel overall liking scores. Furthermore, a^* was identified to be among the strongest indicators of consumer overall liking.

In a follow-up study, Holman et al. (2017) contradicted their previous study finding a^* to be an important indicator of consumer beef color acceptability with an increased sample size (N = 80) (Holman et al., 2017). Furthermore, Holman et al. (2017) established a threshold a^* value of > 12.5 for consumer acceptability. This supports the findings from the current work, but a true comparison cannot be made between the current work and this study as the authors utilized illuminant D_{65}. The current work utilized illuminant A as recommended by the AMSA Meat Color Guidelines as it allows for better detection of redness differences among samples within a study which is establishing the importance of meat redness as a tool to predict consumer purchasing intent (AMSA, 2012). Although data was collected to calculate the percentage of metmyoglobin present in the samples, models for this variable were not reported by Holman et al. (2017). Although Holman et al. (2016) and Holman et al. (2017) included instructions for respondents to set their computer monitors to select true color and the highest screen resolution, it is unknown if respondents followed the direction set. Therefore, it cannot be guaranteed that survey respondents evaluated the photo samples under the same conditions necessary to ensure that the true color and discoloration of the samples were accurately represented.

Carpenter et al. (2001) evaluated consumer preferences for beef color, and its impact on consumer taste scores. The authors packaged beef steaks and ground beef in differing packaging types to allow for each beef color to be achieved (red, purple, brown) (Carpenter et al., 2001). Consumers evaluated each sample and were asked to identify the product color (red, purple, brown), describe their liking of the color and their likelihood to purchase the product. Following the visual analysis, consumers participated in taste panels in which they consumed three samples labeled the same as the ones they visually appraised. However, the samples consumed were all identical and untreated. This allowed the researchers to understand the impact of visual scores on taste scores. Results from this study complement the current work as consumers preferred the samples identified as "red" (a^* value = 14.7), with a correlation (r = 0.90) between appearance scores and consumer likelihood to purchase. Interestingly, color and packaging did not influence taste scores. Unfortunately, it is challenging to compare these results to the current work as the authors utilized illuminant D_{65} as previously mentioned.

Najar-Villarreal et al. (2021) conducted a meta-analysis of thirteen papers from peer-reviewed journals to establish thresholds for the color life of beef *longissimus lumborum* and *psoas major* steaks. This study presented an upper and lower limit to a^* value of 24.07 and 20.24, respectively, for *longissimus lumborum* steaks, and 23.75 and 20.99, respectively for *psoas major* steaks (Najar-Villarreal et al., 2021). These findings complement the current work, as an a^* value of 24.9 corresponded with a 75% purchasing likelihood and an a^* value of 21.6 corresponded with a 50% purchasing likelihood. However, it is important to note that this study used trained sensory panels to determine product acceptability which is not in accordance with the AMSA Color Guidelines (AMSA, 2012) that state consumer sensory panels are the only suitable way to determine acceptability thresholds. The authors also chose an arbitrary point (3.5) on line scales used for the cited studies to assess acceptability, as opposed to panelists answering a yes/no question regarding acceptability. Furthermore, when considering studies which utilized differing line scales, the authors rescaled them to fit their line scale resulting in a manipulated representation of the data.

Evaluation of objective measurements

Results from our study show that all objective measurements evaluated are predictors of consumer purchasing intent. Previous work from Holman et al. (2017) identified *a** as the "most simple and robust prediction of beef color acceptability." However, the current work indicates many other measures are suitable as well. Calculated percentage metmyoglobin and chroma were similar to *a** value at indicating consumer purchase intent. Our results indicate a multitude of objective measurements could be utilized to predict consumer purchasing intent of ground beef in a retail setting, and allow for the research group to select variables which provide the greatest convenience.

Trained sensory panels are a tool commonly used to describe and quantify color characteristics of meat products (Mancini and Ramanathan, 2020). Seyfert et al. (2007) found that trained sensory panel visual color was correlated with *a** and chroma (r = 0.84 and 0.87, respectively) (Seyfert et al., 2007). The trained sensory panel conducted in Colle et al. (2015) classified *gluteus medius* steak color as "dull" with an *a** value of 27.1. However, the trained sensory panel in the previously mentioned study consisted of only two people (Colle et al., 2015). Finally, Kim et al. (2016) reported *a** values of 14.0 corresponded to trained sensory panel visual color as moderately dark red (Kim et al., 2016). Brewer and Wu (1993) found a negative correlation (r = - 0.52) between calculate percentage metmyoglobin and trained panel acceptability scores. Additionally, they found a correlation (r = 0.54) between *a** and trained panel acceptability scores (Brewer and Wu, 1993). As previously mentioned, utilizing trained panels to assess acceptability is not in accordance with AMSA Guidelines (AMSA, 2012). These studies confirm the findings from the current work.

Impact of retail case layout and discounts

Numerous intentional differences existed between Phase 1 and Phase 2 of the current study pertaining to the layout of the retail cases. In Phase 1, consumers evaluated samples representing the entire range of discoloration from each day of retail display, while Phase 2 consumers evaluated samples from only one day of retail display. This deliberate design allowed consumers in Phase 1 to identify the point at which the color of ground beef progressed from acceptable to unacceptable. Therefore, this study captured and evaluated any differences related to how consumers evaluated the samples when a variety of discolored packages were presented at once, and when the entire retail case was of similar appearance.

The changes in methods between phases did lead to some differences in results, as well. All of the objective measurements in Phase 2 were significant, but the extent to which the variables were able to account for variation in the consumer intent to purchase was much lower than Phase 1. Since Phase 2 consumers were evaluating samples from only one day of display it would be expected that they would give the same responses for each sample evaluated, but consumers did not do so. Hood and Riordan (1973) noted that consumer reactions to discolored meat would likely be less discriminatory if all meat being compared contained similar amounts of discoloration. They predicted discolored meat displayed next to bright red meat, similar to the design of Phase 1, would lead to a heightened negative reaction towards the discolored meat. Although discrepancies among the data gathered from the two phases exists, each provide different perspectives to make decisions with.

The current work did find consumers to be more willing to purchase ground beef later in shelf-life if the product was discounted. Similarly, Feuz et al. (2020) reported consumers would require willingness-to-pay discounts of $6.71 for discolored beef with 25% of its surface area discolored. However, this study did not report their parameters for their assessment of discoloration so it is challenging to make comparisons between the two studies. Additionally, the current work allowed for the meat to discolor naturally, while the previously mentioned study images of the samples using a photo editing software. Finally, Feuz et al. (2020) utilized an online survey format which enabled some inaccuracies to exist due to computer monitor differences as previously mentioned.

Conclusion

Overall, our models showed that each of the objective measures evaluated were predictors of consumer purchasing intent. Objective measurements shown to be the best included *a** value and calculated percent metmyoglobin. The models generated from this study provide the ability to predict consumer willingness to purchase ground beef of varying days of retail display, and provide ground beef producers an indication of potential consumer purchasing behaviors based upon objective measures that are easy to measure.

Table 2.1. Demographic characteristics of consumers who participated in consumer sensory panels

Characteristic	Response	Percentage of consumers Phase 1 (N = 216)	Phase 2 (N = 318)
Gender	Male	48.6	62.9
	Female	51.4	37.1
Household size	1 person	22.7	29.9
	2 people	35.2	34.0
	3 people	14.4	8.2
	4 people	14.8	16.0
	5 people	7.9	5.4
	6 people	2.8	3.8
	Greater than 6 people	2.3	2.8
Marital status	Married	44.9	37.7
	Single	55.1	62.3
Age	Under 20	9.7	7.9
	20-29	43.1	49.4
	30-39	5.1	8.8
	40-49	12.5	10.4
	50-59	13.4	12.0
	Over 60	16.2	11.6
Ethnic origin	African American	0.5	0.9
	Asian	1.9	1.6
	Caucasian/white	89.8	87.4
	Hispanic	4.2	4.4
	Mixed race	1.9	2.2
	Native-American	0.9	0.9
	Other	0.9	2.5
Household income level	Under $25,000	27.8	35.5
	$25,000-$34,999	8.3	6.3
	$35,000-$49,999	9.7	8.2
	$50,000-$74,999	14.4	11.6
	$75,000-$99,999	14.8	11.0
	$100,000-$149,999	13.9	13.8
	$150,000-$199,999	6.0	8.2
	Greater than $199,999	5.1	5.4
Education level	Non-high school graduate	0.0	0.3
	High school graduate	13.9	12.9
	Some college/technical school	34.3	31.8
	College graduate	34.7	32.1
	Post-college graduate	17.1	23.0
Weekly beef consumption	0 times	1.4	1.3
	1 to 3 times	59.7	59.4
	4 to 6 times	25.5	29.3
	7 to 9 times	7.4	5.4
	10 or more times	6.0	4.7
Purchasing motivator	Color	19.4	17.3
	Lean/fat content	44.4	44.0
	Packaging content	1.9	2.2
	Price	26.4	29.6
	Primal	3.7	3.1
	Production practices	2.8	3.1
	Other	2.3	0.6

Table 2.2. Summary statistics for independent variables evaluated in the study for retail ground beef

Measurement	Phase 1			Phase 2		
	Minimum	Maximum	Standard deviation	Minimum	Maximum	Standard deviation
*L**	44.90	56.11	0.08	48.53	58.30	0.08
*a**	11.32	36.92	0.33	14.89	37.90	0.23
*b**	15.94	28.14	0.14	17.67	34.15	0.10
Metmyoglobin	21.22	63.30	0.58	20.32	52.50	0.35
Oxymyoglobin	32.96	75.50	0.58	42.23	76.68	0.35
Chroma	19.55	46.42	0.34	23.32	51.02	0.24
Hue angle	0.63	0.99	< 0.01	0.65	0.89	< 0.01
Trained sensory panel redness score[1]	7.50	99.54	1.28	30.17	98.73	0.74
Trained sensory panel discoloration score[2]	0.00	98.63	1.57	0.00	85.33	0.97
Consumer appearance score[3]	2.98	96.61	1.17	8.91	99.72	0.65

[1]Sensory scores: 0 = extremely dark red, 100 = bright cherry red

[2]Sensory scores: 0 = no visible discoloration, 100 = complete discoloration

[3]Sensory scores: 0 = extremely undesirable, 100 = extremely desirable

Table 2.3. Logistic regression equations for predicting consumer sensory panel purchase intent of retail ground beef for Phase 1 of the study

Measurement	Intercept	Slope	Adjusted R^2	P – value	C – statistic[1]	% Correct[2]
Product sold at full price						
*L**	-50.10	0.99	0.58	< 0.01	0.88	82.2
*a**	-7.13	0.33	0.83	< 0.01	0.95	90.1
*b**	-15.93	0.78	0.82	< 0.01	0.94	89.6
Metmyoglobin[3]	6.81	-0.17	0.81	< 0.01	0.94	89.3
Oxymyoglobin[3]	-9.94	0.17	0.81	< 0.01	0.94	89.4
Chroma[3]	-9.76	0.32	0.84	< 0.01	0.94	90.0
Hue angle[3]	18.11	-23.44	0.79	< 0.01	0.95	88.4
Trained sensory panel redness score[4]	-4.29	0.08	0.82	< 0.01	0.94	90.0
Trained sensory panel discoloration score[5]	2.27	-0.06	0.77	< 0.01	0.94	88.4
Consumer appearance score[6]	-4.98	0.10	0.86	< 0.01	0.95	90.1
Product sold at discounted price						
*L**	-39.58	0.80	0.48	< 0.01	0.86	78.1
*a**	-5.54	0.31	0.79	< 0.01	0.93	88.1
*b**	-14.15	0.75	0.76	< 0.01	0.92	86.0
Metmyoglobin[3]	7.17	-0.15	0.78	< 0.01	0.93	87.6
Oxymyoglobin[3]	-7.51	0.15	0.78	< 0.01	0.93	87.3
Chroma[3]	-8.26	0.32	0.79	< 0.01	0.93	87.9
Hue angle[3]	16.25	-19.45	0.77	< 0.01	0.93	87.6
Trained sensory panel redness score[4]	-2.86	0.07	0.77	< 0.01	0.93	87.1
Trained sensory panel discoloration score[5]	3.20	-0.05	0.76	< 0.01	0.93	88.3
Consumer appearance score[6]	-3.32	0.09	0.83	< 0.01	0.95	88.4

[1]Measure of goodness of fit for binary outcomes in a logistic regression model, ranging from 0 – 1
[2]Percentage of correctly classified events and nonevents by the model
[3]Calculated utilizing the equations presented in the AMSA Meat Color Measurement Guidelines (AMSA, 2012)
[4]Sensory scores: 0 = extremely dark red, 100 = bright cherry red
[5]Sensory scores: 0 = no visible discoloration, 100 = complete discoloration
[6]Sensory scores: 0 = extremely undesirable, 100 = extremely desirable

Table 2.4. Logistic regression equations for predicting consumer sensory panel purchase intent of retail ground beef for Phase 2 of the study

Measurement	Intercept	Slope	Adjusted R^2	P – value	C – statistic[1]	% Correct[2]
Product sold at full price						
*L**	-22.44	0.43	0.28	< 0.01	0.74	70.5
*a**	-4.14	0.20	0.42	< 0.01	0.78	74.6
*b**	-8.69	0.43	0.37	< 0.01	0.76	71.7
Metmyoglobin[3]	4.54	-0.12	0.41	< 0.01	0.78	74.6
Oxymyoglobin[3]	-6.37	0.11	0.40	< 0.01	0.77	74.9
Chroma[3]	-5.65	0.19	0.41	< 0.01	0.78	73.8
Hue angle[3]	12.87	-16.27	0.41	< 0.01	0.78	74.0
Trained sensory panel redness score[4]	-3.03	0.05	0.41	< 0.01	0.79	74.3
Trained sensory panel discoloration score[5]	1.61	-0.04	0.39	< 0.01	0.79	75.1
Consumer appearance score[6]	-4.36	0.09	0.65	< 0.01	0.86	80.4
Product sold at discounted price						
*L**	-21.49	0.43	0.26	< 0.01	0.75	77.3
*a**	-3.89	0.22	0.42	< 0.01	0.80	78.0
*b**	-9.18	0.48	0.37	< 0.01	0.78	78.4
Metmyoglobin[3]	5.42	-0.12	0.40	< 0.01	0.80	78.3
Oxymyoglobin[3]	-5.85	0.12	0.39	< 0.01	0.79	77.7
Chroma[3]	-5.68	0.22	0.42	< 0.01	0.79	77.9
Hue angle[3]	13.81	-16.49	0.39	< 0.01	0.80	78.2
Trained sensory panel redness score[4]	-2.28	0.05	0.39	< 0.01	0.80	79.8
Trained sensory panel discoloration score[5]	2.37	-0.03	0.38	< 0.01	0.81	79.1
Consumer appearance score[6]	-3.49	0.09	0.63	< 0.01	0.87	84.0

[1]Measure of goodness of fit for binary outcomes in a logistic regression model, ranging from 0 – 1and poor model to strong model respectively
[2]Percentage of correctly classified events and nonevents by the model accuracy of a logistic regression model
[3]Calculated utilizing the equations presented in the AMSA Meat Color Measurement Guidelines (AMSA, 2012)
[4]Sensory scores: 0 = extremely dark red, 100 = bright cherry red
[5]Sensory scores: 0 = no visible discoloration, 100 = complete discoloration
[6]Sensory scores: 0 = extremely undesirable, 100 = extremely desirable

Table 2.5. 50, 75, 90, and 95% likeliness thresholds for various objective quality measures for consumer purchase intent of 80% lean ground beef for Phase 1

Measurement	50%	75%	90%	95%
Product sold at full price				
*L**	50.6	51.7	52.8	53.6
*a**	21.6	24.9	28.3	30.5
*b**	20.4	21.8	23.2	24.2
Metmyoglobin[1]	40.1	33.6	27.1	22.7
Oxymyoglobin[1]	58.5	64.9	71.4	75.8
Chroma[1]	30.5	33.9	37.4	39.7
Hue angle[1]	0.77	0.73	0.68	0.65
Trained sensory panel redness score[2]	53.6	67.4	81.1	90.4
Trained sensory panel discoloration score[3]	37.8	19.5	1.1	-
Consumer appearance score[4]	49.8	60.8	71.8	79.3
Product sold at discounted price				
*L**	49.5	50.8	52.2	53.2
*a**	17.9	21.4	25.0	27.4
*b**	18.9	20.3	21.8	22.8
Metmyoglobin[1]	47.8	40.5	33.2	28.2
Oxymyoglobin[1]	50.1	57.4	64.7	69.7
Chroma[1]	25.8	29.2	32.7	35.0
Hue angle[1]	0.84	0.78	0.72	0.68
Trained sensory panel redness score[2]	40.9	56.6	72.3	82.9
Trained sensory panel discoloration score[3]	64.0	42.0	20.1	5.2
Consumer appearance score[4]	36.9	49.1	61.3	69.6

[1]Calculated utilizing the equations presented in the AMSA Meat Color Measurement Guidelines (AMSA, 2012)
[2]Sensory scores: 0 = extremely dark red, 100 = bright cherry red
[3]Sensory scores: 0 = no visible discoloration, 100 = complete discoloration
[4]Sensory scores: 0 = extremely undesirable, 100 = extremely desirable

Table 2.6. 50, 75, 90, and 95% likeliness thresholds for various quality measures for consumer purchase intent of 80% lean ground beef for Phase 2

Measurement	50%	75%	90%	95%
Product sold at full price				
*L**	52.2	54.7	57.3	59.0
*a**	20.7	26.2	31.7	35.4
*b**	20.2	22.8	25.3	27.1
Metmyoglobin[1]	37.8	28.7	19.5	13.3
Oxymyoglobin[1]	57.9	67.9	77.9	84.7
Chroma[1]	29.7	35.5	41.3	45.2
Hue angle[1]	0.79	0.72	0.66	0.61
Trained sensory panel redness score[2]	60.6	82.6	-	-
Trained sensory panel discoloration score[3]	40.3	12.8	-	-
Consumer appearance score[4]	48.4	60.7	72.9	81.2
Product sold at discounted price				
*L**	50.0	52.5	55.1	56.8
*a**	17.7	22.7	27.7	31.1
*b**	19.1	21.4	23.7	25.3
Metmyoglobin[1]	45.2	36.0	26.9	20.6
Oxymyoglobin[1]	48.8	57.9	67.1	73.3
Chroma[1]	25.8	30.8	35.8	39.2
Hue angle[1]	0.84	0.77	0.70	0.66
Trained sensory panel redness score[2]	45.6	67.6	89.6	-
Trained sensory panel discoloration score[3]	79.0	42.4	5.8	-
Consumer appearance score[4]	38.8	51.0	63.2	71.5

[1]Calculated utilizing the equations presented in the AMSA Meat Color Measurement Guidelines (AMSA, 2012)
[2]Sensory scores: 0 = extremely dark red, 100 = bright cherry red
[3]Sensory scores: 0 = no visible discoloration, 100 = complete discoloration
[4]Sensory scores: 0 = extremely undesirable, 100 = extremely desirable

Table 2.7. Pearson correlation coefficients for objective color measurements, trained sensory panel color ratings, and subjective consumer ratings[1] (*N* = 600 samples)

	*L**	*a**	*b**	Metmyoglobin[2]	Oxymyoglobin[2]	Chroma[2]	Hue angle[2]	Trained sensory panel redness score[3]	Trained sensory panel discoloration score[4]
Phase 1									
*a**	0.79								
*b**	0.76	0.98							
Metmyoglobin[2]	-0.75	-0.98	-0.93						
Oxymyoglobin[2]	0.73	0.96	0.93	-0.99					
Chroma[2]	0.78	0.10	0.99	-0.96	0.95				
Hue angle[2]	-0.73	-0.96	-0.91	0.99	-0.98	-0.95			
Trained sensory panel redness score[3]	0.80	0.97	0.95	-0.97	0.96	0.97	-0.95		
Trained sensory panel discoloration score[4]	-0.72	-0.94	-0.88	0.98	-0.98	-0.92	0.98	-0.95	
Consumer appearance score[5]	0.76	0.96	0.93	-0.96	0.96	0.95	-0.95	0.96	-0.94
Phase 2									
*a**	0.80								
*b**	0.72	0.97							
Metmyoglobin[2]	-0.84	-0.96	-0.88						
Oxymyoglobin[2]	0.82	0.93	0.86	-0.98					
Chroma[2]	0.78	0.10	0.99	-0.94	0.92				
Hue angle[2]	-0.83	-0.95	-0.86	0.99	-0.97	-0.93			
Trained sensory panel redness score[3]	0.84	0.90	0.81	-0.93	0.92	0.87	-0.93		
Trained sensory panel discoloration score[4]	-0.80	-0.85	-0.73	0.93	-0.93	-0.81	0.94	-0.93	
Consumer appearance score[5]	0.59	0.71	0.64	-0.74	0.74	0.69	-0.73	0.71	-0.72

[1]All reported correlation coefficients were significant ($P < 0.01$)
[2]Calculated utilizing the equations presented in the AMSA Meat Color Measurement Guidelines (AMSA, 2012)
[3]Sensory scores: 0 = extremely dark red, 100 = bright cherry red
[4]Sensory scores: 0 = no visible discoloration, 100 = complete discoloration
[5]Sensory scores: 0 = extremely undesirable, 100 = extremely desirable

Table 2.8. Linear regression equations for predicting consumer sensory panel overall liking scores for retail ground beef (*N* = 600 samples)

Measurement	Intercept	Slope	Adjusted R^2	*P* – value
Phase 1				
*L**	-494.51	10.76	0.57	< 0.01
*a**	-23.90	3.39	0.92	< 0.01
*b**	-109.22	7.70	0.87	< 0.01
Metmyoglobin[1]	129.05	-1.94	0.92	< 0.01
Oxymyoglobin[1]	-57.52	1.93	0.91	< 0.01
Chroma[1]	-50.43	3.32	0.91	< 0.01
Hue angle[1]	249.86	-252.40	0.89	< 0.01
Trained sensory panel redness score[2]	2.56	0.89	0.93	< 0.01
Trained sensory panel discoloration score[3]	80.84	-0.70	0.88	< 0.01
Phase 2				
*L**	-214.75	5.09	0.35	< 0.01
*a**	8.13	2.04	0.50	< 0.01
*b**	-32.76	4.11	0.42	< 0.01
Metmyoglobin[1]	103.29	-1.37	0.54	< 0.01
Oxymyoglobin[1]	-28.15	1.35	0.54	< 0.01
Chroma[1]	-5.40	1.92	0.48	< 0.01
Hue angle[1]	202.59	-193.54	0.53	< 0.01
Trained sensory panel redness score[2]	13.30	0.62	0.50	< 0.01
Trained sensory panel discoloration score[3]	69.78	-0.48	0.52	< 0.01

[1]Calculated utilizing the equations presented in the AMSA Meat Color Measurement Guidelines (AMSA, 2012)
[2]Sensory scores: 0 = extremely dark red, 100 = bright cherry red
[3]Sensory scores: 0 = no visible discoloration, 100 = complete discoloration

Table 2.9. Summary statistics for independent variables evaluated in the study for retail ground beef

Measurement	Phase 1			Phase 2		
	Minimum	Maximum	Standard deviation	Minimum	Maximum	Standard deviation
*L**	44.90	56.11	0.08	48.53	58.30	0.08
*a**	11.32	36.92	0.33	14.89	37.90	0.23
*b**	15.94	28.14	0.14	17.67	34.15	0.10
Metmyoglobin	21.22	63.30	0.58	20.32	52.50	0.35
Oxymyoglobin	32.96	75.50	0.58	42.23	76.68	0.35
Chroma	19.55	46.42	0.34	23.32	51.02	0.24
Hue angle	0.63	0.99	< 0.01	0.65	0.89	< 0.01
Trained sensory panel redness score[1]	7.50	99.54	1.28	30.17	98.73	0.74
Trained sensory panel discoloration score[2]	0.00	98.63	1.57	0.00	85.33	0.97
Consumer appearance score[3]	2.98	96.61	1.17	8.91	99.72	0.65

[1]Sensory scores: 0 = extremely dark red, 100 = bright cherry red

[2]Sensory scores: 0 = no visible discoloration, 100 = complete discoloration

[3]Sensory scores: 0 = extremely undesirable, 100 = extremely desirable

Figure 2.1. Training anchors used in panel trainings for trained sensory panelists

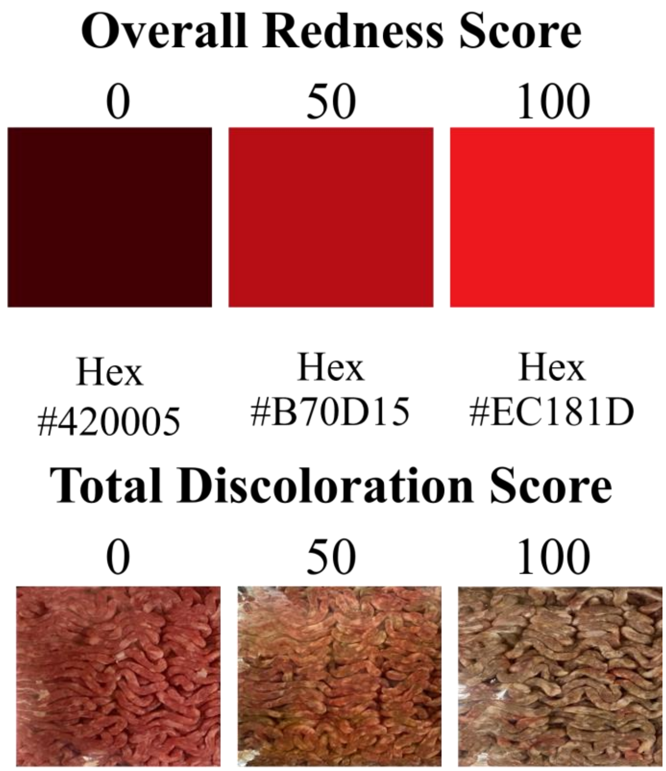


Figure 2.2. Probability of a consumer purchasing an 80% lean ground beef package based on *a** value and pricing - Phase 1

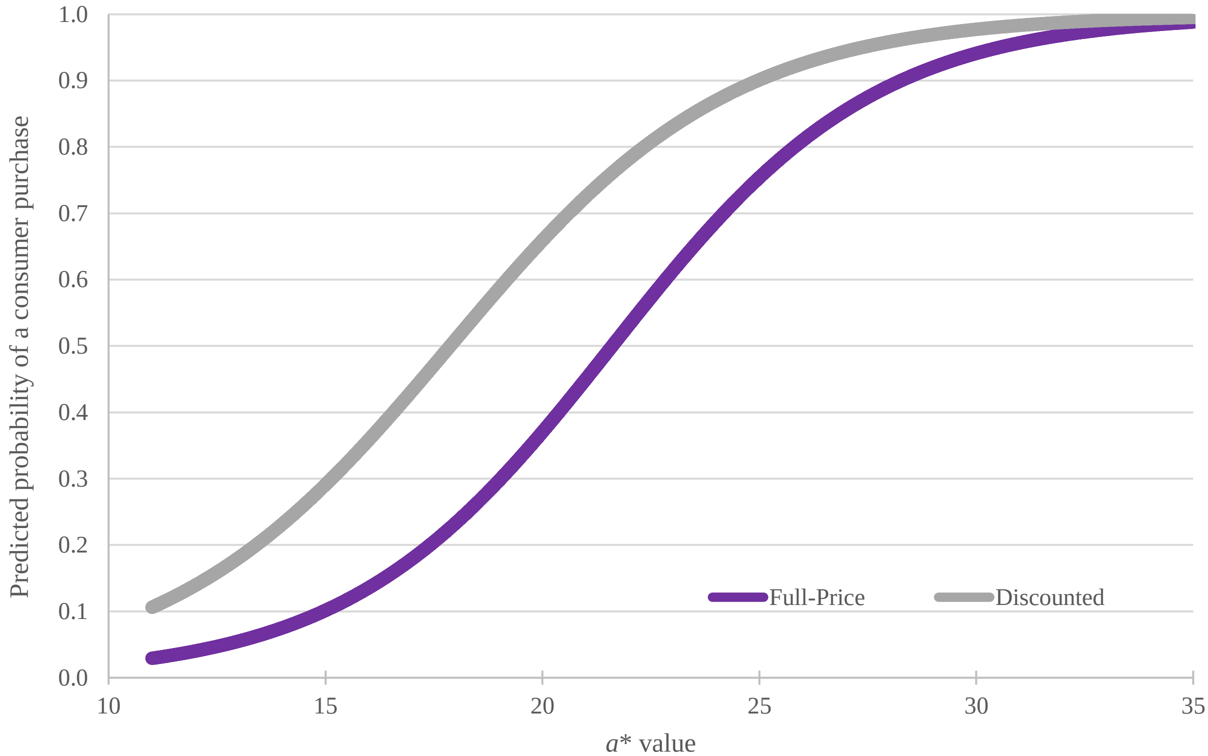


Figure 2.3. Probability of a consumer purchasing an 80% lean ground beef package based on calculated metmyoglobin percentage and pricing - Phase 1

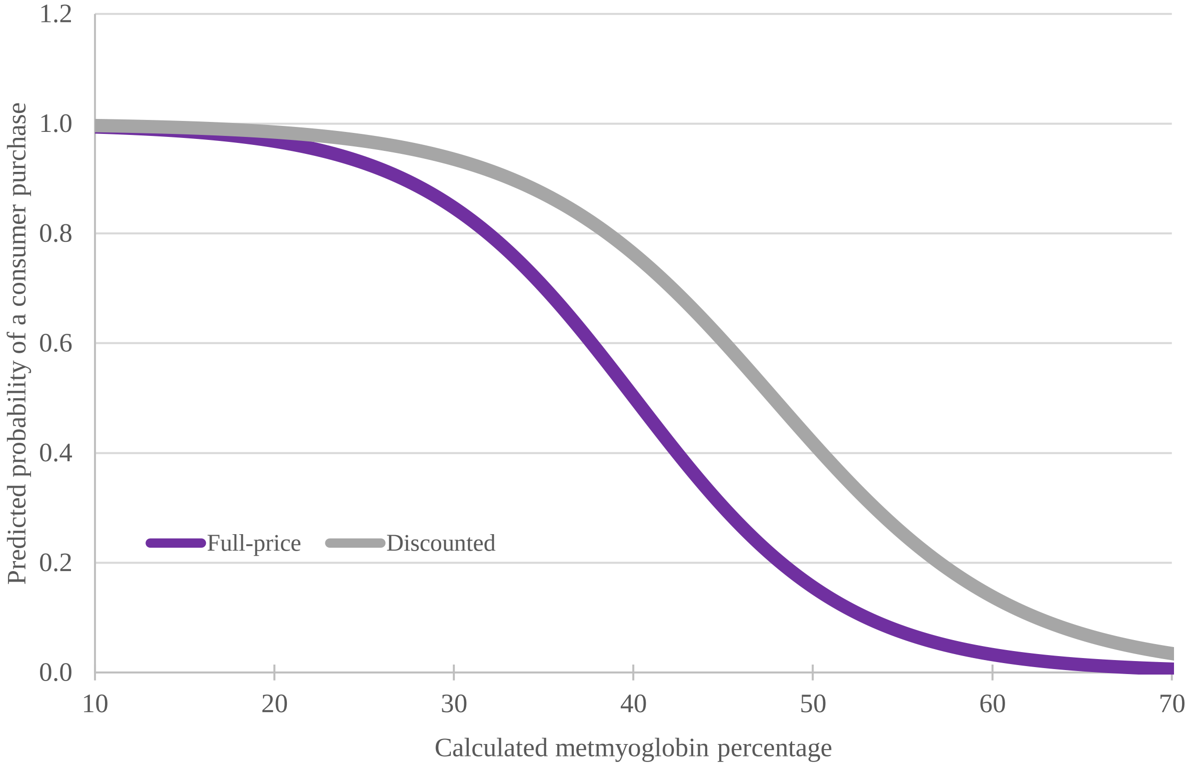


Figure 2.4. Probability of a consumer purchasing an 80% lean ground beef package based on trained sensory panel discoloration score and pricing - Phase 1

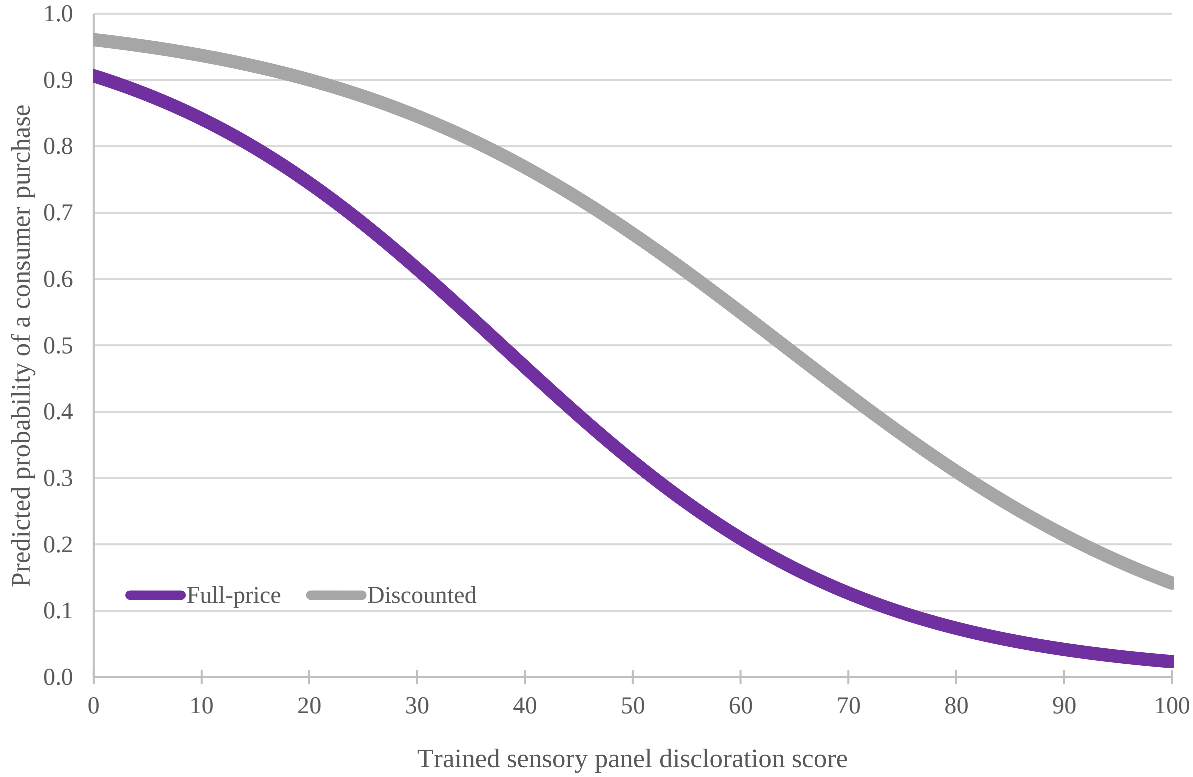


Figure 2.5. Probability of a consumer purchasing an 80% lean ground beef package based on *a** value and pricing - Phase 2

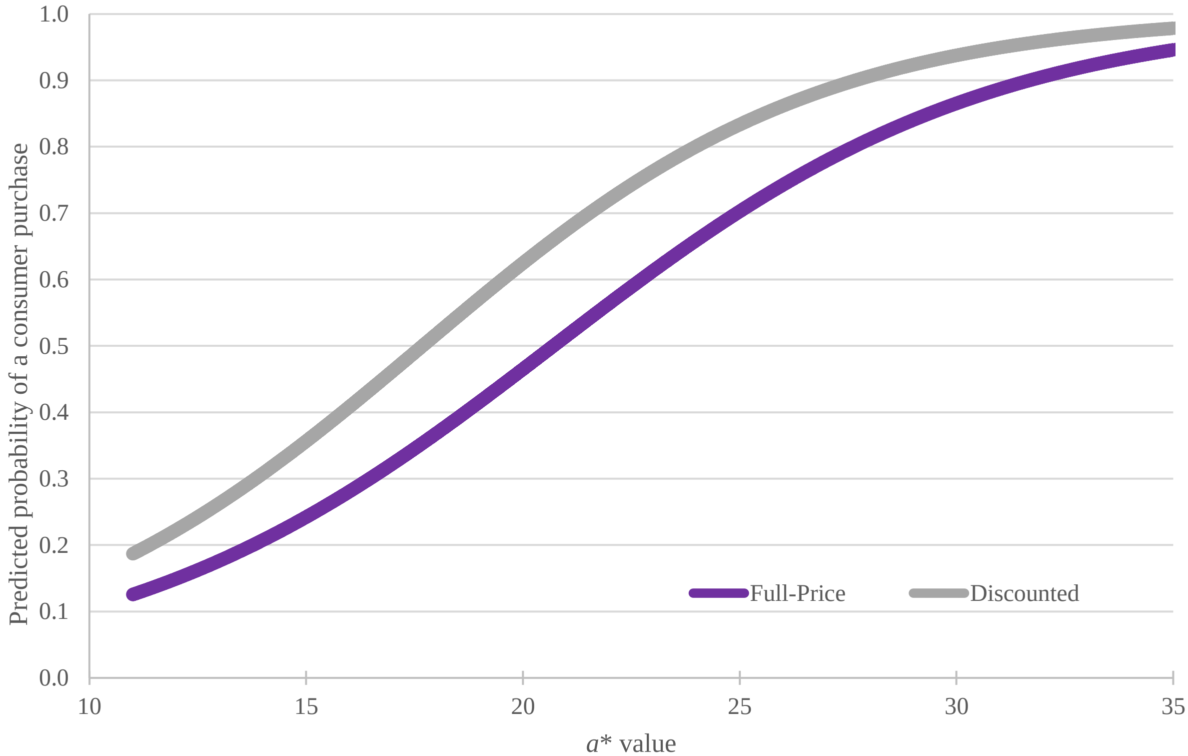


Figure 2.6. Probability of a consumer purchasing an 80% lean ground beef package based on calculated metmyoglobin percentage and pricing - Phase 2

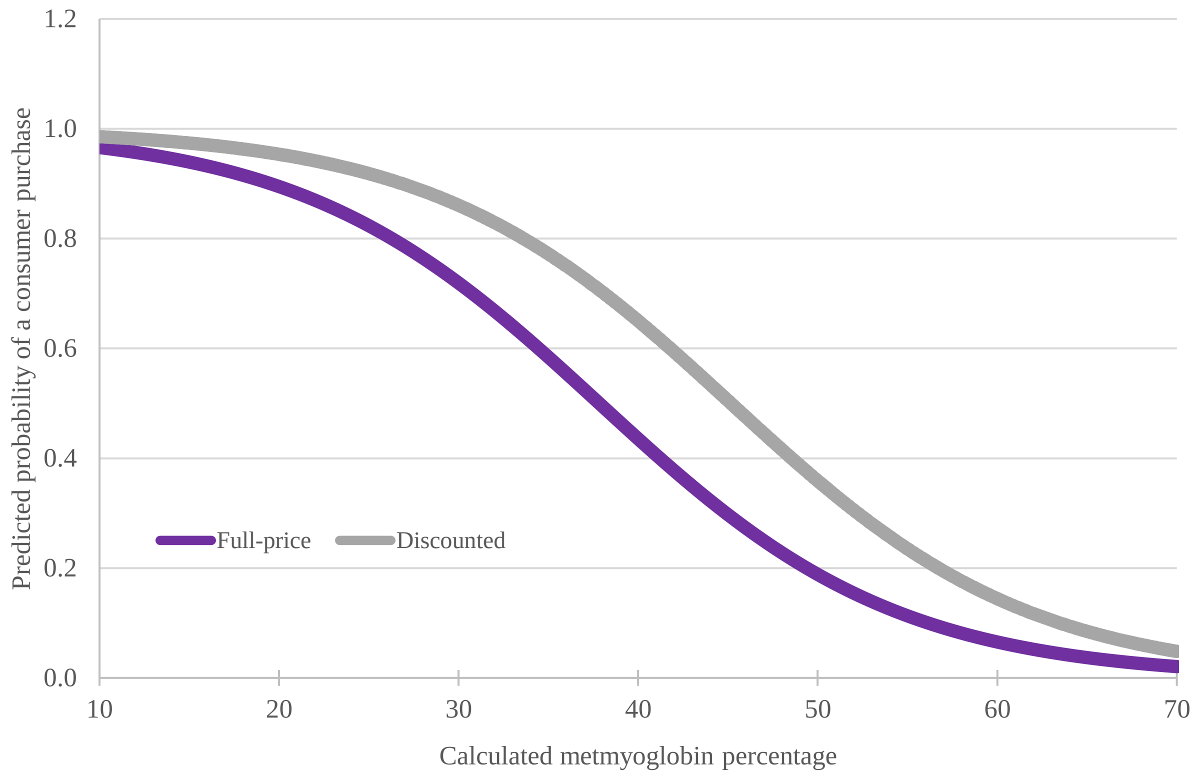


Figure 2.7. Probability of a consumer purchasing an 80% lean ground beef package based on trained sensory panel discoloration score and pricing - Phase 2

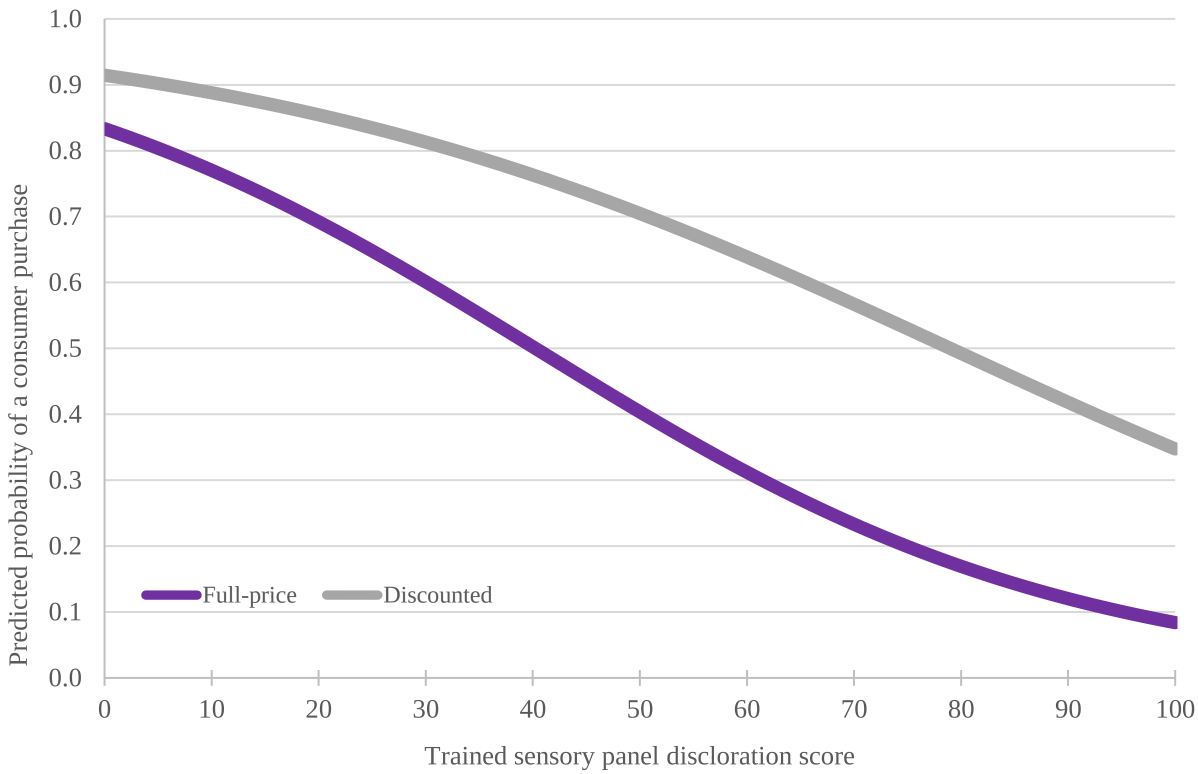


Figure 2.8. Linear regressions for predicting consumer overall appearance rating based on *a** value

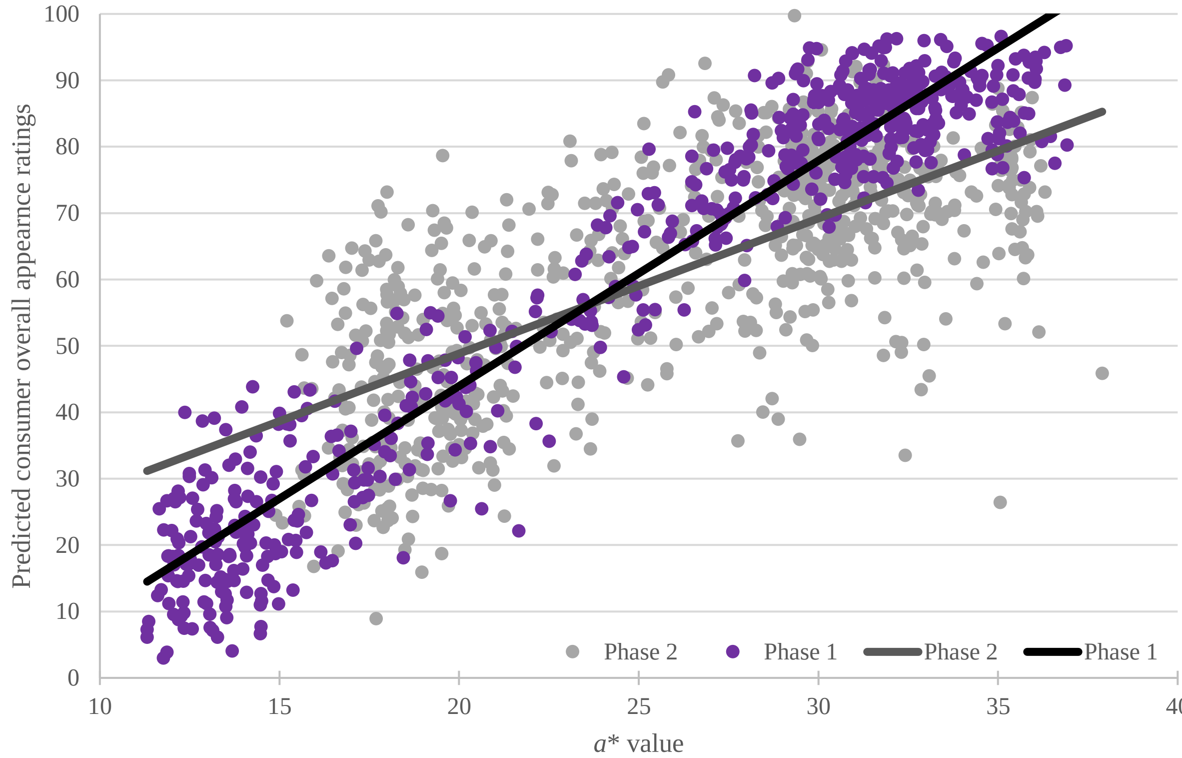


Figure 2.9. Linear regressions for predicting consumer overall appearance rating based on calculated metmyoglobin percentage

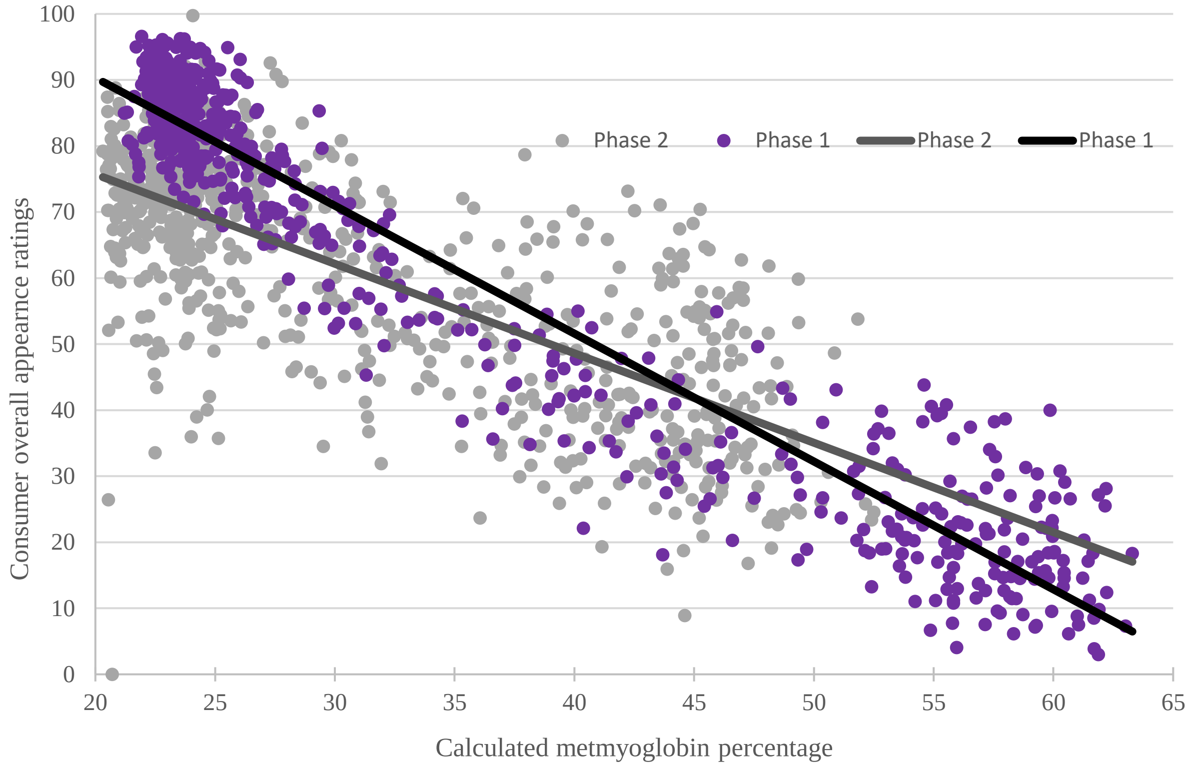
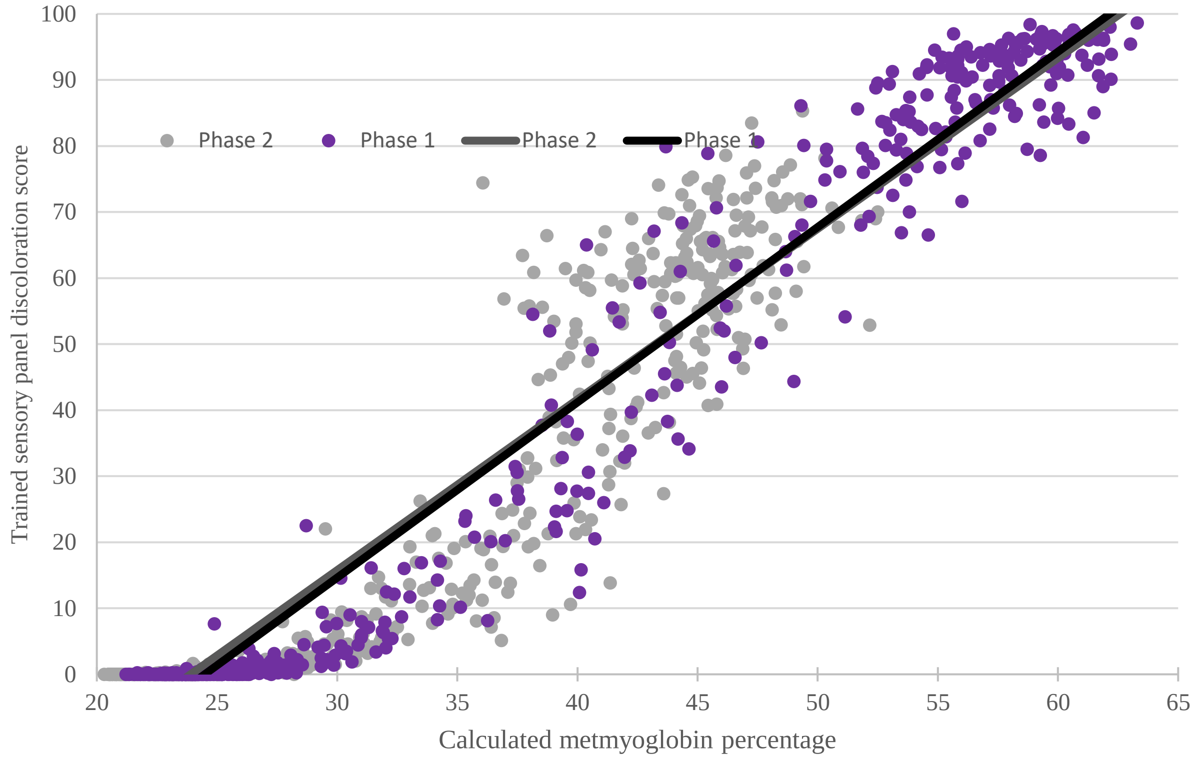


Figure 2.10. Linear regressions for predicting trained sensory discoloration score based on calculated metmyoglobin percentage



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Appendix A - Multivariate logistic regression equations

Table A.1. Multivariate logistic regression equations for predicting consumer sensory panel purchase intent of retail ground beef for Phase 1 of the study

Measurement	Estimate	Adjusted R^2	*P* – value	*C* – statistic[1]	% Correct[2]
Product sold at full price					
Intercept	-8.89	0.84	< 0.01	0.94	90.1
Chroma[3]	0.27	0.84	< 0.01	0.94	90.1
Trained sensory panel redness score[4]	0.01	0.84	< 0.01	0.94	90.1
Product sold at discounted price					
Intercept	-4.96	0.80	< 0.01	0.93	87.8
*a**	0.24	0.80	< 0.01	0.93	87.8
Trained sensory panel redness score[4]	0.02	0.80	< 0.01	0.93	87.8

[1]Measure of goodness of fit for binary outcomes in a logistic regression model, ranging from 0 – 1
[2]Percentage of correctly classified events and nonevents by the model
[3]Calculated utilizing the equations presented in the AMSA Meat Color Measurement Guidelines (AMSA, 2012)
[4]Sensory scores: 0 = extremely dark red, 100 = bright cherry red

Table A.2. Multivariate logistic regression equations for predicting consumer sensory panel purchase intent of retail ground beef for Phase 2 of the study

Measurement	Estimate	Adjusted R^2	*P* – value	*C* – statistic[1]	% Correct[2]
Product sold at full price					
Intercept	-14.55	0.46	0.19	0.80	75.5
*L**	-0.18	0.46	0.19	0.80	75.5
*b**	-1.42	0.46	0.19	0.80	75.5
Chroma[3]	1.01	0.46	0.19	0.80	75.5
Hue angle[3]	30.32	0.46	0.19	0.80	75.5
Trained sensory panel redness score[4]	0.01	0.46	0.19	0.80	75.5
Trained sensory panel discoloration score[5]	-0.03	0.46	0.19	0.80	75.5
Product sold at discounted price					
Intercept	-26.95	0.46	0.29	0.81	80.1
*L**	-0.16	0.46	0.29	0.81	80.1
*a**	1.68	0.46	0.29	0.81	80.1
Chroma[3]	-1.07	0.46	0.29	0.81	80.1
Hue angle[3]	42.16	0.46	0.29	0.81	80.1
Trained sensory panel redness score[4]	0.01	0.46	0.29	0.81	80.1
Trained sensory panel discoloration score[5]	-0.03	0.46	0.29	0.81	80.1

[1]Measure of goodness of fit for binary outcomes in a logistic regression model, ranging from 0 – 1and poor model to strong model respectively

[2]Percentage of correctly classified events and nonevents by the model

[3]Calculated utilizing the equations presented in the AMSA Meat Color Measurement Guidelines (AMSA, 2012)

[4]Sensory scores: 0 = extremely dark red, 100 = bright cherry red

[5]Sensory scores: 0 = no visible discoloration, 100 = complete discoloration

Table A.3. Multivariate linear regression equations for predicting consumer sensory panel overall liking scores for retail ground beef for Phase 1 of the study

Measurement	Estimate	Adjusted R^2	P – value
Intercept*	-8.17	0.94	< 0.01
*a**	1.24	0.94	< 0.01
Oxymyoglobin[1]	0.32	0.94	< 0.01
Trained sensory panel redness score[2]	0.32	0.94	< 0.01
Trained sensory panel discoloration score[3]	-0.09	0.94	< 0.01

[1]Calculated utilizing the equations presented in the AMSA Meat Color Measurement Guidelines (AMSA, 2012)

[2]Sensory scores: 0 = extremely dark red, 100 = bright cherry red

[3]Sensory scores: 0 = no visible discoloration, 100 = complete discoloration

Appendix B - Sensory panel evaluation forms

Informed Consent Statement

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

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

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

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

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

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

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

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

_______________________________   _______________________________

Printed name   Signature

Please sign and return one copy. The second copy is for your records.

Consumer Sensory Panel Ballot

KANSAS STATE
UNIVERSITY

Color Consumer Panel 1

Please tell us a little about yourself.

Panelist Initials

Are you color blind?

- Yes
- No
- Click to write Choice 3

Gender

- Male
- Female

Age

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

Ethnic Origin

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

Marital Status

- Single
- Married

Household Size

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

Annual Household Income

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

Highest Level of Education Completed

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

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

Color

Lean/Fat Content

Packaging Content

Price

Primal (ex: ground chuck or ground round)

Production Practices (ex. grass-fed, natural, USDA Organic)

Other

How many times a week do you consume ground beef?

0 3 6 9 12 15 18 21

None

KANSAS STATE UNIVERSITY

Sample Number

2426

Overall Appearance

Extremely Undesirable	Neither Desirable or Undesirable	Extremely Desirable
0	50	100

Appearance

Would you purchase the sample at retail?

Yes

No

Trained Sensory Panel Ballot

KANSAS STATE
UNIVERSITY

Case #1 - November 16, 2021

Participant Initials

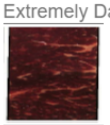
Date(MM/DD)

Time

Sample ID

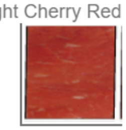
Overall Redness Score

Extremely Dark Red



0

Bright Cherry Red



100

Redness ☐ NA

Total Discoloration Score (% Metmyogolobin)

No Visible Discoloration 0

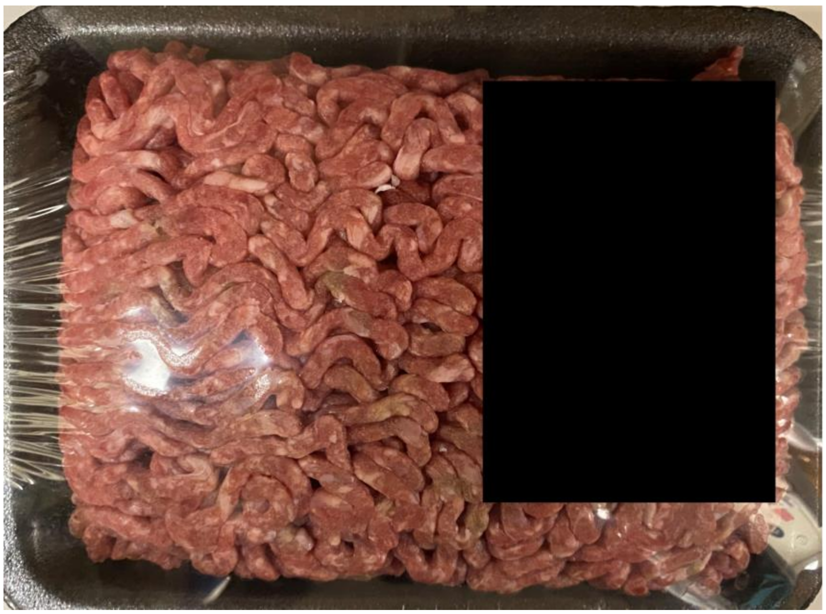
50% Discoloration 50

Complete Discoloration 100

Discoloration ☐ NA

Appendix C - Sample photos with corresponding consumer likelihood to purchase thresholds

a* value (full-priced) – Phase 1



50% likelihood to purchase

*a**: 21.6

75% likelihood to purchase

*a**: 24.9

90% likelihood to purchase

*a**: 28.3

95% likelihood to purchase

*a**: 30.5

*a** value (discounted) – Phase 1

50% likelihood to purchase

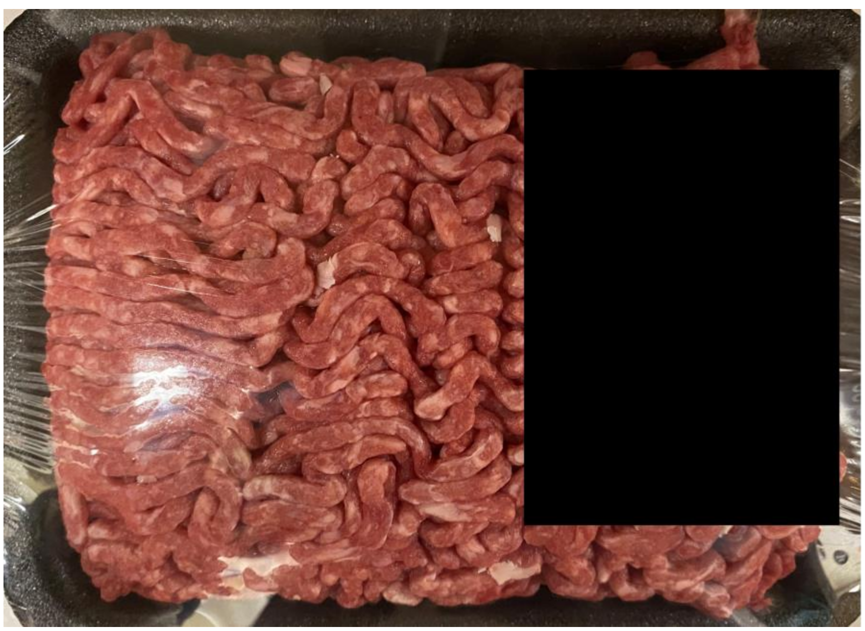
*a**: 17.9

75% likelihood to purchase

*a**: 21.4

90% likelihood to purchase

*a**: 25.0



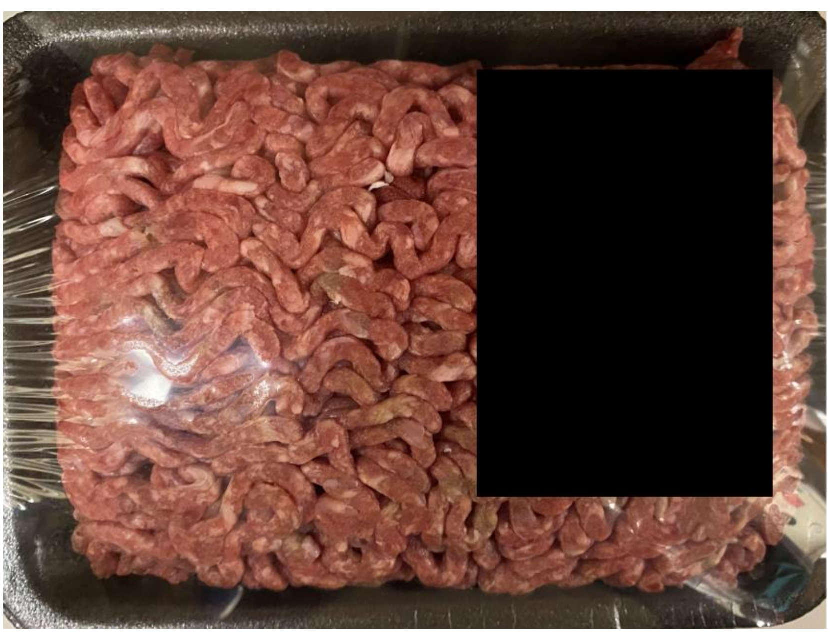
95% likelihood to purchase

*a**: 27.4

Calculated metmyoglobin percentage (full-priced) – Phase 1

50% likelihood to purchase

Calculated metmyoglobin percentage: 40.1



75% likelihood to purchase

Calculated metmyoglobin percentage: 33.6

90% likelihood to purchase

Calculated metmyoglobin percentage: 27.1

95% likelihood to purchase

Calculated metmyoglobin percentage: 22.7

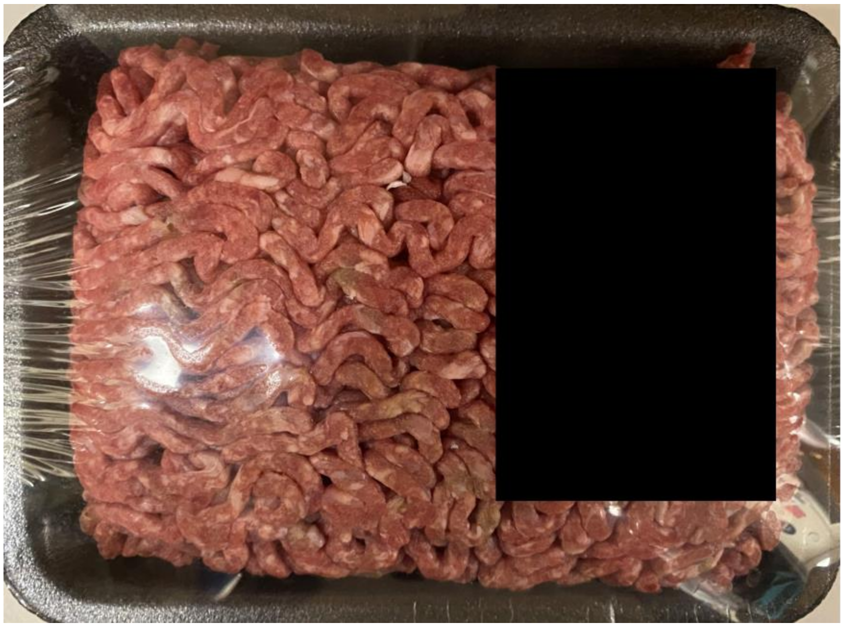
Calculated metmyoglobin percentage (discounted) – Phase 1

50% likelihood to purchase

Calculated metmyoglobin percentage: 47.8

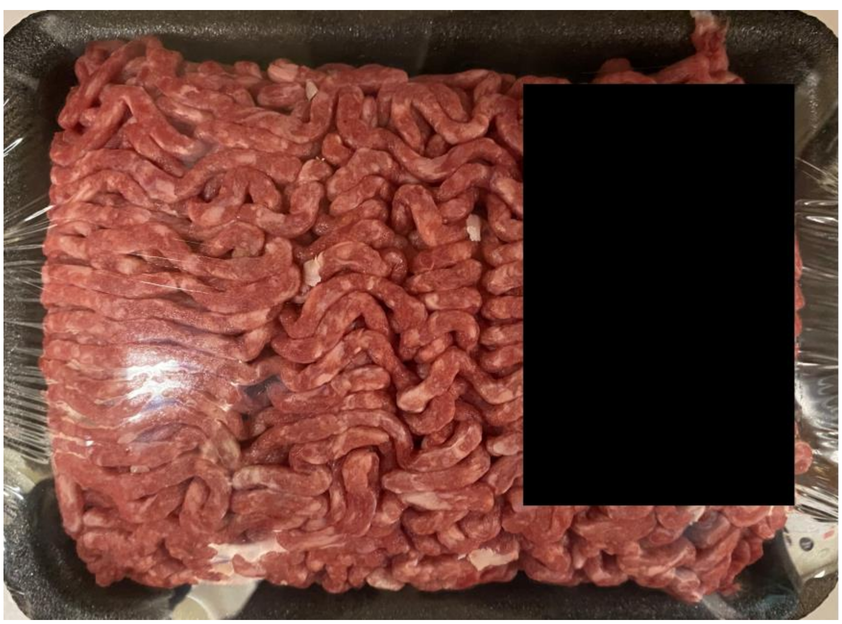
75% likelihood to purchase

Calculated metmyoglobin percentage: 40.5



90% likelihood to purchase

Calculated metmyoglobin percentage: 33.2



95% likelihood to purchase

Calculated metmyoglobin percentage: 28.2

*a** value (full-priced) – Phase 2

50% likelihood to purchase

*a** value: 20.7

75% likelihood to purchase

*a** value: 26.2

90% likelihood to purchase

*a** value: 31.7

95% likelihood to purchase

*a** value: 35.4

*a** value (discounted) – Phase 2

50% likelihood to purchase

*a** value: 17.7

75% likelihood to purchase

*a** value: 22.7

90% likelihood to purchase

*a** value: 27.7

95% likelihood to purchase

*a** value: 31.1

Calculated metmyoglobin percentage (full-priced) – Phase 2

50% likelihood to purchase

Calculated metmyoglobin percentage: 37.8

75% likelihood to purchase

Calculated metmyoglobin percentage: 28.7

90% likelihood to purchase

Calculated metmyoglobin percentage: 19.5

95% likelihood to purchase

Calculated metmyoglobin percentage: 13.3

Calculated metmyoglobin percentage (discounted) – Phase 2

50% likelihood to purchase

Calculated metmyoglobin percentage: 45.2

75% likelihood to purchase

Calculated metmyoglobin percentage: 36.0

90% likelihood to purchase

Calculated metmyoglobin percentage: 26.9

95% likelihood to purchase

Calculated metmyoglobin percentage: 20.6

Appendix D - Product Characteristics

Figure D.1. Average pH results from both phases of the study

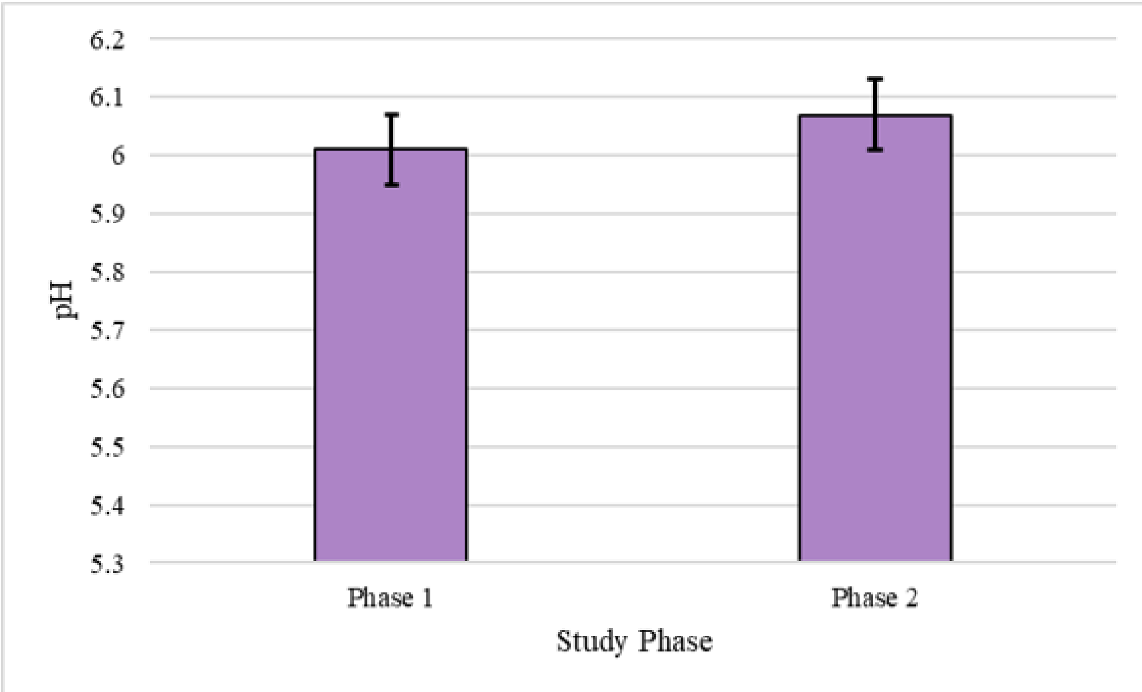


Figure D.2. Average aerobic plate counts from both phases of the study