Meat and Muscle Biology™

Combined Effects of Storage Temperature, Storage Time, Display Temperature, and Display Time on Ground Beef Color and Economic Losses

Richard A. Mancini[1]*, Melvin C. Hunt[2], Ryan Feuz[3], Ranjith Ramanathan[4], Don H. Kropf[2], Dallas E. Johnson[5], and Kathy A. Hachmeister[2]

[1]Department of Animal Science, University of Connecticut, Storrs, CT 06269, USA
[2]Department of Animal Sciences and Industry, Kansas State University, Manhattan, KS 66506, USA
[3]Department of Applied Economics, Utah State University, Logan, UT 84322, USA
[4]Department of Animal and Food Sciences, Oklahoma State University, Stillwater, OK 74078, USA
[5]Department of Statistics, Kansas State University, Manhattan, KS 66506, USA
*Corresponding author. Email: Richard.mancini@uconn.edu (Richard A. Mancini)

Abstract: Although various studies have evaluated individual factors that influence meat discoloration, limited research has assessed the effects of multiple ground beef cold chain parameters on color. This study evaluated the combined effects of storage temperature, storage time, display temperature, and display time on ground beef color and economic losses due to poor cold chain management. Fresh ground beef chubs (81% lean) were randomly assigned to combinations of 3 storage temperatures (0, 4.5, and 8.9°C), 4 storage times (0, 4, 8, and 12 d), and 3 display temperatures (0, 4.5, and 8.9°C). Visual color was measured every 24 h and a^* was measured every 6 h during the 48 h display period. Storage at 0°C minimized discoloration during display compared with storage at 4.5 and 8.9°C. Longer storage times at 0°C did not increase discoloration, whereas prolonged storage at 4.5 and 8.9°C decreased color stability during display. Economic analysis suggested that expected sales loss due to discoloration is positively correlated with storage days, storage temperature, and display temperature. Ground beef stored and displayed at 0°C is shown to minimize expected sales loss with an average loss of $0.29/kg or 2.8% of average retail value. Our results suggest that the total losses to U.S. retailers from cold chain mismanagement are expected to range from $630 million to $1.33 billion when compared with storage and display at 0°C. Simultaneous control of all cold chain parameters is essential for maximizing ground beef color and shelf life.

Key words: ground beef color, cold chain management, discoloration, myoglobin
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Introduction

Meat purchasing decisions are influenced by color more than any other quality factor because consumers associate surface discoloration with unwholesomeness (Kropf, 1984; Mancini et al., 2022; Thies et al., 2024). Thus, a change in meat color from bright red oxymyoglobin to brown metmyoglobin results in consumer rejection, reduced shelf life, and decreased profit. More specifically, consumer likeness threshold decreases when the metmyoglobin level reaches 13 to 22% (Lybarger et al., 2023). A recent study noted that the U.S. beef industry loses $3.73 billion annually due to discoloration (Ramanathan et al., 2022). Previous work has demonstrated that the average consumer would require substantial discounts for both discolored beef steaks and ground beef, with the level of discount often exceeding the market value of the product (Feuz et al., 2020). Thus, factors that decrease discoloration will effectively maximize color life and profitability of the meat industry.

Researchers have demonstrated that meat color deteriorates with time postmortem (English et al., 2016; Prommachart et al., 2020; Wang et al., 2021;

Smith et al., 2024). Therefore, the most critical factor for maintaining attractive meat retail color is temperature (Greer and Jeremiah, 1981; Martin et al., 2013). Low temperatures allow meat to maintain a bright red color by increasing oxygen penetration and the depth of surface oxymyoglobin, slowing enzyme activity, and reducing respiratory activity (Ledward et al., 1977; Renerre, 1990; Mancini and Ramanathan, 2014).

Although discoloration is inevitable, it can be slowed by applying the concepts of cold chain management. The cold chain is a set of parameters (each having target condition and optimum input values) that must be applied to meat in order to effectively maintain shelf life and wholesomeness. The U.S. Food and Drug Administration food code recommends that refrigerated food should be stored at or below 4.0°C (U.S. Food and Drug Administration, 2022); however, the prevalence of incomplete cold chain management has been reported. For example, 16% of cases had temperatures between 5 and 10°C (EcoSure, 2007), and a recent report suggests that the average retail case temperature ranges between 0 and 5.5°C (Maia Research Analysis, 2024).

Since a lack of cold chain management commonly occurs, this project was initiated to assess the consequences of failing to use optimum inputs in the cold chain of ground beef. Previous research typically has accounted for the role of individual areas of the cold chain in meat discoloration. Therefore, the objectives of this project were to evaluate both the storage and display portions of the cold chain by assessing the combined effects of storage temperature, storage time, display temperature, and display time on both ground beef color and expected economic consequences. Although the effects of temperature and time on meat color are known, the evaluation of both discoloration and economic losses resulting from multiple ground beef cold chain parameters (storage and display temperatures and times) during simulated "real world" conditions is a unique aspect of this research. In addition, color was measured every 6 h for 48 h during display in the current project (most published studies reported 24-h intervals).

Materials and Methods

Ground beef processing

Ground beef chubs ($n = 108$, 4.55 kg, coarse ground with a 1.27-cm grinding plate, 81% lean) were obtained from a local purveyor on the day of grinding. Chubs were shipped to the Kansas State University Meat Lab at 0°C, verified by both in-box recorders during transit and the temperature at the geometric center of each chub upon arrival (measured using a thermocouple, Model 450-ATT, Omega Engineering Inc., Stamford, CT, USA). All chubs were stored for 6 d at 0°C before being randomly assigned to 1 of 12 storage temperature and time combinations (Table 1). The 6-d storage period represents an approximate time that meat products are stored in a cold room prior to fine grinding and packaging (Rogers et al., 2014).

Grinding and packaging

In the current study, all vacuum-packaged chubs (opaque packaging material) were intact, and no discoloration was noticed. Hence, all chubs were utilized in the study. Each chub was mixed by hand and ground once through a 0.32-cm plate (Model 4732, Hobart Mfg. Co., Troy, OH, USA). After grinding, approximately 454 g of ground beef was placed on a 2S Styrofoam® tray (Tenneco, Lake Forest, IL, USA) with a Dry-Loc pad (AC-50, Cryovac, Duncan, SC, USA) and overwrapped with polyvinyl chloride (PVC) film (23,250 cc/m^2/24 h at 23°C and 0% relative humidity, Borden Packaging and Industrial Products, North Andover, MA, USA). In addition, approximately

Table 1. Storage temperature, storage time, and display temperature treatment combinations assigned to ground beef

Chub pre-treatment storage time (d) at 0°C	Chub storage temperature (°C)	Chub storage time (d) at assigned temperature	Days post coarse grind (d)	Package retail display temperature (°C)
6	0	0	6	All rows were displayed at 0, 4.5, and 8.9°C for 48 h.
6	4.5	0	6	
6	8.9	0	6	
6	0	4	10	
6	4.5	4	10	
6	8.9	4	10	
6	0	8	14	
6	4.5	8	14	
6	8.9	8	14	
6	0	12	18	
6	4.5	12	18	
6	8.9	12	18	

108 chubs were used.

150 g was collected and placed in a Whirl-Pak bag® (Nasco, Modesto, CA, USA) for proximate analyses.

Display

After grinding, one package per chub was assigned to display at each of 3 temperatures (Table 1). Ground beef was displayed continuously for 48 h at either 0, 4.5, or 8.9°C in one of three 2.44-m wide open-top display cases (Model DMF8, Tyler Refrigeration Corporation, Niles, MI, USA) under 1614 lux of Ultra-Lume fluorescent light (3000K, Philips Lighting, Salina, KS, USA). The 0°C case had 2 defrost cycles/d, the 4.5°C case had 1 defrost cycle/d, and the 8.9°C case had no defrost cycles.

Instrumental color

Ground beef surface color was analyzed every 6 h throughout the 48 h display period using a HunterLab MiniScan EZ spectrophotometer (Hunter Associates Laboratory Inc., Reston, VA, USA) with a 3.18-cm diameter aperture, Illuminant A, and a 10° observer. Initial color (0 h) was evaluated 30 min after the meat was ground and packaged. Instrumental color was characterized using a^* value (King et al., 2023). Three separate areas of each package were scanned, and the average was calculated for statistical analysis. In the current study, we recorded L^*, a^*, b^*, and reflectance data, and calculated hue, chroma, and metmyoglobin levels; however, due to the complexity of interactions, we reported only a^* values. In addition, research in our laboratory and a recent study also noted that a^* values and other instrumental parameters such as hue, chroma, and metmyoglobin are highly correlated and a^* values alone can be used to explain redness loss (Mancini et al., 2022; Lybarger et al., 2023).

Visual color

Visual color was appraised at 0, 24, and 48 h of display by 7 trained panelists (King et al. 2023), all of whom passed the Farnsworth-Munsell 100-Hue Test (Macbeth, Newburgh, NY, USA). A 5-point color scale of 1 = very bright cherry red, 2 = bright cherry red, 3 = slightly dark red to tannish red, 4 = moderately grayish/tan to brown, and 5 = tan to brown was used in increments of 0.5.

Proximate analysis and pH

Representative samples from all chubs after fine grinding were used for proximate and pH analysis. Samples were analyzed for moisture (CEM, Model #910800, Matthews, NC, USA), fat (CEM), and protein (Leco, Model #602-600, St. Joseph, MI, USA). pH was determined by homogenizing 10 g of tissue with 100 ml of deionized-distilled water for 30 s with a Stomacher Lab Blender (Seward Stomacher 400 Lab Blender, Seward Medical, UK). Following homogenization, a combination electrode attached to an Accumet pH meter (Accumet standard, Fischer Scientific, Pittsburgh, PA, USA) was used to measure pH.

Economic consequences resulting from poor cold chain management

The sales loss of the ith treatment was calculated as:

$$Sales\,Loss_i = SP_i - RP$$

$$RP\ if\ ST < Hours\_Dis_i;\ when\ SP_i = RP\,x\,Dis\ if\ Hours\_UN_i > ST > Hours\_Dis_i;\ 0\ if\ ST > Hours\_UN_i \tag{1}$$

where RP is the average retail price; SP_i is the sales price of the ith treatment; $Hours\_Dis_i$ and $Hours\_UN_i$ are the number of hours before ground beef for the ith treatment must be discounted or is deemed unacceptable, respectively, based on visual color ratings (Figure 1 and Table 3); Dis is the discount percentage; and ST is the shelf time or the assumed time (hours) required on average for a retailer to successfully market a package of ground beef after placing it in the retail display case. To analyze the expected sales loss for each treatment while accounting for risk, RP, ST, and Dis were stochastically determined, and $Sales\ Loss_i$ was simulated across 10,000 iterations using Palisades @Risk Decision Tools Suite 7.6 (2019). The distribution for the retail price (RP) variable was fit to the past 10 y of monthly retail ground beef price data (U.S. Bureau of Labor Statistics, 2022a) adjusted for inflation using the Consumer Price Index as a deflator (U.S. Bureau of Labor Statistics, 2022b). The triangle distribution was selected according to "best fit" using the minimization of the Akaike information criterion (AIC) with a minimum of \$8.29/kg, a maximum of \$12.21/kg, and a most likely value of \$9.77/kg. The Dis variable also relied on a triangle distribution with a minimum of 5%, a maximum of 50%, and a most likely value of 16%. Discounts of this average size were taken from Ramanathan et al. (2022) and adjusted for inflation. A triangle distribution with a minimum value of 0 h, a maximum of 72 h, and a most likely value of 48 h was used for the ST variable. In addition to expected sales loss, the expected percent sales loss was also simulated for each treatment as $(RP-SP_i)/RP$.

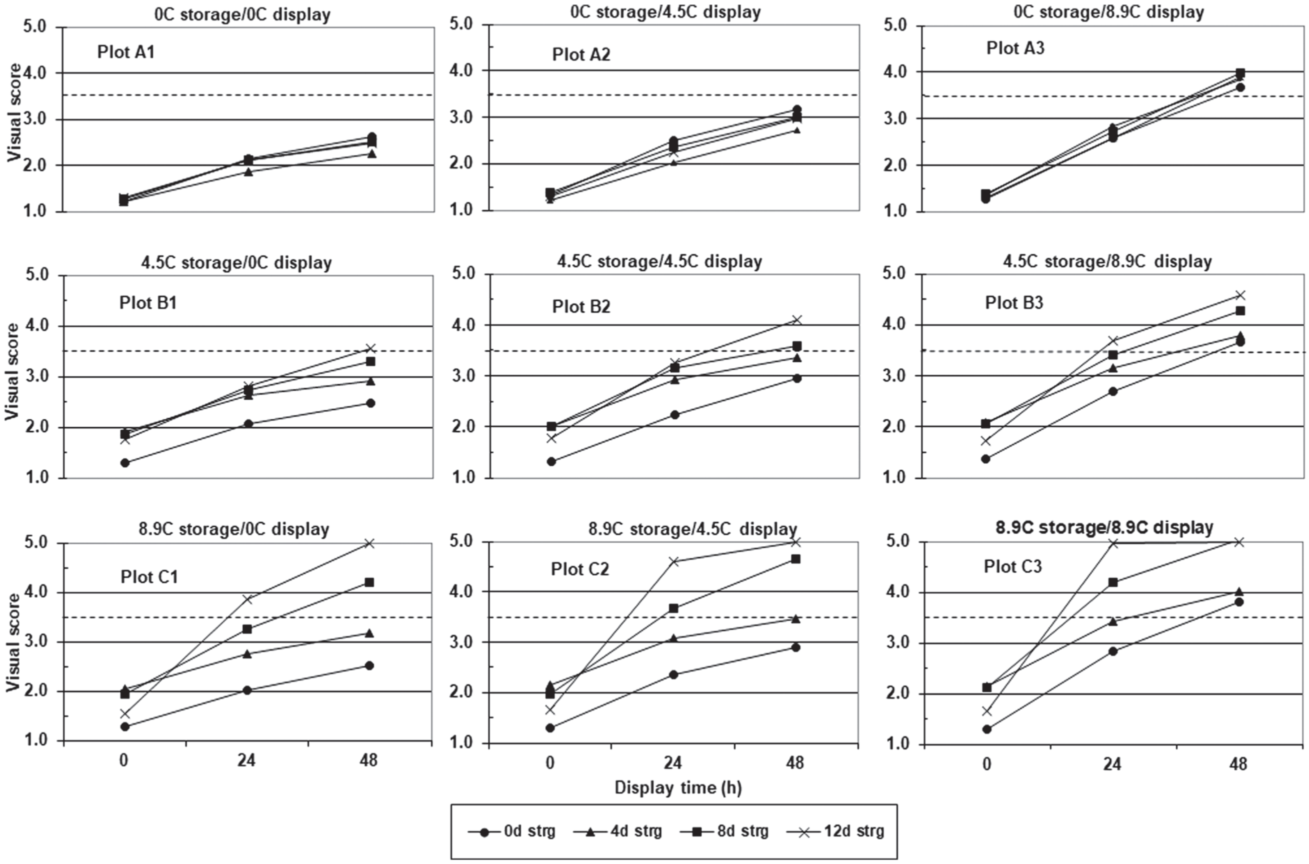

Figure 1. Combined effects of storage temperature (°C), storage time (strg, d), display temperature (°C), and display time (h) on visual color[a] least-squares means. Standard error of differences for each treatment: storage temperature = 0.15 and time = 0.14; display temperature = 0.12 and time = 0.12. [a]Visual color: 1 = very bright cherry red; 3 = slightly dark to tannish red; 3.5 = unacceptable color; 5 = tan to brown.

Statistical analysis

The experiment consisted of 4 fixed effects (3 storage temperatures, 4 storage times, 3 display temperatures, and display time [3 for visual color and 9 for a^*]) and their interactions. The overall experiment consisted of 324 PVC overwrapped packages of fine ground product resulting from 3 replicated trials. Each trial used 36 course ground chubs ($n = 108$ total chubs for all 3 trials). For the overall experiment, $n = 36$ chubs were assigned to each storage temperature, $n = 27$ chubs were assigned to each storage time, and $n = 9$ chubs were assigned to each storage temperature × storage time treatment combination.

The experimental design for color variables was a split plot with repeated measures. In the whole plot, coarse ground chubs served as experimental units assigned to storage treatments in a completely randomized design with a factorial treatment structure (3 temperatures × 4 times). In the subplot, PVC overwrapped packages from each chub were subplot units assigned to 1 of 3 display temperatures. The color of these packages was repeatedly measured during display.

Main effects and all possible interactions for Type 3 Tests of fixed effects were analyzed using the Mixed procedure of the Statistical Analysis System (SAS; 9.4). Random effects included the whole plot error associated with chubs (Error A) and the subplot error associated with packages (Error B). Denominator degrees of freedom (DDFM) were adjusted using DDFM = SATTERTH. The Repeated option was used to assess covariance structure among repeated measures associated with display time, and AIC was used to determine the most appropriate structure. The random effect associated with display time was accounted for by the repeated statement and the type of covariance structure. Main effects and interactions were considered significant at $P < 0.05$. Least significant differences (LSD) were used to separate least-squares means generated from each main effect or interaction.

Results

Ground beef chubs had a pH of 5.7 ± 0.03 (standard error included along with each parameter). Proximate analysis indicated the percent moisture was 63 ± 1.2, percent fat was 19 ± 0.8, and percent protein was 17 ± 0.9. Therefore, the desired lean level was achieved, and ground beef chubs were of normal pH (5.7).

Interaction of storage and display variables

The highest-order interaction was reported in this study. Analysis of variance (data not shown) showed a 4-way interaction of storage temperature × storage time × display temperature × display time for both visual color and a^*. Since visual panel scores best represent what consumers might see, these scores will be considered the "standard" for statistical treatment comparisons, and a^* will be used to confirm treatment effects. Previous studies also noted visual and instrumental a^* values were highly correlated and explained the loss of redness during storage (Mancini et al., 2022).

Effects of storage temperature × storage time × display temperature × display time on visual color

General overall effects. The combined effects of storage and display on ground beef visual color are presented in Figure 1 and Table 3. Ground beef stored at 0°C had a brighter-red initial bloomed color (lower 0 h color scores) than ground beef stored at either 4.5 or 8.9°C, which were similar. As storage temperature and display temperature increased, discoloration during display occurred faster. Storage at 0°C (A1, 2, and 3) consistently resulted in less ($P < 0.05$) discoloration than storage at 8.9°C (C1, 2, and 3), whereas the effects of storage at 4.5°C (B1, 2, and 3) were intermediate. Although storage at 0°C (A1, 2, and 3) maintained desirable ground beef color during display, storage time had more pronounced effects (discoloration increased with increasing storage time) at warmer storage and display temperatures (B1, 2, 3 and C1, 2, 3).

Visual and instrumental color stability during display. Storage temperature affected ground beef color differently as storage time increased (Figure 1 and Table 3). At all display temperatures, 4 d of storage at 0°C resulted in a brighter ($P < 0.05$) red color than 4.5° or 8.9°C storage for 4 d, which were similar ($P > 0.05$). However, when storage time increased to 8 or 12 d, discoloration at all display temperatures increased ($P < 0.05$) as storage temperature increased. Discoloration during display (0, 24, and 48 h) did not increase ($P > 0.05$) with longer storage at 0°C, regardless of display temperature (Figure 1; plots A1, 2, and 3). Similarly, storage at 4.5°C and display at 0°C resulted in 24 h color scores that did not differ ($P > 0.05$) with storage time (Figure 1; B1). The effects of storage time at 4.5°C on visual color scores became more pronounced when display temperature increased (Figure 1; B1 vs. B3). torage at 8.9°C (all display temperatures, Figure 1; C1, 2, and 3) caused color scores at 24 and 48 h to increase (more discoloration, $P < 0.05$) as storage time increased (4 < 8 < 12 d).

At 0-d storage at 0°C (Figure 1; A1, 2, 3 and Table 2), 24 h discoloration increased ($P < 0.05$) as display temperature increased (0 < 4.5 < 8.9°C). However, after 4, 8, and 12 d of storage at 0°C, display at 0 and 4.5°C resulted in 24 h color scores that were similar ($P > 0.05$) but less ($P < 0.05$) than 8.9°C display. Storage at 4.5°C for 4 or 8 d followed by display at 4.5 or 8.9°C resulted in 24 h color scores that were similar ($P > 0.05$) but greater ($P < 0.05$) than with 0°C display (Figure 1; B1, 2, and 3); however, as storage time increased to 12 d, a trend occurred where 24 h display color scores significantly increased as display temperature increased (0 < 4.5 < 8.9°C). This trend also occurred after all storage times at 8.9°C (24 h display, Figure 1; C1, 2, and 3). After 48 h of display, storage temperature and time did not influence display temperature effects, and color scores increased ($P < 0.05$) as display temperature increased (Figure 1; 0 < 4.5 < 8.9°C display).

Economic impact of poor cold chain management. Based on the differences noted between the rate of color loss (Figures 1 and 2), various storage and display treatments are expected to differ in sales loss due to discoloration. Prior to the simulation of expected sales loss and percent sales loss, an additional adjustment was made pre-simulation for the 8- and 12-d 8.9°C storage treatments to account for the observed chub loss percentage during storage. This was accomplished by randomly assigning a proportion of iterations within these treatments to 100% expected sales loss matching the proportions recorded in Table 3. This ensures that the simulation results account for the chub loss expected prior to retail display for those treatments that demonstrated high microbial counts, extreme surface discoloration, off odors, and/or gas pockets, thus rendering them unsuitable for grinding and display. The simulation results of expected sales loss (equation 1) and the percent sales loss are summarized in Table 4 and Figure 3. The results demonstrate that 4 d of storage at 0°C followed by display at 0°C is expected to minimize sales loss. This treatment had a loss of $0.18/kg or 1.8% of the average retail price. Comparatively, 12 d of storage at 8.9°C followed by display at 8.9°C is expected to result in an average sales loss of $10.03/kg or 99.4% of the average retail price.

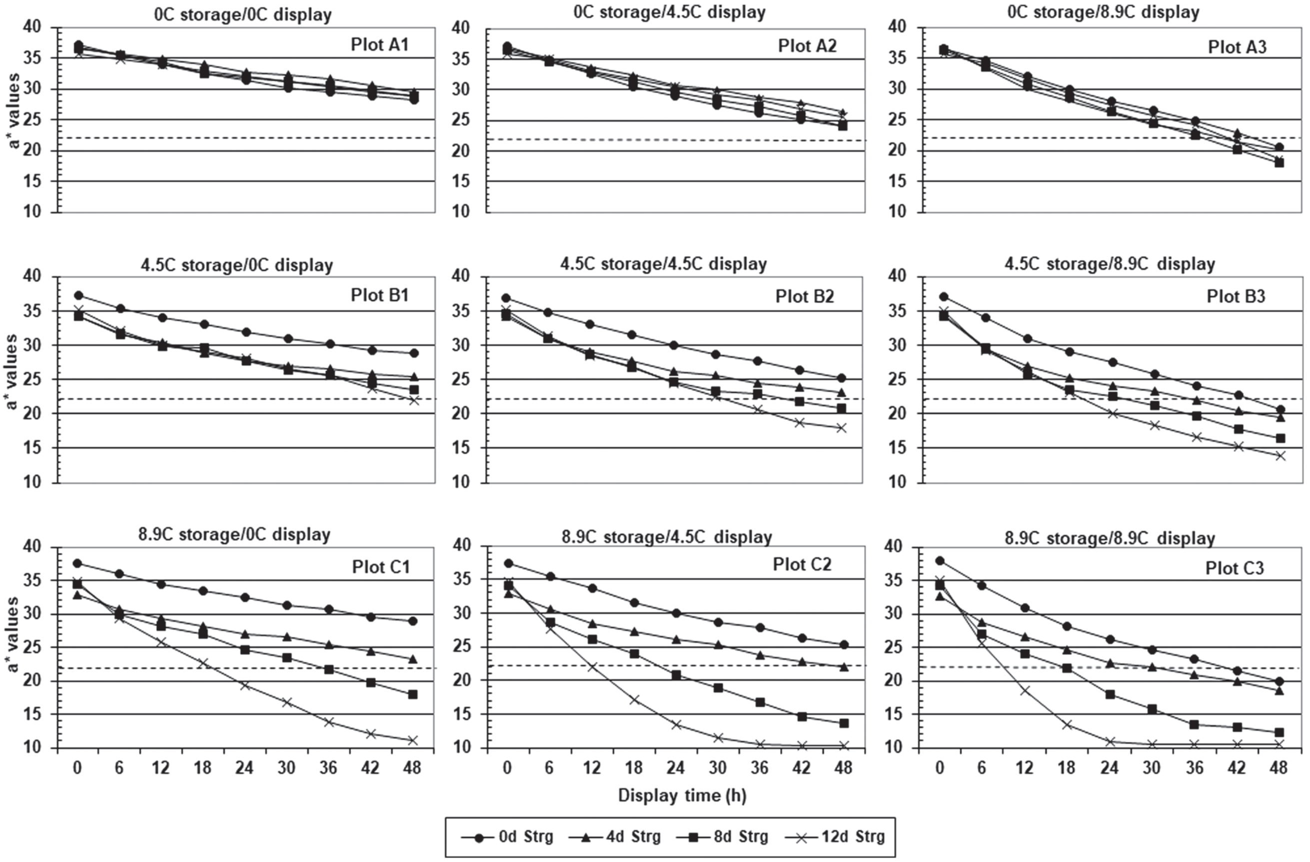

Figure 2. Combined effects of storage temperature (°C), storage time (strg, d), display temperature (°C), and display time (h) on *a** least-squares means for ground beef. Standard error of differences for each treatment: storage temperature = 0.99 and time = 0.95; display temperature = 0.73 and time = 0.73.

The general trend within Table 4 demonstrates, as expected, that sales loss is positively correlated with storage days, storage temperature, and display temperature.

Discussion

Most previous work has focused on the effects of individual portions of the cold chain on meat color rather than accounting for the role of multiple combinations of storage and display conditions in ground beef surface color and economic losses. This project was unique in that it assessed both color (measured every 6 h for *a**) and economic consequences resulting from combined storage and display factors commonly associated with ground beef, thus simulating the "real world" conditions.

The data implied that ground beef consistently discolored as display time increased, which supports the results of Lavelle et al. (1995), who found that *a** and saturation indices of ground beef (90% lean) decreased during display at 0°C. Similarly, Eckert et al. (1997) and Martin et al. (2013) found that during display at 4°C, ground beef (81% lean) discoloration increased with longer display time. Since ground beef discoloration during display is inevitable, cold chain management is crucial to minimize discoloration and maximize color life. Despite recommendations and the benefits associated with cold chain management, retailers frequently violate the temperature and time restraints necessary to ensure maximum shelf life. Therefore, the following discussion will assess the consequences associated with this lack of cold chain control.

In general, poor temperature choices (improper cold chain management) accelerated ground beef discoloration during display, measured by visual appraisal and supported by *a** values. This work supports the findings of previous researchers who have shown that ground beef visual color scores and instrumental values are affected by temperature and time (Shivas et al., 1984; Troutt et al., 1992; Eckert et al., 1997; Murano et al., 1998; Rogers et al., 2014). In addition, earlier work with steaks demonstrated similar trends (Macdougall et al., 1975; Nortje et al., 1986).

Table 2. Effects of storage temperature, storage time, display temperature, and display time on ground beef visual color[1] least-squares means

			Storage temperature (°C)		
Storage time (d)	Display temperature (°C)	Display time (h)	0	4.5	8.9
0	0	0	1.2^{adtx}	1.3^{adtx}	1.3^{adtx}
0	0	24	2.1^{adty}	2.1^{adty}	2.0^{adty}
0	0	48	2.6^{aetz}	2.5^{adtz}	2.5^{adtz}
0	4.5	0	1.3^{adtx}	1.3^{adtx}	1.3^{adtx}
0	4.5	24	2.5^{aeuy}	2.2^{adty}	2.3^{aduy}
0	4.5	48	3.2^{aeuz}	2.9^{aduz}	2.9^{aduz}
0	8.9	0	1.4^{adtx}	1.4^{adtx}	1.3^{adtx}
0	8.9	24	2.8^{advy}	2.7^{aduy}	2.8^{advy}
0	8.9	48	3.8^{advz}	3.7^{advz}	3.8^{advz}
4	0	0	1.2^{adtx}	1.9^{betx}	2.0^{betx}
4	0	24	1.9^{adty}	2.6^{bety}	2.7^{bety}
4	0	48	2.2^{adtz}	2.9^{betz}	3.2^{betz}
4	4.5	0	1.2^{adtx}	2.0^{betx}	2.2^{bftx}
4	4.5	24	2.0^{adty}	2.9^{beuy}	3.1^{beuy}
4	4.5	48	2.7^{aduz}	3.4^{beuz}	3.5^{beuz}
4	8.9	0	1.3^{adtx}	2.1^{bftx}	2.1^{bftx}
4	8.9	24	2.6^{aduy}	3.2^{beuy}	3.4^{bevy}
4	8.9	48	3.7^{advz}	3.8^{abdvz}	4.0^{bdvz}
8	0	0	1.3^{adtx}	1.9^{betx}	1.9^{betx}
8	0	24	2.1^{adty}	2.7^{bety}	3.2^{cfty}
8	0	48	2.5^{adetz}	3.3^{bftz}	4.2^{cftz}
8	4.5	0	1.4^{adtx}	2.0^{betx}	2.0^{bftx}
8	4.5	24	2.4^{aety}	3.2^{befuy}	3.7^{cfuy}
8	4.5	48	3.1^{aeuz}	3.6^{beuz}	4.6^{cfuz}
8	8.9	0	1.4^{adtx}	2.1^{bftx}	2.1^{bftx}
8	8.9	24	2.7^{aduy}	3.4^{befuy}	4.2^{cfvy}
8	8.9	48	4.0^{advz}	4.3^{bevz}	5.0^{cevz}
12	0	0	1.3^{adtx}	1.8^{betx}	1.5^{abdtx}
12	0	24	2.1^{adty}	2.8^{bety}	3.9^{cgty}
12	0	48	2.5^{adetz}	3.6^{bftz}	5.0^{cgtz}
12	4.5	0	1.3^{adtx}	1.8^{betx}	1.7^{betx}
12	4.5	24	2.2^{adety}	3.3^{bfuy}	4.6^{cguy}
12	4.5	48	3.0^{adeuz}	4.1^{bfuz}	5.1^{cgtz}
12	8.9	0	1.3^{adtx}	1.7^{betx}	1.7^{betx}
12	8.9	24	2.6^{aduy}	3.7^{bfvy}	5.0^{cgvy}
12	8.9	48	3.9^{advz}	4.6^{bfvz}	5.1^{cety}

[1] Visual color: 1 = very bright cherry red; 3 = slightly dark red to tannish red; 3.5 = unacceptable color; 5 = tan to brown. Standard error of treatments = 0.1.

^{abc}Storage temperature means within a row with a different letter differ ($P < 0.05$).

^{def}Storage time means within a column with the same display temperature and display time with a different letter differ ($P < 0.05$).

^{tuv}Display temperature means within a column with the same storage time and display time with a different letter differ ($P < 0.05$).

^{xyz}Display time means within a column with the same storage time and display temperature with a different letter differ ($P < 0.05$).

Maximizing desirable ground beef color

Consequences of failing to use cold storage temperatures. Prior to display, storage at 0°C resulted in a brighter red initial bloomed color than storage at either 4.5 or 8.9°C. In addition, failure to use 0°C storage resulted in ground beef that discolored faster during display. As a result, compared with storage at 4.5 and

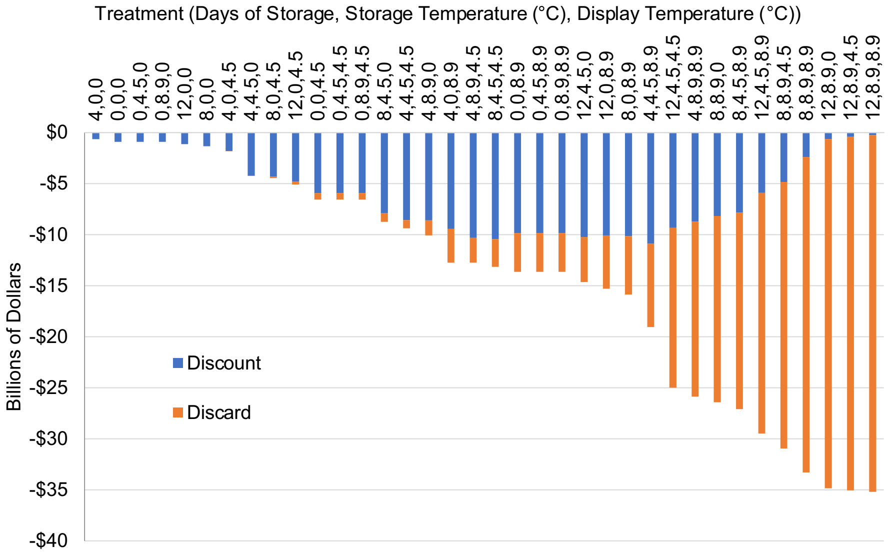

Figure 3. Total projected U.S. ground beef retail loss from discoloration (discount and discard) by storage and display treatment. The x-axis represents temperature in °C.

8.9°C, storage at 0°C minimized discoloration resulting from longer storage time. If elevated storage temperatures must be used, storage time should be reduced. These results support those of Bevilacqua and Zantzky (1986), who found that the rate of metmyoglobin formation was twice as fast at 4°C than at 0°C. Others have shown that meat discolors 2 to 5 times faster at 10°C than at 0°C (Hood, 1980). In addition, aging at 5°C also favored more discoloration of beef longissimus steaks than at 0°C (Mancini and Ramanathan, 2014).

Consequences of failing to use cold display temperatures. Failing to maintain cold display temperatures also resulted in rapid discoloration. When 0°C storage was coupled with 0°C display (Figure 1; plot A1), storage time effects were so minimal that at no point during display did color scores become greater than 3.0 (slightly dark red); however, following storage at 0°C with warm display temperatures (>0°C) accelerated discoloration. More specifically, 12 more days of storage at 0°C were obtained by lowering display temperature from 8.9 to 0°C.

More visual discoloration and decreases in a^* values occurred when desirable temperature choices (0°C storage and display) combined with brief storage periods (0 and 4 d) were not used. Therefore, utilizing only cold storage temperatures and allowing abusive display temperatures fully negated the benefits of 0°C storage and did not optimize ground beef color stability.

Economic consequences resulting from poor cold chain management. In 2021, 8.89 billion kg of beef went towards the retail supply chain in the U.S. (USDA ERS, 2022) with ground beef comprising approximately 39.46% of this total (Statista, 2021). This suggests approximately 3.51 billion kg of ground beef makes its way to U.S. retailers. Multiplying this value by the treatment expected sales loss values (Figure 1 and Table 3) provides a projected total loss to U.S. retailers if a specific treatment protocol were followed by all retailers. The projected total losses for each treatment are contained in Figure 3, with the totals subdivided by the proportion lost due to discount or discard. The results further demonstrate that loss due to discoloration is minimized with storage and display temperatures of 0°C. Expected total losses for these treatments range from a minimum of $630 million to a maximum of $1.33 billion for storage times of 4 to 8 d, respectively. Ramanathan et al. (2022) estimated annual loss due to discoloration in ground beef just outside of this range at $1.48 billion.

Within the 0°C storage and display treatments, loss from discoloration is almost exclusively due to discount rather than discard (Figure 3). Increasing either the storage or display temperature is related to increased loss expected from discard. Initially, the expected loss from the discount is also positively correlated with the storage and display temperatures before the increases in loss due to discarding eventually outweigh the possibility of a sale at a discount. The amount of expected loss due to discard after discoloration approaches 100% for the treatment of 12 storage days stored and displayed at 8.9°C. The U.S. Food and Drug Administration requires retail case temperature to be maintained at or below 5°C (U.S. Food and Drug Administration, 2022). Yet our

Table 3. Sales loss ($/kg) and percent sales loss for ground beef

		A. Expected sales loss ($/kg)			B. Percent sales loss		
		Storage temperature (°C)					
Storage time (d)	Display temperature (°C)	0	4.5	8.9	0	4.5	8.9
0	0	−0.26 (0.81)	−0.26 (0.81)	−0.26 (0.81)	2.5% (8)	2.5% (8)	2.5% (8)
4		−0.18 (0.69)	−1.21 (1.42)	−2.87 (3.24)	1.8% (7)	12% (14)	28.5% (32)
8		−0.38 (0.96)	−2.49 (2.79)	−7.53 (3.95)	3.8% (10)	24.7% (28)	74.7% (39)
12		−0.32 (0.89)	−4.17 (4.06)	−9.93 (1.41)	3.2% (9)	41.4% (40)	98.4% (12)
0	4.5	−1.87 (2.96)	−1.87 (2.96)	−1.87 (2.96)	18.6% (29)	18.6% (29)	18.6% (29)
4		−0.52 (1.33)	−2.67 (2.56)	−3.63 (3.31)	5.1% (13)	26.5% (25)	36% (33)
8		−1.27 (2.08)	−3.75 (3.41)	−8.82 (3.07)	12.7% (21)	37.3% (34)	87.5% (30)
12		−1.45 (2.46)	−7.12 (3.95)	−9.99 (1.21)	14.4% (24)	70.6% (39)	99% (9)
0	8.9	−3.89 (4.04)	−3.89 (4.04)	−3.89 (4.04)	38.6% (40)	38.6% (40)	38.6% (40)
4		−3.63 (4.01)	−5.43 (4.17)	−7.37 (3.92)	36.1% (40)	53.9% (41)	73.1% (38)
8		−4.52 (4.34)	−7.72 (3.83)	−9.49 (2.32)	44.9% (43)	76.6% (37)	94.1% (22)
12		−4.36 (4.27)	−8.4 (3.5)	−10.03 (1.1)	43.2% (42)	83.3% (34)	99.4% (7)

Note: Mean values are listed for both sales loss and percent sales loss with standard deviations included in parentheses. Expected sales loss is the average amount ($/kg) that is expected to be lost to a retailer from discount or discard due to discoloration. Percent sales loss is the sales loss divided by the retail price.

results would suggest that maintaining storage coolers and display coolers at 4.5°C rather than 0°C would increase the expected total loss from cold chain mismanagement to the retail ground beef system on average from $1.0 billion to $13.52 billion. Therefore, the results strongly support maintaining storage and display at cooler temperatures near 0°C to minimize loss from discoloration.

In the current study, 81% lean ground beef was utilized to understand the effects of cold chain on ground beef color and losses. Various factors, such as fat level, quality grade, postmortem age, trim characteristics, animal finishing systems, and lighting type, can influence ground beef discoloration. Hence, considering these factors in future studies will provide more specific information about the importance of cold chain management and factors affecting ground beef discoloration.

Conclusion

For 81% lean ground beef, the use of 0°C throughout the cold chain was far superior to storage and display at 4.5 and/or 8.9°C. Failure to maintain 0°C throughout the cold chain will accelerate discoloration and increase sales losses. Except at 0°C, increasing storage time is detrimental to color; therefore, chub storage should be as brief as possible. To maximize color life and minimize expected sales loss, 0°C during storage and display is strongly recommended for 81% lean ground beef. Ground beef (81% lean) stored and displayed at 0°C is shown to minimize expected sales loss with an average loss of $0.29/kg or 2.8% of average retail value. The results from this study overwhelmingly suggest that complete and appropriate cold chain management is essential. Controlling only one aspect of the cold chain will not maximize shelf life and profit.

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