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Characterization of Pork Loin Chop Color Stability Using Loin Quality Traits and Instrumental Discoloration Measures

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Abstract: The objective of this study was to characterize the color stability of pork loin chops using fresh quality traits and instrumental measures of discoloration. Boneless pork loins ($N = 484$) were evaluated for quality traits at 11 or 14 d postmortem. One chop was cut from each loin near the 10th rib for retail display, overwrapped, and displayed under constant fluorescent lighting for 7 d. Objective color, myoglobin redox forms, and subjective visual discoloration traits were evaluated daily. After retail display, chops were categorized based on final visual discoloration (Day 7) as Very Color Stable (VCS; 0% to 5% discoloration), Color Stable (CS; 5% to 10% discoloration), Neutral (10% to 25% discoloration), Color Labile (CL; 25% to 30% discoloration), or Very Color Labile (VCL; >30% discoloration). Quality and color traits were analyzed using the GLIMMIX (visual discoloration) or MIXED (all other measures) procedure of SAS. Retail display data were analyzed as repeated measures. Chops ultimately classified as CS or VCS were darker, redder, and had lesser surface metmyoglobin ($P < 0.01$) than CL and VCL chops at both Day 1 of retail display and throughout display. Stable chops also had generally increased R630/580 values as well as decreased visual discoloration scores and yellowness during display. A group × day interaction was observed for all traits measured during retail display ($P < 0.0001$). No differences in aged loin ventral surface redness were observed between color stability groups ($P \geq 0.16$). Overall, chops ultimately classified as CS came from aged loins that were generally darker, redder, and less yellow, with greater pH values, greater marbling scores, and decreased purge loss.

Key words: pork, color, discoloration, quality, color stability, myoglobin
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Introduction

It is well-known that consumers use color in their meat purchasing decisions, typically preferring bright, cherry-red beef or lamb (Hood and Riordan, 1973; Schwimmer, 1981) and reddish-pink pork (Brewer and McKeith, 1999). In contrast, consumers discriminate against brown or purple hue when purchasing meat, using color as an indicator of wholesomeness and freshness (Font-i-Furnols and Guerrero, 2014). Accordingly, retailers may discount or rework discolored meat products to increase the likelihood of consumer purchase; however, extensive discoloration may ultimately result in products being discarded. For these reasons, the premature discoloration of fresh meat poses enormous economic and food waste challenges. For reference, in 2019, fresh beef discoloration resulted in an estimated $14 billion of lost revenue globally (Ramanathan et al., 2022). In order to minimize losses resulting from discolored products, it is important to understand discoloration in meat and the factors that contribute to it.

Although fresh beef discoloration characteristics and mechanisms have been investigated extensively, similar research in fresh pork is limited.

Zhu and Brewer (1998) and King et al. (2011b) evaluated differences in color traits between stable and labile pork but did not investigate differences in other common quality traits such as pH or marbling. In fresh beef, a number of studies have demonstrated relationships between color stability and loin quality traits. For example, previous studies have reported that *Longissimus lumborum* (LL) steaks with less marbling (Wheeler et al., 2005) or lower ultimate pH values (Ledward et al., 1986; O'Grady et al., 2001) were more color stable (CS). Further, several studies have indicated redder steaks discolor more quickly (McKenna et al., 2005; Faustman et al., 2010; Canto et al., 2015). Although multiple studies have characterized quality traits of the US pork supply (Arkfeld et al., 2017; Newman et al., 2019; Price et al., 2019; Redifer et al., 2020), none have evaluated characterized color stability using these traits. Further, substantial differences between beef and pork myoglobin (Mb), intramuscular fat content, and fatty acid profiles (de Vizcarrondo et al., 1998; Suman et al., 2006; Nerimetla et al., 2017) likely limit the ability of beef-specific quality and discoloration findings to accurately represent pork color stability. Therefore, the objective of this study was to characterize color stability of boneless pork loins using fresh quality traits and instrumental measures of discoloration. It was hypothesized that CS pork chops would possess quality characteristics different from what has been observed in CS beef.

Materials and Methods

In total, 484 loins representing 4 independent shelf-life trials (designated A through D) were used. All pigs were slaughtered at processing facilities under the supervision of USDA Food Safety Inspection Service. Pigs used in this study represented different commercial sire lines, housing systems, and slaughter conditions. However, all pigs received an industry-typical corn-soy finishing diet. Handling details for each of the 4 studies are outlined in Table 1. Live animal interaction occurred for pigs from Trial C; therefore, all protocols for that trial were approved by the University of Illinois Institutional Animal Care and Use Committee (Protocol #20095). All animals were held in lairage for approximately 16 h prior to slaughter with no access to feed and ad libitum access to water, then slaughtered and allowed to chill prior to fabrication. Pigs slaughtered at the University of Illinois were immobilized via head-to-heart electrical stunning and terminated via exsanguination, after which carcasses were allowed to chill at 4°C for approximately 22 h. Pigs slaughtered at other facilities were immobilized via CO_2 stunning and harvested by exsanguination, then blast-chilled for approximately 90 min and held in an equilibration cooler until fabrication at approximately 22 h. After chilling, all carcasses were fabricated into primal cuts using North American Meat Processors cutting specifications (NAMI, 2007), and loins were further fabricated into boneless Canadian back loins (NAMP #414). Loins from pigs slaughtered at the university were weighed, then vacuum packaged and aged until 14 d postmortem. Loins acquired from pigs slaughtered at commercial facilities were vacuum packaged, then transported to the University of Illinois Meat Science Laboratory, where they were stored at 4°C until 11 d (Trial D) or 14 d (Trial C) postmortem. Aging durations (11 or 14 d postmortem) represented in the current study are within the industry-typical range (10 to 35 d postmortem) prior to retail delivery.

Aged ventral loin (the ventral, lean surface of boneless Canadian back loin) quality traits were measured on all loins used in this study. Loins acquired from pigs slaughtered at the University of Illinois were removed from bags and weighed a second time to determine purge loss ([initial wt. − final wt.]/initial wt. × 100). Loins fabricated in commercial production facilities were weighed in the vacuum bag, then removed from packaging and weighed a second time to determine purge loss using the previous calculation. The initial weight of these loins was determined by subtracting

Table 1. Handling and slaughtering conditions for pigs from trials used in this study

Trial	Pigs, *n*	Housing	Diet	Harvest	Stunning	Chilling[1]	Aging Duration[2]	Display Lighting
A	48	Commercial	Commercial	Commercial	CO_2	Blast-chilled	14 d	3,000 K
B	54	University	Commercial	University	Electric	Slow-chilled	14 d	3,000 K
C	148	University	Commercial	University	Electric	Slow-chilled	14 d	3,000 K
D	234	Commercial	Commercial	Commercial	CO_2	Blast-chilled	11 d	6,500 K

[1]Blast chilled carcasses were chilled in a blast freezer for approximately 90 min, then held in an equilibration cooler at 4°C for 22 h. Slow chilled pigs were placed in a cooler at 4°C immediately after slaughter and held for approximately 22 h.

[2]All loins, regardless of aging duration, were aged at 4°C.

the average weight of bags used from the weight of the bagged loin. The ventral surface of loins was then trimmed free of any remaining fat or connective tissue and allowed to oxygenate for 20 min prior to ventral loin quality evaluations. All quality evaluations were conducted on the ventral face of the loin at the approximate location of the 10th rib. Instrumental Commission Internationale de l´Eclairage (CIE) L^* (lightness), a^* (redness), and b^* (yellowness; CIE, 1976) measurements were collected using a Konica Minolta CR-400 Chroma Meter (Minolta Camera Co., Ltd., Osaka, Japan) with a D65 illuminant, closed (clear measurement window cap for protecting the instrument optics from moisture) 8 mm aperture, and 2° observer and calibrated with a white tile specific to the machine. The Minolta Chroma Meter was used for evaluation of ventral loin surface instrumental color to reflect instrumentation most commonly used for on-line loin quality evaluations by commercial processors. Ultimate pH was measured at the approximate location of the 10th rib using a Hanna pH meter fitted with a glass tipped electrode (model HI98163, Hanna Instruments. Woonsocket, RI) calibrated using pH 4 and pH 7 buffer at 4°C. Visual color, visual marbling (NPPC, 1999), and subjective firmness (NPPC, 1991) of ventral loin surfaces were evaluated by a single trained technician. After ventral loin quality measurements were completed, a single 2.54-cm-thick chop was cut from each loin at the area of the 10th rib for retail display. Individual chops were placed on polystyrene trays (27.3 × 14.9 cm, Dyne-A-Pak, Laval, Quebec, Canada) and overwrapped using oxygen-permeable polyvinyl chloride (PVC) film (O_2 transmission rate = 23,250 mL·m^2 · d^{-1}, 72 gauge; Resinite packaging films, Borden, Inc., North Andover, MA). Packaged chops were displayed under constant lighting (Ecolux with Starcoat, 3,000 K, GE, Boston, MA, for Trials A, B, and C; Octron XP, 6,500 K, Osram Sylvania, Wilmington, MA, for Trial D) at 4°C for 7 d. Chops were removed from simulated retail display after 7 d. Subjective discoloration estimates and objective color measurements were collected each day of analysis in 24 h intervals. Overwrapped chops were allowed a 1-h oxygenation period before evaluation of initial Day 1 discoloration and objective color. Samples were evaluated for subjective discoloration by a trained technician using a 10 cm unstructured line scale anchored at 0%, 50%, and 100% discoloration. Objective color measurements during retail display were collected using a HunterLab MiniScan EZ spectrophotometer (HunterLab, Reston, VA) in order to collect tristimulus CIE L^* (lightness), a^* (redness), and b^* (yellowness) as well as spectral data ranging from 400 to 700 nm (King et al., 2022). HunterLab spectrophotometer was equipped with a D65 illuminant, 10° observer, and 31.8 mm aperture and calibrated with a black and white tile covered with the same PVC film used to wrap the chops. Instrumental reflectance values were used to calculate the ratio of reflectance at 630 nm to the reflectance at 580 nm (smaller ratio indicates greater discoloration; R630/580) and estimated Mb redox forms (metmyoglobin [MMb], deoxymyoglobin [DMb], and oxymyoglobin [OMb]) using the method described by Krzywicki (1979). Using this method, reflectance at 474, 525, and 572 nm was determined by interpolation using wavelength reflectance determined by the HunterLab MiniScan EZ spectrophotometer. These reflectance values, in addition to the reflectance at 700 nm, were then converted to attenuance (A) values by the equation: $A = \log(1/R)$, where R = reflectance. Percentages of Mb redox forms on surface were calculated using the following equations:

$$\%\text{Metmyoglobin (MMb)} = \left\{1.395 - \left(\frac{A_{572} - A_{700}}{A_{525} - A_{700}}\right)\right\} \times 100$$

$$\%\text{Deoxymyoglobin (DMb)} = \left\{1.395 - \left(\frac{A_{474} - A_{700}}{A_{525} - A_{700}}\right)\right\} \times 100$$

$$\%\text{Oxymyoglobin (OMb)} = 100 - (\%\text{MMb} + \%\text{DMb})$$

Statistical analyses

Loins were sorted into 5 color stability categories based on chop visual discoloration on the final day of display (Day 7): Very Color Stable (0% to 5% discoloration; VCS), CS (5% to 10% discoloration), Neutral (10% to 25% discoloration; NT), Color Labile (25% to 30% discoloration; CL), and Very Color Labile (30% + discoloration, VCL). Data were analyzed using the MIXED procedure of SAS (SAS v9.4, SAS Inst. Inc., Cary, NC) with loin serving as the experimental unit. Postmortem quality traits and color stability measures at the initial (Day 1) and final (Day 7) point of display were analyzed as a 1-way analysis of variance with stability group as a fixed effect and shelf-life trial (A through D) as a random effect. A multivariance model was fitted using the repeated statement because of heterogeneous variance due to differences in sample size between stability categories. Although a variety of conditions were represented in this study, Arkfeld et al. (2017) reported that marketing group (first barn cut vs. second cut) and production focus (lean growth vs. meat quality genetics) together contributed less than 10% of variation in pork

loin *L**, *a**, and *b**. This variation and other variations contributed by factors included in Table 1 were accounted for by including a trial as a blocking factor in the model. Visual discoloration data were determined to be non-normal and were thus analyzed using the GLIMMIX procedure of SAS, whereas quality data and other color stability traits (*L**, *a**, *b**, R630/580, and MMb) were analyzed using the MIXED procedure. Data from the 7 d simulated retail display period were analyzed as repeated measures with stability group, day, and the interaction between the two as fixed effects, and shelf-life trial (A through D) as a random effect. No interactions ($P \geq 0.18$) between shelf-life trial and day of display were observed for any color stability traits. Visual discoloration data over display was analyzed using the GLIMMIX procedure with day as a random statement. Other color stability traits were analyzed using the MIXED procedure with a Toeplitz covariance structure chosen to minimize variance. Least-square means were separated using the PDIFF option for both the GLIMMIX and MIXED procedures. Main effects and interactions were considered significantly different at $P \leq 0.05$ and trending at $0.05 \leq P \leq 0.10$.

Results

Summary statistics for initial (Day 1), final (Day 7), and Δ (Day 7 – Day 1) color stability traits are displayed in Table 2. Initial loin color averaged

Table 2. Population summary statistics of initial (Day 1), final (Day 7), and overall change in (Δ, Day 7 – Day 1) display characteristics

Variable	*N*	Mean	Minimum	Maximum	SD[1]	CV[2]
Initial, Day 1 Retail Display[3]						
Lightness, *L**	484	57.27	46.84	68.60	3.25	5.67
Redness, *a**	484	8.77	4.44	14.03	1.72	19.62
Yellowness, *b**	484	16.71	12.07	20.51	1.28	7.68
R630/580	484	2.61	2.06	3.56	0.25	9.50
Visual discoloration, %	484	0.02	0.00	3.00	0.21	1287.31
Metmyoglobin (MMb), %[4]	484	9.12	1.96	15.06	2.20	24.18
Deoxymyoglobin (DMb), %[5]	483	24.96	0.32	68.19	12.93	51.80
Oxymyoglobin (OMb), %[6]	483	65.93	24.83	86.40	12.08	18.32
Final, Day 7 Retail Display[3]						
Lightness, *L**	484	58.02	43.29	70.38	3.50	6.02
Redness, *a**	484	8.63	4.56	14.58	1.54	17.89
Yellowness, *b**	484	17.05	12.51	24.18	1.05	6.14
R630/580	484	2.17	1.45	3.28	0.33	15.25
Visual discoloration, %	484	19.63	0.00	54.00	8.11	41.31
MMb, %[4]	484	23.89	8.64	46.39	7.37	30.85
DMb, %[5]	484	7.57	−21.28	59.75	7.07	93.46
OMb, %[6]	484	68.55	12.93	84.47	8.92	13.01
Δ (Day 7 – Day 1)						
Lightness, *L**	484	0.75	−16.80	14.18	4.31	576.06
Redness, *a**	484	−0.14	−6.95	6.06	2.40	−1,693.45
Yellowness, *b**	484	0.34	−4.06	7.15	1.47	428.67
R630/580	484	−0.44	−1.85	0.35	0.39	−88.13
Visual discoloration, %	484	19.61	0.00	54.00	8.09	41.29
MMb, %	484	14.77	2.28	40.56	6.30	42.67
DMb, %	483	−17.45	−85.52	24.21	12.36	−70.81
OMb, %	483	2.75	−47.64	72.38	15.08	547.49

[1]Standard deviation.

[2]Coefficient of variation, calculated by (SD/mean) × 100%.

[3]Instrumental color during retail display was evaluated using a HunterLab MiniScan EZ spectrophotometer set to collect tristimulus CIE *L**, *a**, and *b** with a D65 illuminant, 10° observer, 31.8 mm aperture.

[4]Calculated as $\%MMb = \{1.395 - (\frac{A_{572}-A_{700}}{A_{525}-A_{700}})\} \times 100$, where A represents reflex attenuance at a given wavelength.

[5]Calculated as $\%DMb = \{2.375 \times (1 - \frac{A_{572}-A_{700}}{A_{525}-A_{700}})\} \times 100$, where A represents reflex attenuance at a given wavelength.

[6]Calculated as %OMb = 100 – %MMb – %DMb.

an L^* of 57.27 (range: 46.84 to 68.60), a^* of 8.77 (range: 4.44 to 14.03), and b^* of 16.71 (range: 12.07 to 20.51). Initial DMb averaged 24.96% (range: 0.32 to 68.19) and initial discoloration was minimal with a range from 0% to 3%. Initial MMb was 1.96% to 15.06%, initial DMb was 0.32% to 68.19%, and initial OMb was 24.83% to 86.40%. After 7 d of display, loin chop color ranges were similar to those of Day 1 display with the exception of DMb, which decreased from an average of 24.96% on Day 1 to 7.57% on Day 7. Magnitudes of color change during display differed between loins, as Δ L^* ranged from −16.80 to 14.18, Δ a^* ranged from −6.95 to 6.06, and Δ b^* ranged from −4.06 to 6.06. The average final visual discoloration of loins used in this study was 19.6%, with a minimum final discoloration of 0% and a maximum final discoloration of 54.0%. MMb ranged from 8.64% to 46.39% at Day 7 of display. Therefore, some loin chops did experience discoloration and MMb formation during retail display. Images representing final discoloration of chops from each of the 5 categories are displayed in Figure 1.

The percentages of loins from each trial that were included in each category based on Day 7 display visual discoloration are displayed in Figure 2. In total, 17 loins were categorized as "very color stable," 23 were categorized as "color stable," 305 were categorized as "neutral," 77 were categorized as "color labile," and 62 were categorized as "very color labile." All 4 trials were represented in 4 of the 5 categories, with the exception of the VCS category, in which all observations were from either Trial A or B. However, the 2 trials represented in the VCS category represented both commercial and university housing and slaughter conditions. Proportions of chops in a stability category were similar across color groups.

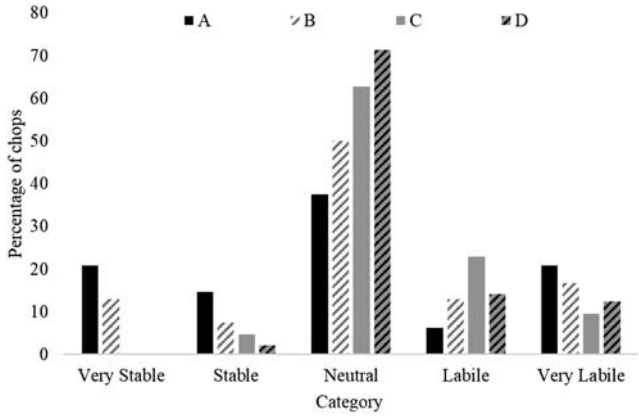

Figure 2. Percentage of chops from each trial represented in color stability categories.

Differences in retail display traits on Day 7 of display are presented in Table 3. Visual discoloration scores at Day 7 of display were different between all color stability groups ($P < 0.0001$); this was expected because color stability categories were determined using final day visual discoloration. Unsurprisingly, chops in stable categories (CS and VCS) also had greater R630/580 ($P < 0.0001$) and decreased MMb ($P < 0.0001$) than chops in labile categories (CL and VCL) on Day 7. Additionally, on Day 7 of display, no difference ($P = 0.14$) in MMb of CL and VCL was observed, but there was a tendency for greater MMb in chops from CS loins compared with chops from VCS loins ($P = 0.08$). No differences in chop redness, yellowness, DMb, or OMb were observed between stability categories on Day 7 ($P \geq 0.23$).

Aged loin quality and color stability

Effects of color stability categories on aged ventral loin quality traits and Day 1 of display color traits are shown in Table 4. Loins categorized as stable (CS and

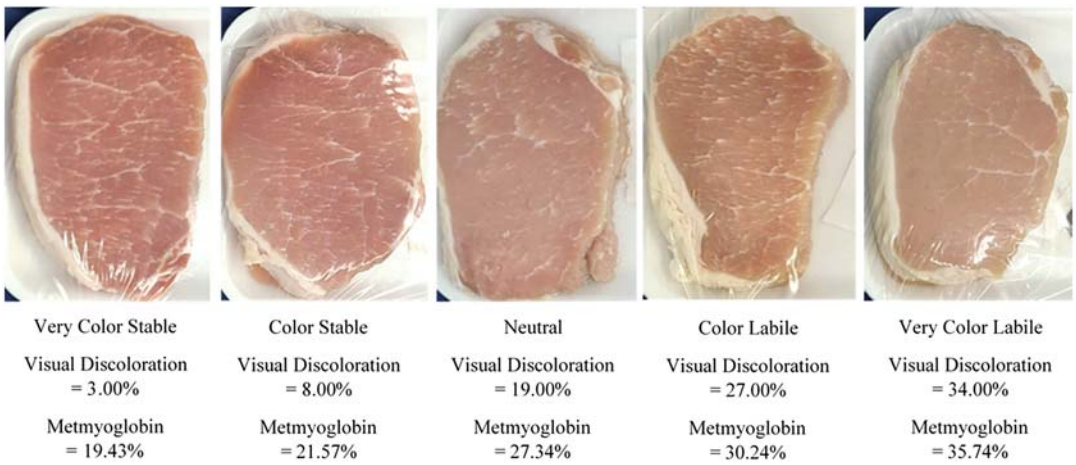

Figure 1. Average final (Day 7) visual discoloration and metmyoglobin concentration of chops representing each color stability category.

Table 3. Effect of color stability category on color stability of boneless pork loin chops at Day 7 of retail display[1,2]

Item	VCS	CS	NT	CL	VCL	SEM	*P* Value
n	17	23	305	77	62		
Visual discoloration, %	1.47^{e}	8.35^{d}	17.21^{c}	26.02^{b}	32.79^{a}	0.73	<0.0001
Lightness, *L**	54.92^{c}	58.11^{b}	58.52^{b}	57.91^{b}	59.57^{a}	1.05	<0.0001
Redness, *a**	9.02	8.24	8.28	8.20	8.03	0.52	0.23
Yellowness, *b**	16.82	17.06	17.24	17.12	17.36	0.31	0.30
R630/580	2.32^{a}	2.31^{a}	2.12^{b}	1.88^{c}	1.79^{d}	0.13	<0.0001
Metmyoglobin (MMb), %[3]	21.72^{c}	23.88^{c}	26.27^{b}	29.50^{a}	30.56^{a}	3.33	<0.0001
Deoxymyoglobin (DMb), %[4]	6.15	7.29	7.11	6.76	6.60	0.93	0.67
Oxymyoglobin (OMb), %[5]	75.65	76.06	76.40	76.27	75.82	3.33	0.89

[1]Treatments with a row lacking common superscripts are different ($P < 0.05$); CL = Color Labile (25% to <30% final discoloration), CS = Color Stable (5% to <10% final discoloration), NT = Neutral (10% to <25% final discoloration), VCL = Very Color Labile (≥30% final discoloration), VCS = Very Color Stable (<5% final discoloration).

[2]Instrumental color during retail display was evaluated using a HunterLab MiniScan EZ spectrophotometer set to collect tristimulus CIE *L**, *a**, and *b** with a D65 illuminant, 10° observer, 31.8 mm aperture.

[3]Calculated as $\%MMb = \{1.395 - (\frac{A_{572}-A_{700}}{A_{525}-A_{700}})\} \times 100$, where A represents reflex attenuance at a given wavelength.

[4]Calculated as $\%DMb = \{2.375 \times (1 - \frac{A_{572}-A_{700}}{A_{525}-A_{700}})\} \times 100$, where A represents reflex attenuance at a given wavelength.

[5]Calculated as %OMb = 100 − %MMb − %DMb.

Table 4. Effect of color stability category on postmortem loin quality traits and color stability of boneless pork loin chops at Days 1 and 7 of retail display[1]

Item	VCS	CS	NT	CL	VCL	SEM	*P* value
n	17	23	305	77	62		
Aged Ventral Surface Quality[2,3]							
Ultimate pH	5.70^{a}	5.72^{a}	5.64^{b}	5.54^{c}	5.52^{c}	0.05	<0.0001
Color	3.85^{a}	3.96^{a}	3.49^{b}	3.05^{c}	3.02^{c}	0.11	<0.0001
Marbling	2.82^{a}	2.46^{ab}	2.32^{b}	2.04^{c}	2.03^{c}	0.22	<0.0001
Firmness	3.04^{a}	2.80^{ab}	2.94^{a}	2.76^{b}	2.90^{ab}	0.24	0.01
Lightness, *L**	47.22^{b}	45.04^{c}	47.53^{b}	50.01^{a}	50.74^{a}	1.06	<0.0001
Redness, *a**	7.20	7.44	7.40	7.38	7.38	0.51	0.99
Yellowness, *b**	4.55^{b}	4.22^{b}	4.73^{b}	5.36^{a}	5.63^{a}	0.40	<0.0001
Purge loss, %[4]	1.34^{c}	1.68^{c}	2.26^{b}	3.05^{a}	2.86^{a}	0.66	<0.0001
Initial, Day 1 Retail Display[5]							
Visual discoloration, %	0.00	0.00	0.00	0.03	0.05	0.04	0.25
Lightness, *L**	54.70^{d}	54.29^{d}	57.01^{c}	59.63^{b}	60.71^{a}	0.87	<0.0001
Redness, *a**	9.51^{a}	9.54^{a}	9.21^{ab}	9.21^{ab}	8.77^{b}	0.67	0.04
Yellowness, *b**	16.68^{bc}	16.34^{c}	16.98^{b}	17.51^{a}	17.44^{a}	0.51	<0.0001
R630/580	2.79^{a}	2.79^{a}	2.67^{b}	2.57^{c}	2.50^{c}	0.08	<0.0001
Metmyoglobin (MMb), %[6]	10.02	9.20	9.53	10.01	9.97	0.75	0.12
Deoxymyoglobin (DMb), %[7]	15.12^{a}	10.06^{bc}	9.00^{c}	10.22^{b}	9.89^{bc}	3.43	<0.01
Oxymyoglobin (OMb), %[8]	67.24^{c}	71.42^{bc}	73.09^{ab}	73.11^{ab}	74.03^{a}	2.39	0.01

[1]Treatments with a row lacking common superscripts are different ($P < 0.05$); CL = Color Labile (25% to <30% final discoloration), CS = Color Stable (5% to <10% final discoloration), NT = Neutral (10% to <25% final discoloration), VCL = Very Color Labile (≥30% final discoloration), VCS = Very Color Stable (<5% final discoloration).

[2]Aged quality measurements were collected at Day 11 or 14 postmortem on the ventral face of the loin at the approximate location of the 10th rib.

[3]Aged ventral surface instrumental color was evaluated using a Minolta CR-400 Chroma Meter set to collect tristimulus CIE *L**, *a**, and *b** with a D65 illuminant, 2° observer, and closed 8 mm aperture.

[4]Purge loss was calculated as ([initial wt. − final wt.]/initial wt. × 100).

[5]Instrumental color during retail display was evaluated using a HunterLab MiniScan EZ spectrophotometer set to collect tristimulus CIE *L**, *a**, and *b** with a D65 illuminant, 10° observer, and 31.8 mm aperture.

[6]Calculated as $\%MMb = \left\{1.395 - \left(\frac{A_{572}-A_{700}}{A_{525}-A_{700}}\right)\right\} \times 100$, where A represents reflex attenuance at a given wavelength.

[7]Calculated as $\%DMb = \left\{2.375 \times \left(1 - \frac{A_{572}-A_{700}}{A_{525}-A_{700}}\right)\right\} \times 100$, where A represents reflex attenuance at a given wavelength.

[8]Calculated as %OMb = 100 − %MMb − %DMb.

VCS), based on chop discoloration at Day 7 of display, were at least 2.79 L^* units darker ($P < 0.01$), were at least 0.81 b^* units less yellow ($P < 0.0001$), and had visual color scores at least 0.80 units greater ($P < 0.0001$) than loins categorized as labile (CL and VCL). Loins categorized as CS or VCS also had ultimate pH values at least 0.16 units greater ($P < 0.01$), marbling scores at least 0.42 units greater ($P < 0.0001$), and purge losses at least 1.18% lesser ($P < 0.0001$) than CL and VCL loins. NT loins were intermediate ($P \leq 0.04$) in ultimate pH ($P < 0.0001$), visual color score ($P < 0.0001$), and purge loss ($P < 0.0001$) to stable (CS and VCS) and labile (CL and VCL) loins. Despite differences between stable and labile loins, there were no differences in ultimate pH, visual color score, yellowness, or purge loss between CS and VCS loins ($P \geq 0.26$). Similarly, there were no differences in ultimate pH, visual color score, yellowness, or purge loss between CL and VCL loins ($P \geq 0.41$). No differences in ventral surface redness were observed between color stability categories ($P = 0.99$).

Initial chop color traits and color stability during retail display

On Day 1 of retail display, CL and VCL chops were lighter ($P < 0.0001$) and yellower ($P < 0.0001$) compared with NT, CS, and VCS chops ($P \leq 0.02$). No differences in visual discoloration or MMb were observed between color stability categories ($P \geq 0.12$) on Day 1. However, chops categorized as CL and VCL did exhibit lesser R630/580 at Day 1 than chops in stable categories (CS and VCS; $P < 0.0001$). Chops categorized as CS and VCS were redder than VCL chops on Day 1 of display ($P = 0.04$) but not different from NT or CL chops ($P \geq 0.46$). Chops from the VCS category had the greatest DMb on Day 1 ($P < 0.01$). Chops from CL and VCL categories had increased OMb compared with VCS chops ($P < 0.01$) at Day 1 of display.

An interaction between color stability category and day of retail display was for all color stability traits ($P < 0.0001$). Chops from labile categories (CL and VCL) displayed increased visual discoloration compared with NT, CS, and VCS chops as early as Day 2 of display (Figure 3A; $P < 0.0001$). Chops from the VCL category did not begin to discolor until Day 5 of display. On all days of display, chops categorized as CS and VCS had greater R630/580 (Figure 3B) compared with chops categorized as CL and VCL ($P < 0.0001$). Over the entire 7 d display period,

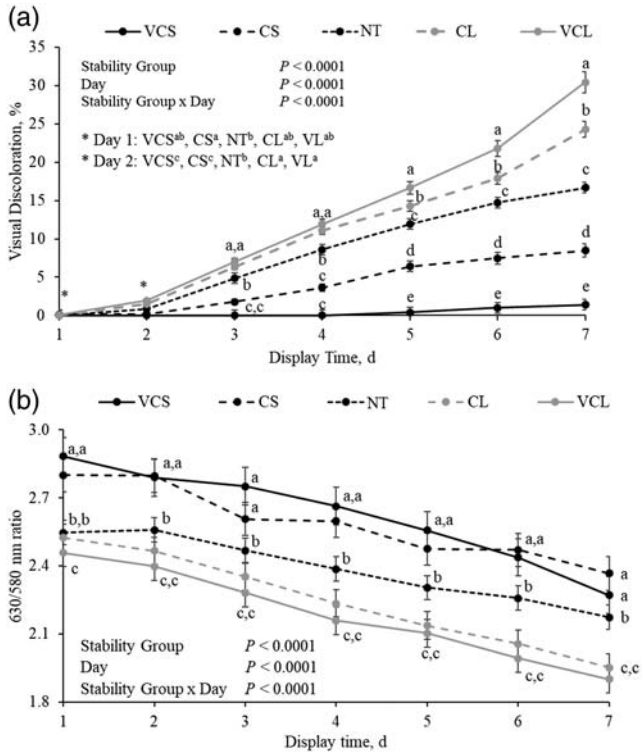

Figure 3. Effect of color stability group on visual discoloration (A) and R630/580 (B) of boneless pork chops across 7 d of retail display. Color stability categories, within a day, lacking common superscripts were different ($P < 0.05$). CS = Color Stable (5% to <10% final discoloration), NT = Neutral (10% to <25% final discoloration), CL = Color Labile (25% to <30% final discoloration), VCL = Very Color Labile (≥30% final discoloration), VCS = Very Color Stable (<5% final discoloration).

R630/580 did not differ between VCS and CS chops ($P \geq 0.08$). Furthermore, VCL and CL chops did not differ in R630/580 from Day 2 to 7 ($P \geq 0.09$). On Day 1 of display, chops categorized as NT had R630/580 values similar to CL chops ($P = 0.52$) but were intermediate to chops from stable (CS and VCS) and labile (CL and VCL) categories for all remaining days of display ($P < 0.0001$).

Although an interaction ($P < 0.0001$) between stability group and day was observed for chop lightness (Figure 4A), this interaction was likely the result of an increase in CS and NT chop lightness between Day 6 and 7 of display. In agreement with ventral loin quality observations, chops categorized as CL and VCL were lighter than CS and VCS chops throughout the entire display period ($P < 0.0001$), with chops categorized as NT intermediate to chops from stable (CS and VCS) and labile (CL and VCL) categories ($P < 0.0001$) during the same period. Instrumental redness also aligned with quality observations. Chops categorized as CS and VCS were redder than chops categorized as CL and VCL for all days of display except Day 7 ($P < 0.0001$; Figure 4B). Redness of all chops

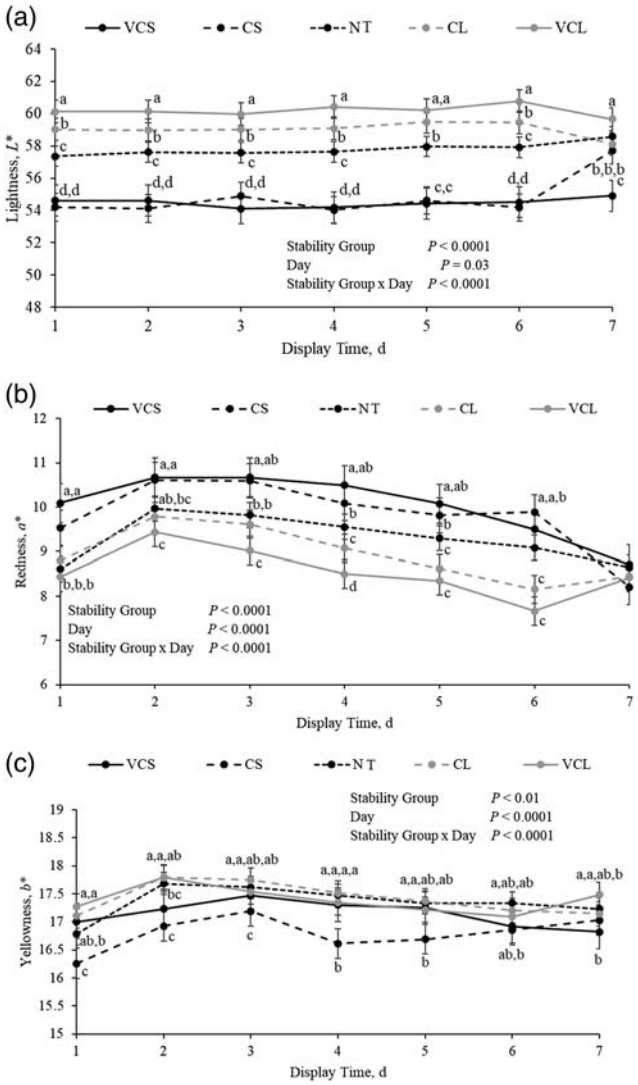

Figure 4. Effect of color stability group on instrumental lightness (A), redness (B), and yellowness (C) of boneless pork chops across 7 d of retail display. Color stability categories, within a day, lacking common superscripts were different ($P < 0.05$). CL = Color Labile (25% to <30% final discoloration), CS = Color Stable (5% to <10% final discoloration), NT = Neutral (10% to <25% final discoloration), VCL = Very Color Labile (≥30% final discoloration), VCS = Very Color Stable (<5% final discoloration),.

increased from Day 1 to 2 ($P < 0.0001$), regardless of stability category, before decreasing between Day 2 and 6 ($P < 0.0001$). Chops from CL and VCL loins had greater decreases in redness from Day 2 to 6 (Δ a^* = 1.63 and 1.77, respectively) compared with chops from NT, CS, and VCS loins (Δ a^* = 0.88, 0.73, and 1.17, respectively). Minimal differences in yellowness during display were observed between chops from stable (CS and VCS) and labile (CL and VCL) categories (Figure 4C). Interestingly, differences in yellowness were driven by decreased yellowness values for chops from NT loins from Day 1 to 5 of display compared with other categories ($P < 0.0001$). Minimal differences in yellowness were observed between color stability categories during display.

Chops categorized as NT had MMb that was similar to CL and VCL chops until Day 4 of display ($P \geq 0.08$; Figure 5A), after which *N* chops were intermediate to either stable (CS and VCS) and labile (CL and VCL) categories ($P < 0.0001$). Furthermore, chops from VCS, CS, and NT loins had smaller numerical decreases in MMb from Day 1 to 7 of display (Δ MMb = 14.80, 14.36, and 13.60, respectively) compared with CL and VCL loins (Δ MMb = 17.33 and 17.55, respectively). A day × stability category interaction was observed for both DMb and OMb ($P <$ 0.0001; Figure 5B and 5C, respectively). Chops from

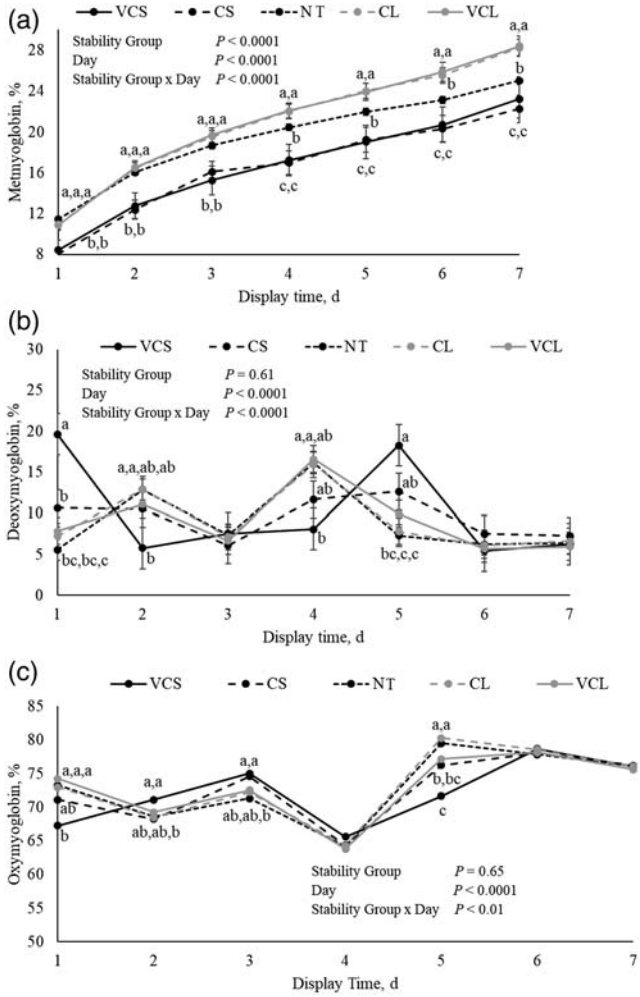

Figure 5. Effect of color stability group on metmyoglobin (A), deoxymyoglobin (B), and oxymyoglobin (C) content of boneless pork chops across 7 d of retail display. Color stability categories, within a day, lacking common superscripts were different ($P < 0.05$). Abbreviations: CL = Color Labile (25% to <30% final discoloration), CS = Color Stable (5% to <10% final discoloration), NT = Neutral (10% to <25% final discoloration), VCL = Very Color Labile (≥30% final discoloration), VCS = Very Color Stable (<5% final discoloration).

VCS loins had the greatest DMb and least OMb on Day 1 of display ($P < 0.0001$). However, differences in DMb and OMb between groups were inconsistent from Day 2 to 7 of display.

Discussion

Despite substantial research into consumer perception of and biochemical mechanisms behind fresh beef discoloration, little is known regarding fresh pork color stability. Many of the quality traits commonly measured in both beef and pork, including color, marbling, and pH, are related to beef color stability (O'Grady et al., 2001; McKenna et al., 2005; Wheeler et al., 2005) and may likely affect pork color stability as well. Although Zhu and Brewer (1998) and King et al. (2011b) have identified color traits associated with CS and CL pork loins, limited research has related other commonly measured quality traits to pork color stability. This is problematic because substantial differences in pork and beef color make it difficult to draw conclusions about pork color stability using beef-specific research. Mb, the water-soluble protein primarily responsible for meat color, has structural differences between pork and beef that may influence discoloration patterns between the two (Suman et al., 2006). For example, homology-based modeling has indicated that differences in the distance between distal histidines and heme may contribute to differences between bovine and porcine Mb oxygen affinity (Nerimetla et al., 2016). Oxidation byproducts preferentially bind to different sites on beef Mb compared with pork Mb, resulting in decreased oxidative stability for beef Mb (Suman et al., 2006). Additionally, Mb forms (DMb, OMb, and MMb) in beef typically differ in lightness and redness on a unit for unit basis (Hunt et al., 1999) while differing in lightness but not redness in pork (Fernández-López et al., 2000). Therefore, further investigation into the relationship between quality traits and pork color stability was necessary.

Pork loins in the present study represented a wide range of visual discoloration scores (final discoloration scores ranged from 0% to 54% discoloration). The majority of loins were categorized as NT, with 63% of loins falling into this category. More loins were categorized as labile (CL or VCL) than stable (CS or VCS), as 3.51% and 4.75% of loins were VCS and CS, respectively, whereas 15.91% and 12.81% of loins were CL and VCL, respectively. As expected, chops from loins in different categories differed in their rate of discoloration and final discoloration score. Categories began to differ in discoloration score as early as Day 3, then from Day 4 to 7, no categories had the same average discoloration score. There was at least a 6.61% difference in visual discoloration between groups on Day 7 of display. Overall, categorizing loins based on final discoloration score successfully differentiated loins based on rate of discoloration as well.

In comparing quality traits, chops that were considered "stable" (CS and VCS) came from loins with greater pH values and decreased purge loss after aging compared with NT or "labile" (CL and VCL) chops. As the pH of meat increases, the polarity of meat increases as well and water-holding capacity is improved, resulting in less purge loss (Huff-Lonergan and Lonergan, 2005). Thus, the observation of increased pH and reduced purge loss was expected. Purge loss per se is not expected to alter color stability. However, pH difference may directly impact color stability. Fresh meat contains enzymatic systems that are capable of reducing MMb to DMb (Mancini and Hunt, 2005). Activity of these enzymatic processes increase with increasing pH, ultimately reducing MMb accumulation (Bekhit and Faustman, 2005). Further prolonging color shelf life, Mb is oxidized at a slower rate when pH increases (Faustman and Cassens, 1990). Despite this, the impact of pH on LL color stability in beef is unclear. Ledward et al. (1986) and O'Grady et al. (2001) each reported greater color stability of higher pH LL steaks, whereas King et al. (2011a) and Canto et al. (2015) observed no pH differences between LL steaks classified as CS or CL. The latter study, however, had a small range of pH values (5.41 to 5.74), whereas O'Grady et al. (2001) reported pH ranges of 5.25 to 6.26 (O'Grady et al., 2001). Ledward et al. (1986) did not report ranges in pH values; however, they had low and high pH groups with average pH values of 5.60 and 5.94, respectively. Had there been a greater range in pH values in the studies by King et al. (2011a) and Canto et al. (2015), differences between stability groups may have been observed.

Chops categorized as VCS or CS were also initially (Day 1 of retail display) darker than VCL and CL chops when evaluated subjectively and instrumentally and remained darker during display. In contrast, minimal differences in lightness were observed between beef *longissimus* steaks classified as CS or CL, both initially and during retail display (McKenna et al., 2005; King et al., 2011b; Canto et al., 2015). Differences in lightness between stability categories in the current study may have been attributable to pH differences. Ledward et al. (1986) observed that steaks with greater pH values tended to have decreased lightness compared with lower pH steaks. When more water is

present, the surface of the meat absorbs more light and appears darker (Huff-Lonergan and Lonergan, 2005). In pork, instrumental lightness has been negatively correlated with ultimate pH and positively correlated with NPPC color score and water-holding capacity (Huff-Lonergan et al., 2002; Boler et al., 2010). Despite differences in lightness between color stability categories, chop lightness (L^*) did not change over display for any individual stability category until Day 7. Zhu and Brewer (1998) also reported that pork chop lightness did not change during retail display. Initial lightness may be more important for pork color stability than changes in lightness during display. Overall, stable pork chops came from loins that were darker and had higher ultimate pH values. These would typically be considered "higher quality" loins and, according to the present study, would also possess improved color stability.

There were no differences in ventral loin surface instrumental redness between color stability groups. However, over the course of retail display, chops from stable categories were generally redder than chops from NT and labile categories. The lack of differences during quality analyses may be due to instrumentation used. Aged ventral loin instrumental color was measured using a Minolta colorimeter, whereas instrumental color of loin chops during retail display was measured using a HunterLab spectrophotometer. Because the Minolta colorimeter has a smaller aperture than the HunterLab (8 vs. 31.8 mm), the magnitude of difference between a^* redness values is reduced (AMSA, 2012). Greater redness values observed in CS loin chops were unexpected because greater redness in beef is typically associated with a lower overall color stability (Faustman et al., 2010). In beef, greater redness has been associated with a greater proportion of oxidative muscle fibers containing a greater number of mitochondria and Mb for use in oxidative metabolism (Ramanathan and Mancini, 2018). In postmortem muscle, mitochondria produce reactive oxygen species as a byproduct of aerobic respiration that can accumulate and exacerbate Mb oxidation (Ramanathan et al., 2018). Alternatively, glycolytic fibers contain greater concentration of glycolytic enzymes, which may generate nicotinamide adenine dinucleotide to be used in MMb reducing reactions (Nair et al., 2018). Beef cattle possess a greater proportion of oxidative fibers than pigs (30% in beef *longissimus* vs. 10% in pork *longissimus*; Zhang et al., 2017). Because pork skeletal muscle is more glycolytic by nature, pork may contain a greater proportion of glycolytic enzymes capable of supplying nicotinamide adenine dinucleotide to reduce MMb than beef. As a result, the increased number of mitochondria associated with more oxidative muscle may not have as pronounced an effect on pork loin color stability. Alternatively, oxidative muscle experiences a less intense decline in pH decline compared with glycolytic fibers due to a decreased glycogen content (Huff-Lonergan and Lonergan, 2005). This increased pH may promote enzymatic MMb reduction and improve color stability in more oxidative pork. Further research is necessary to determine whether differences in redness is an important indicator of color stability in pork as it is in beef. However, results of the current study would indicate that redder pork loins have increased color stability.

CS and VCS chops were less yellow at Day 1 of retail display and came from loins that were less yellow prior to slicing. Stable loins also had increased DMb and decreased OMb on Day 1 of display, both of which are related to decreased yellowness in pork (Karamucki et al., 2013). Despite these differences, minimal changes in yellowness were observed within color stability categories over the retail display period. Zhu and Brewer (1998) and King et al. (2011a) also observed decreased yellowness in pork loins or loin chops that were considered stable. Alternatively, conflicting results have been observed in beef, as King et al. (2011b) reported increased yellowness in CS steaks, whereas Canto et al. (2015) observed no differences in yellowness between steaks assigned to different color stability groups. Instrumental yellowness is not typically related to meat, partially because consumers have difficulty determining differences in meat yellowness during sensory evaluation (O'Sullivan et al., 2003; Mancini and Hunt, 2005). However, based on results of this study and previous research, initial (Day 1 of display) yellowness may be more important for pork stability characterization than for standard loin color evaluations and may be more relevant for color stability of pork compared with beef. Overall, decreased yellowness appears to be associated with increased color stability in pork chops.

Stable chops in the current study generally had greater amounts of marbling on the ventral loin surface compared with labile chops. Limited research is available investigating the relationship between marbling and color stability, regardless of animal type. However, Wheeler et al. (2005) speculated that metabolic differences contributing to increased muscle growth and decreased fatness may contribute to increased color stability in beef. This would imply that animals with a greater level of marbling discolor at a faster rate, in contrast to what was observed in the current study. The present study involved pigs from different sire lines, including some lines considered as meat

quality–focused. Typically, loins from meat quality–focused pigs are darker and redder in color, have an increased pH, and have a greater proportion of marbling than lean growth-focused pigs (NPPC, 1998; Arkfeld et al., 2017; Lowell et al., 2018). In the present study, loins that produced CS chops possessed traits that are already typically associated with high quality pork. This may indicate that selecting for meat quality traits that are already important in the industry, such as higher marbling, may result in greater color stability as well. Nonetheless, further research is necessary to determine the direct impact of marbling on pork color stability.

Stable chops had increased R630/580 and decreased MMb over the display period compared with labile chops. This was expected because an increased 630/580 nm ratio is indicative of greater redness and less brownness on the surface of fresh meat (AMSA, 2012). For this study, the Krzywicki (1979) method was used to determine MMb content. Although MMb estimates generated using this method are different compared with the K/S method of determination (using absorption and scattering coefficients), which provides a more accurate assessment of true MMb content, both methods are highly correlated ($R^2 = 0.9390$) to each other and equivalent for statistical analysis to determine differences in pigment concentration between samples (Hernández et al., 2015). However, 20% MMb measured using the Krzywicki method is approximately equivalent to 20% measured using the K/S method (Hernández et al., 2015). This percentage is important because 20% is the amount of MMb commonly referenced, in beef, as the threshold at which consumers begin to discriminate against discoloration (Renerre and Labas, 1987; Gill and Jones, 1994). Assuming the threshold is similar in pork, instrumental MMb values in this study would indicate that "labile" and "very labile" chops reach a perceptible level of discoloration at Day 4 of retail display, whereas "neutral" chops do not discolor to a meaningful degree until Day 5 and "stable" or "very stable" chops are acceptable until Day 6. These values do not necessarily align with visual discoloration scores because VCL and CL chops did not reach 20% discoloration on average until Day 6 and 7, respectively, whereas NT, VCS, and CS did not reach 20% discoloration during the study. However, both instrumental MMb determination and visual discoloration scores would indicate that VCL chops discolored at least 2 d earlier than chops from stable groups. Although further research is needed to determine actual consumer discrimination thresholds for discoloration in pork, data from this study would indicate that selecting for "color stable" pork could improve retail display duration by as much as 2 d.

Conclusions

Differences in color stability were observed between boneless pork chops classified as "stable" and "labile" in this study based on instrumental and visual discoloration assessment. CS chops were generally from loins that were darker and redder and had greater levels of pH and marbling compared with labile chops. This study would also indicate differences in characteristics of stable pork compared with beef because stable chops in the current study typically came from loins that were redder and had greater marbling on the ventral surface, whereas in beef, CS steaks are typically less red and have been indicated to contain less marbling. Data from this study would also indicate that retail display duration of chops could be improved by as much as 2 d if loins were selected for greater color stability. However, further research into consumer discrimination of discolored pork is necessary to draw further conclusions.

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