Meat and Muscle Biology™

Chilling Rates Impact Carcass and Meat Quality Parameters of *Bos indicus* Cattle

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Abstract: This study evaluated the impact of chilling decline rates on carcass and meat quality parameters of *Bos indicus* cattle. Eighty Nellore bull carcass halves were used, allocated equally into 2 treatments: conventional and dynamic chilling environment. Temperature and pH were recorded at 0, 2, 4, 6, 12, and 24 h in the *longissimus thoracis* muscle. Cold carcass weight and meat samples were extracted 24 h post-slaughter. Cold carcass weight tended to be lower in the dynamic environment ($P = 0.096$). Shrink percentage was higher in the conventional than in the dynamic chilling environment ($P = 0.049$). The pH values were significantly higher in the dynamic chilling environment at 2, 4, 6, and 12 h after slaughter ($P < 0.022$). Also, there was a tendency for high ultimate pH in the dynamic treatment ($P = 0.059$). Temperature values were significantly lower in the dynamic treatment from 4 to 24 h postmortem ($P < 0.001$) compared with the conventional treatment. Carcasses subjected to the conventional chilling rate presented higher temperatures at pH 6 ($P < 0.001$), which was reached in a shorter period ($P = 0.024$). Carcasses in the conventional treatment had a lower pH at the temperature of 18°C than in the dynamic chilling environment ($P < 0.001$). There were no differences in water losses and sarcomere length between chilling environments ($P \geq 0.344$). However, meat samples from the conventional chilling environment had higher mean values for color parameters a^*, b^*, oxymyoglobin, and chroma ($P \leq 0.006$) and a tendency for lower shear force ($P = 0.06$). In contrast, the deoxymyoglobin value was higher in the dynamic than the conventional chilling treatment ($P = 0.002$). The variation in chilling rate impacted mainly the decline in meat pH and meat color, with the dynamic chilling environment producing a less bright red color.

Key words: color, beef industry, Nellore, pH, temperature decline, tenderness
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Introduction

During the first 24 h postmortem, the chilling environment directly impacts carcass temperature and pH decline rates, which are considered critical regulators of the development of meat quality parameters (White et al., 2006). Temperature and pH play an important role in establishing rigor mortis and enzyme activity during the aging process, which can mainly affect meat color and tenderness (Jerez-Timaure et al., 2019).

According to the ideal temperature/pH window concept, beef carcasses should reach the pH value of 6 while the carcass temperature is still between 12°C and 35°C (Thompson, 2002). This concept emerged from the studies of Locker and Hagyard (1963), who demonstrated that myofibrillar shortening would increase when muscles were exposed to temperatures outside of this range. In agreement, Devine et al. (2002) showed that rigor at approximately 10°C to 18°C minimizes sarcomere shortening and maximizes aging potential, which leads to tender meat. Furthermore, some studies have shown that rapid chilling rates can result in darkening of the meat (Janz et al., 2002; Holdstock et al., 2023).

Traditional chilling protocols, with temperatures ranging from 0°C to 4°C, are widely used in the meat industry. Different chilling protocols have been studied to reduce the extent of cold shortening or reduce carcass weight loss, e.g., delayed and fast chilling, respectively (Zhang et al., 2019). However, the extent to which the chilling rate can be altered without causing noticeable darkening or toughening in beef is unknown (Holdstock et al., 2023). Because meat color and tenderness are key drivers of consumer purchasing decisions, chilling environments must be periodically evaluated to avoid low standards in meat quality.

Most studies evaluating the chilling effects on carcass and meat quality were conducted either on small ruminant carcasses (Devine et al., 2002; Vieira and Fernández, 2014; Hopkins et al., 2015) or *Bos taurus* carcasses (White et al., 2006; Haines et al., 2022; Holdstock et al., 2023). Usually, the rate of temperature change typically varies both between and within carcasses, with smaller carcasses and superficial muscles experiencing a more rapid cooling process (Jacob and Hopkins, 2014). Thus, accelerating the chilling process of *Bos indicus* carcasses, known for their lighter weight, to achieve the desired deep tissue temperature within 24 h postmortem may impact the overall quality of the meat.

Therefore, we hypothesized that slight increases in temperature decline rate on *Bos indicus* carcasses would yield tougher and darker meat. To test this hypothesis, our study aimed to evaluate the effect of conventional chilling compared with a dynamic chilling environment, designed to accelerate the cooling rate, on the temperature/pH decline rate and meat quality parameters of *Bos indicus* carcasses.

Materials and Methods

Experimental design

This study was carried out in a commercial slaughter facility with export certificates. Chilling rates and meat quality parameters were evaluated on *Bos indicus* carcasses placed into 2 chilling environments according to the industry standards: conventional and dynamic.

In the conventional environment, the chilling room was characterized by a steady setup of 4°C for 24 h and equipped with evaporators on one side. In contrast, the dynamic chilling room implemented a programmable temperature protocol, initiating at 9°C and gradually decreasing by 1.425°C per hour during the initial 4 h postmortem, followed by a setup of 3.3°C until 24 h. In this arrangement, the cooler room was equipped with evaporators on 2 opposing sides to enhance the cooling rate of the carcasses.

Eighty carcasses of *Bos indicus* Nellore bulls were evenly distributed between the 2 treatment groups. The animals had an average age of 23.67 ± 5.12 mo old and a cold carcass weight (CCW) averaging at 296.2 ± 16.7 kg. Fat cover was classified as scarce (1 to 3 mm), whereas muscle conformation was classified as regular, based on the commercial plant classification. The evaluations were performed over 2 d, with daily assessments of 20 carcasses per treatment group, resulting in a total of 40 carcasses per treatment.

Temperature, pH, and sample collection

Carcasses temperature and pH were recorded at 0, 2, 4, 6, 12, and 24 h in the *longissimus thoracis* (LT) muscle between the level of the 12th and 13th ribs. The initial time (0 h) was considered when the chilling room was filled and closed. A portable pH meter, Pro2Go (Mettler Toledo, Columbus, OH), and a digital food thermometer (−50°C to +300°C) were used to measure pH and temperature, respectively. The pH meter was calibrated using pH standards of 4 and 7.

Following 48 h of chilling, the LT of each left carcass was sampled, vacuum-packaged individually, frozen, and stored at −20°C until subsequent meat quality analysis.

Meat quality analysis

The difference between the CCW and hot carcass weights (HCW) was used to calculate the 24 h shrink percentage as follows: $Shrink\ percentage = (1 - (CCW \div HCW)) \times 100$.

Meat quality analysis was performed at the Meat Science Laboratory of the Universidade Federal de Viçosa, MG, Brazil. One-inch steaks were obtained from the frozen LT portion using a butcher band saw. One steak was used for color measurements, whereas another was used for evaluating water losses, Warner-Bratzler shear force (WBSF), and sarcomere length.

Color measurements

For meat color measurement, steaks were thawed overnight at 4°C, removed from vacuum packages, and exposed to oxygen 30 min prior to measurements. Values of L^* (lightness), a^* (redness), and b^* (yellowness) and the reflected light wavelengths were obtained from 5 readings performed at different points of the steak

surface using a Hunter MiniScan EZ colorimeter (4500L; HunterLab, Inc., Reston, VA) adjusted to the illuminant source D65, aperture size of 31.8 mm, and observer 10° angle. The estimated chroma and hue values were calculated using the equations provided in the American Meat Science Association (AMSA) Meat Color Measurement Guidelines (King et al., 2023): $Chroma = [(a^{*2} + b^{*2})^{0.5}]$ and $Hue = [(arctangent\ (b^*/a^*)]$.

The wavelengths were used to determine the percentage of metmyoglobin (MMb), deoxymyoglobin (DMb), and oxymyoglobin (OMb) following AMSA equations (King et al., 2023): $\%MMb = \{1.395 - [(A572 - A730) \div (A525 - A730)]\} \times 100$; $\%DMb = \{2.375 \times [1 - (A474 - A730) \div (A525 - A730)]\} \times 100$; and $\%OMb = 100 - (\%MMb + \%DMb)$.

Thawing, cooking, and total losses

The thawing loss was estimated by the weight difference between frozen and thawed steaks. Thawed steaks were vacuum-packed and cooked in a water bath at 70°C for 30 min. Subsequently, the steaks were placed in an ice bath for 10 min to stop the cooking process and kept in the refrigerator for 24 h. Lastly, steaks were removed from the package and weighed again to obtain water cooking loss. The total water loss in each steak was calculated using the following equation: $Total\ water\ loss\ (\%) = [(frozen\ steak\ weight - cooked\ steak\ weight)/frozen\ steak\ weight] \times 100$.

Warner-Bratzler shear force

To determine WBSF, cooked steaks were cooled for 24 h at 4°C, following the guidelines of AMSA (American Meat Science Association, 2016). Six cylindrical samples, each measuring 1.27 cm in diameter, were then removed from the steaks parallel to the long axis of the muscle fibers, using a stainless-steel device to extract samples (AMSA, 2016). The shear force was determined by perpendicular incision of the muscle fibers of each cylinder of meat by Warner-Bratzler shear device (G-R Electrical Manufacturing Company, Manhattan, KS) equipped with a 1.1684 mm thick V-notched (60° angle) cutting blade at a constant speed of 2 mm/s and with a rechargeable 500 N digital force gauge (Mecmesin Basic Force Gauge; Mecmesin, Sterling, VA) to measure and record peak force during sample processing.

Sarcomere length

Sarcomere length was estimated according to the laser diffraction technique (Cross et al., 1981). Six individual muscle fibers were teased from the muscle bundle and placed on a microscope slide with a drop of 0.2 M sucrose solution (0.2 M glucose and 0.1 M sodium phosphate buffer with pH 7). Sarcomere length was measured by laser diffraction using a 05-LHR-021 laser (Melles Griot, Carlsbad, CA) and calculated by using the following equation: $Sarcomere\ length\ (\mu m) = [0.6328 \times D \times \sqrt{(T/D)^2 + 1}]/T$, in which D = distance (mm) from the specimen-holding device to the screen (D had a constant value of 120 mm), and T = the separation (mm) between the zero and the first maximum band.

Statistical analysis

Data were analyzed on SAS v. 9.4 (SAS Institute, Inc., Cary, NC), with each carcass treated as an experimental unit in a completely randomized design. Outliers were removed based on CCW using the SGPLOT procedure, eliminating experimental units with CCW outside of the minimum and maximum fence of the box plot. After this step, 39 experimental units were retained for each treatment.

To estimate the decline rate in pH and temperature as a function of time after slaughter, we used the NLIN procedure according to the following exponential equation: $Y_{(t)} = A_{(i)} + (A_{(u)} \times (exp^{(Kt)}))$, in which $Y_{(t)}$ is the pH or temperature at time t; $A_{(i)}$ is the initial pH or temperature; $A_{(u)}$ is the ultimate pH or temperature the carcasses can reach; K is the decay rate; and t is the time in hours after slaughter.

The parameters $A_{(i)}$, $A_{(u)}$, and K were used to predict pH and temperature decline during the first 24 h of carcass chilling and to predict the pH in different temperature degrees (Figures 1 and 2, respectively) as well as the time in hours to reach pH 6 (time_pH6), the carcass temperature at pH 6 (temp@pH6), the time in hours to reach temperature 18°C (time_temp18), and

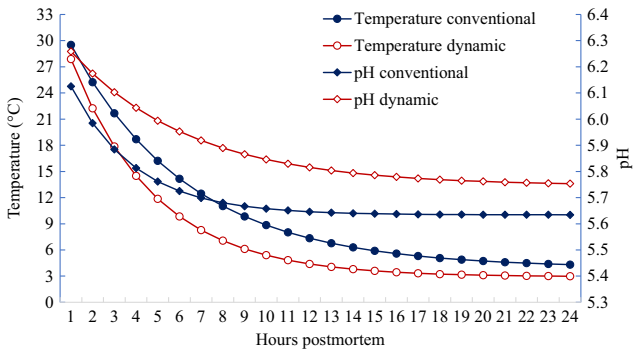

Figure 1. Estimated temperature and pH decline of conventional and dynamic chilling environments during the first 24 h postmortem period.

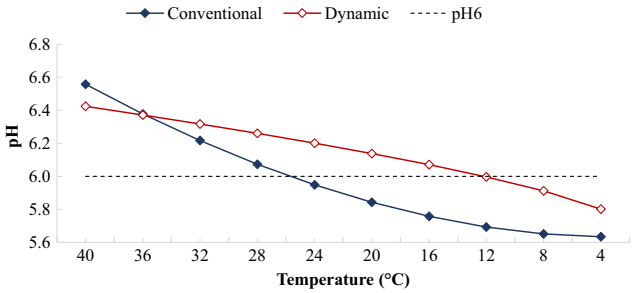

Figure 2. pH declines of conventional and dynamic chilling environments applied on the pH/temperature window.

the carcass pH at temperature 18°C (pH@temp18). The relationships between temperature/pH parameters and beef quality measurements were performed using Pearson correlation (Table 1).

To evaluate the effects of chilling environments (conventional vs. dynamic) on carcass and meat quality parameters, we used mixed models (PROC MIXED) with CCW included as a covariate and slaughter day as a random effect to compare the mean of the pH and temperature parameters, following the statistical model as follows: $Y_{ij} = \mu + T_i + cov(CCW) + D_j + e_{(i)j}$, in which Y_{ij} is the response measured in carcass j subjected to treatment i; μ is the overall mean; T_i is the fixed effect of treatment i (conventional or dynamic); $cov(CCW)$ is the CCW added as covariate; D_j is the random effect associated with days of collection for carcass j; and $e_{(i)j}$ is the residual error associated with each experimental unit j.

The model used to evaluate CCW, HCW, shrink percentage, and meat quality parameters comprised the fixed effect of treatment and residual error. The least squares means (LSMEANS) were used to determine significant differences among treatments. Significance was declared at $P \leq 0.05$, and a tendency was reported if $0.05 < P < 0.10$.

Results

The estimated temperature and pH decline of conventional and dynamic chilling environments during the first 24 h postmortem period and the pH decline alongside the temperature decline are shown in Figures 1 and 2, respectively. During the first 24 h window, pH values of the dynamic chilling environment remained higher than the conventional chilling. Carcasses in the conventional environment reached pH of 6.0 at a higher temperature ($P < 0.01$) than carcasses in the dynamic environment (Table 1 and Figure 2).

Pearson correlation coefficients reveal significant correlations between temperature and pH, specifically time_pH6, temp@pH6, time_temp18, and pH@temp18, and meat quality parameters, with variations observed across different chilling environments (Table 1).

Percentage of MMb was negatively correlated with L^*, a^*, b^*, and chroma ($r = -0.33$, -0.47, -0.40, and -0.50, respectively) values in the dynamic chilling environment. In contrast, there were no correlations ($P \geq 0.102$) between MMb and color parameters in the conventional chilling environment. DMb was negatively correlated ($P \leq 0.018$) with meat color parameters (L^*, a^*, b^*, and chroma), whereas OMb was positively correlated with L^*, a^*, b^*, and chroma ($P \leq 0.004$) in conventional chilling and with a^*, b^*, and chroma ($P \leq 0.002$) in dynamic chilling environment.

Carcass and meat quality parameters are presented in Tables 2 and 3, respectively. There was a tendency ($P = 0.096$) for higher CCW in the conventional treatment. The shrink percentage was higher in conventional than dynamic chilling environments, 1.63% and 1.48%, respectively ($P = 0.049$), representing an average loss of 0.48 kg per carcass (Table 2).

There was a tendency ($P = 0.059$) for higher ultimate pH within the dynamic chilling environment. The pH values were significantly higher in the dynamic chilling environment at 2, 4, 6, and 12 h after slaughter ($P < 0.05$), whereas temperature values were significantly lower in the dynamic treatment from 4 to 24 h postmortem ($P < 0.001$) compared with the conventional treatment (Table 2).

Carcasses subjected to the conventional chilling presented higher temperatures at pH of 6 ($P < 0.001$), which was reached in a shorter period ($P = 0.024$) than the dynamic environment, 2.51 and 5.75 h, respectively. Furthermore, carcasses in the conventional treatment had a lower pH at the temperature of 18°C than the dynamic treatment ($P < 0.001$), taking 0.87 h longer to reach the same temperature ($P < 0.001$).

There were no differences in water losses (thawing loss, cooking loss, and total water loss) between chilling environments ($P > 0.05$) (Table 3). However, there were notable differences in color parameters between the 2 treatments. Meat samples subjected to conventional chilling environment exhibited significantly higher mean values for parameters a^*, b^*, chroma, and OMb, ($P \leq 0.006$). In contrast, the DMb value was higher in the dynamic chilling treatment than in the conventional ($P = 0.002$) (Table 3). Parameters L^* and hue, however, remained consistent across both treatments.

There was no difference in sarcomere length between treatments ($P = 0.538$). However, there was

Table 1. Pearson correlations and *P* values indicating the relationships between temperature/pH parameters and beef quality measurements

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. Time_pH6	1	**−0.567**	0.014	**0.623**	**−0.605**	0.096	−0.177	**−0.527**	−0.010	**−0.393**	−0.233	**0.418**	0.041	−0.182	0.125	**−0.491**	−0.316
		0.001	0.939	**<0.001**	**<0.001**	0.607	0.342	**0.002**	0.956	**0.029**	0.207	**0.019**	0.825	0.326	0.502	**0.005**	0.084
2. Temp@pH6	**−0.906**	1	0.259	**−0.950**	0.165	−0.162	−0.102	0.334	0.245	**0.424**	**0.392**	−0.239	−0.023	−0.056	0.055	−0.158	**0.413**
	<0.001		0.160	**<0.001**	0.375	0.383	0.585	0.067	0.185	**0.018**	**0.029**	0.195	0.902	0.764	0.770	0.395	**0.021**
3. Time_temp18	0.022	0.215	1	−0.247	0.033	**0.356**	**0.351**	−0.095	0.301	0.101	0.223	0.103	−0.112	−0.210	0.217	0.126	0.025
	0.897	0.208		0.180	0.849	**0.036**	**0.039**	0.593	0.084	0.571	0.205	0.562	0.527	0.234	0.217	0.472	0.886
4. pH@temp18	**0.823**	**−0.915**	−0.283	1	−0.183	0.196	0.130	**−0.369**	−0.225	**−0.460**	**−0.402**	0.291	−0.011	0.059	−0.041	0.108	**−0.449**
	<0.001	**<0.001**	0.094		0.324	0.291	0.486	**0.041**	0.223	**0.009**	**0.025**	0.112	0.952	0.753	0.825	0.563	**0.011**
5. TL	0.026	−0.168	**−0.689**	0.189	1	−0.187	**0.353**	**0.676**	−0.085	**0.596**	0.316	**−0.763**	−0.037	0.156	−0.103	**0.751**	0.106
	0.881	0.328	**<0.001**	0.269		0.254	**0.028**	**<0.001**	0.611	**<0.001**	0.053	**<0.001**	0.824	0.351	0.540	**<0.001**	0.522
6. CL	0.147	0.033	**0.797**	−0.132	**−0.585**	1	**0.853**	−0.264	0.125	**−0.424**	−0.199	**0.555**	0.081	−0.019	−0.023	0.146	**−0.361**
	0.391	0.848	**<0.001**	0.441	**<0.001**		**<0.001**	0.109	0.454	**0.008**	0.230	**<0.001**	0.629	0.909	0.891	0.375	**0.024**
7. TWL	0.191	−0.033	**0.649**	−0.079	−0.269	**0.938**	1	0.107	0.077	−0.084	−0.018	0.121	0.056	0.059	−0.071	**0.539**	−0.281
	0.265	0.849	**<0.001**	0.645	0.098	**<0.0001**		0.522	0.647	0.618	0.915	0.469	0.738	0.727	0.670	**<0.001**	0.083
8. Color *L**	0.298	−0.143	0.220	−0.007	−0.029	0.232	0.270	1	0.073	**0.769**	**0.511**	**−0.827**	**−0.337**	−0.046	0.192	**0.390**	**0.342**
	0.077	0.406	0.185	0.968	0.859	0.156	0.096		0.665	**<0.001**	**0.001**	**<0.001**	**0.039**	0.782	0.247	**0.016**	**0.036**
9. Color *a**	−0.027	0.146	**0.633**	−0.294	**−0.538**	**0.551**	**0.425**	0.178	1	**0.502**	**0.846**	0.159	**−0.477**	**−0.667**	**0.736**	−0.138	**0.504**
	0.877	0.396	**<0.001**	0.082	**<0.001**	**<0.001**	**0.007**	0.279		**0.001**	**<0.001**	0.340	**0.002**	**<0.001**	**<0.001**	0.410	**0.001**
10. Color *b**	−0.035	0.105	0.273	−0.308	−0.156	0.117	0.074	**0.455**	**0.739**	1	**0.885**	**−0.770**	**−0.403**	**−0.381**	**0.481**	0.248	**0.596**
	0.840	0.542	0.097	0.068	0.344	0.478	0.657	**0.004**	**<0.001**		**<0.001**	**<0.001**	**0.012**	**0.018**	**0.002**	0.133	**<0.001**
11. Chroma	−0.028	0.136	**0.527**	−0.315	**−0.417**	**0.407**	0.306	**0.319**	**0.958**	**0.900**	1	**−0.388**	**−0.506**	**−0.594**	**0.694**	0.072	**0.640**
	0.870	0.431	**0.001**	0.061	**0.008**	**0.010**	0.058	**0.048**	**<0.001**	**<0.001**		**0.016**	**0.001**	**<0.001**	**<0.001**	0.669	**<0.001**
12. Hue	−0.022	0.092	**0.588**	−0.036	**−0.598**	**0.640**	**0.504**	**−0.376**	**0.550**	−0.146	0.289	1	0.094	−0.043	−0.011	−0.431	−0.303
	0.900	0.592	**<0.001**	0.835	**<0.001**	**<0.001**	**0.001**	**0.018**	**<0.001**	0.375	0.075		0.574	0.798	0.949	0.007	0.064
13. MMb	**−0.507**	**0.417**	−0.176	**−0.386**	0.181	−0.249	−0.214	−0.214	−0.266	−0.224	−0.268	−0.117	1	0.265	**−0.669**	−0.007	−0.134
	0.002	**0.012**	0.289	**0.020**	0.270	0.126	0.191	0.191	0.102	0.171	0.098	0.479		0.108	**<0.001**	0.967	0.421
14. DMb	0.023	−0.166	**−0.571**	0.309	**0.397**	**−0.421**	**−0.338**	**−0.378**	**−0.704**	**−0.580**	**−0.705**	−0.291	−0.067	1	**−0.894**	0.124	**−0.450**
	0.896	0.333	**<0.001**	0.066	**0.012**	**0.008**	**0.035**	**0.018**	**<0.001**	**<0.001**	**<0.001**	0.072	0.684		**<0.001**	0.457	**0.005**
15. OMb	0.267	−0.096	**0.594**	−0.041	**−0.447**	**0.505**	**0.412**	**0.448**	**0.763**	**0.631**	**0.765**	**0.319**	**−0.478**	**−0.844**	1	−0.093	**0.409**
	0.115	0.577	**<0.001**	0.811	**0.004**	**0.001**	**0.009**	**0.004**	**<0.001**	**<0.001**	**<0.001**	**0.048**	**0.002**	**<0.001**		0.580	**0.011**

Table 1. (*Continued*)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
16. WBSF	**0.387**	**−0.342**	0.058	**0.406**	0.205	0.217	0.346	0.005	−0.179	−0.276	−0.235	0.096	−0.328	0.206	−0.005	1	−0.107
	0.020	**0.041**	0.732	**0.014**	0.211	0.185	0.031	0.977	0.276	0.090	0.150	0.561	0.041	0.208	0.975		0.518
17. SL	**−0.394**	0.286	**−0.615**	−0.195	**0.457**	**−0.602**	**−0.507**	0.031	**−0.363**	−0.019	−0.242	**−0.515**	0.301	0.228	**−0.362**	**−0.433**	1
	0.019	0.096	**<0.001**	0.262	**0.004**	**<0.001**	**0.001**	0.854	**0.025**	0.908	0.143	**0.001**	0.066	0.169	**0.026**	**0.007**	

Note: Values above the main diagonal represent the correlation between variables in the dynamic environment, whereas values below the main diagonal represent the correlation between variables within the conventional environment.

Time_pH6 = time in hours to reach pH of 6; Temp@pH6 = carcass temperature at pH of 6; Time_temp18 = time in hours to reach temperature 18°C; pH@temp18 = carcass pH at temperature 18°C.

1. Time_pH6 (hours); 2. Temp@pH6 (°C); 3. Time_temp18 (hours); 4. pH@temp18; 5. Thawing loss (%); 6. Cooking loss (%); 7. Total water loss (%); 8. Color *L**; 9. Color *a**; 10. Color *b**; 11. Chroma; 12. Hue; 13. Metmyoglobin (%); 14. Deoxymyoglobin (%); 15. Oxymyoglobin (%); 16. Warner-Bratzler shear force (kgf); 17. Sarcomere length (μm).

Significant correlations ($P \leq 0.05$) are highlighted in bold.

Table 2. Effect of conventional and dynamic chilling rates on carcass, pH, and temperature parameters of *Bos indicus* beef carcasses

	Chilling environments			
	Conventional	Dynamic	SEM	*P* value
Hot carcass weight (kg)	348.30	341.88	1.91	0.389
Cold carcass weight (kg)	342.16	336.22	1.89	0.096
Shrink percentage	1.63	1.48	0.04	0.049
pH				
0 h	6.35	6.38	0.02	0.519
2 h	5.99	6.15	0.03	0.014
4 h	5.84	6.08	0.03	0.001
6 h	5.81	6.01	0.03	<0.001
12 h	5.75	5.88	0.03	0.022
24 h	5.68	5.79	0.03	0.059
Temperature (°C)				
0 h	34.78	34.99	0.32	0.753
2 h	24.19	23.24	0.30	0.139
4 h	18.07	15.27	0.31	<0.001
6 h	14.21	9.97	0.38	<0.001
12 h	7.66	4.83	0.28	<0.001
24 h	4.18	3.2	0.10	<0.001
Time_pH6 (hours)	2.51	5.75	0.82	<0.001
Temp@pH6 (°C)	25.41	14.42	1.22	<0.001
Time_temp18 (hours)	4.15	3.28	0.12	<0.001
pH@temp18	5.81	6.07	0.03	<0.001

Time_pH6 = time in hours to reach pH of 6; Temp@pH6 = carcass temperature at pH of 6; Time_temp18 = time in hours to reach temperature 18°C; pH@temp18 = carcass pH at temperature 18°C; SEM = standard error of the mean.

Table 3. Effect of conventional and dynamic chilling rates on water losses, color, and tenderness parameters of *Bos indicus* beef carcasses

	Chilling environments			
	Conventional	Dynamic	SEM	*P* value
Thawing loss (%)	7.91	8.26	0.28	0.533
Cooking loss (%)	22.1	21.79	0.52	0.763
Total water loss (%)	27.91	28.68	0.45	0.344
Color *L**	36.41	35.74	0.30	0.270
Color *a**	15.59	14.42	0.21	0.006
Color *b**	13.55	12.41	0.19	0.002
Chroma	20.69	19.06	0.26	0.001
Hue	48.87	49.41	0.35	0.440
Metmyoglobin (%)	24.29	24.52	0.29	0.698
Deoxymyoglobin (%)	7.47	10.51	0.51	0.002
Oxymyoglobin (%)	68.24	64.97	0.60	0.006
WBSF (kgf)	7.11	7.94	0.22	0.060
Sarcomere length (μm)	1.42	1.43	0.01	0.538

SEM = standard error of the mean; WBSF = Warner-Bratzler shear force.

a tendency ($P = 0.06$) for tougher meat in the dynamic chilling environment compared with the conventional chilling environment (Table 3).

Discussion

The decline in chilling rate impacts meat pH, tenderness, and color, which are key quality parameters influencing purchasing decisions (Mancini and Hunt, 2005; Starkey et al., 2015). Factors such as the amount of cover fat, carcass size, spray chilling, and chilling protocol can affect the carcass chilling rate (Park et al., 2007; Djimsa et al., 2022). However, it is unclear to what extent an increase in chilling rate would negatively affect tenderness and color among carcasses with similar characteristics. In this study, we evaluated carcass and meat quality parameters of *Bos indicus* cattle subjected to 2 different chilling environments, a conventional treatment of 4°C for 24 h and a dynamic treatment implemented to increase the rate of carcass cooling. As can be seen in Figure 1 and Table 2, the treatments were effectively applied, resulting in differences on temperature decay.

As expected, the dynamic chilling environment resulted in a lower shrink percentage. According to Savell et al. (2005), weight loss due to shrinkage can reach up to 2% of the HCW, causing major economic concerns in the industry. The dynamic chilling rate in this study reduced 0.15% of the carcass shrinkage without a spray-chilling system, a well-known practice used to control carcass shrinkage. Other rapid chilling systems, which apply temperatures below freezing point, significantly reduce cooling time and shrinkage. However, these systems have also been associated with an increased proportion of darker and tougher meat, making them economically unfeasible (Aalhus et al., 2001; Savell et al., 2005; Zhang et al., 2019).

Under normal conditions, the pH falls from about 7 upon harvest to 5.4–5.7 during the first 24 h postmortem in beef carcasses, with an increased temperature accelerating the rate of pH decline (Braden, 2013). Even though we found differences in pH values among treatments, the ultimate pH values were within the typical values range. In this study, there was, on average, 11°C difference in the temperature at the pH of 6 between treatments and 3.24 h difference to achieve the pH value of 6. Even so, both chilling environments achieved the goal established by the ideal temperature/pH window with apparently no impact on sarcomere length but with a tendency for higher shear force in the dynamic environment. This outcome may be correlated with the higher pH observed in the dynamic environment. Although the glycolytic potential might be the same among treatments, the reduced glycolysis rate due to temperature decline might be influencing proteolysis, consequently impacting beef tenderness.

Pflanzer et al. (2019) conducted a study monitoring carcass temperature and pH decline in the *longissimus dorsi* of slight and lean beef carcasses ($n = 30$) divided into 2 chilling environments: control (2°C for 24 h) and delayed chilling (10°C for 10 h followed by 2°C for 14 h). Despite employing a delayed carcass chilling approach, the pH of 6 was achieved 11 h postmortem when the carcass temperature was below 7°C and 4°C for the delayed and control half carcasses, respectively, achieving the cold shortening zone of the superficial muscles of both environments. There is a wide range of variation in the response of carcass temperature and pH decay to chilling environments. Consequently, comparing chilling environments among studies becomes challenging because of the numerous factors influencing carcass chilling rates beyond the temperature of the cooling room.

Also working with Nellore males, Malheiros et al. (2020) and Sant'anna et al. (2019) found lower shear force compared with the values obtained in this study, 6.05 and 5.70 kg, respectively. Shear force values depend on the degree of myofibrillar contraction in the muscle after *rigor mortis*, exhibiting an inverse relationship (Hopkins, 2014). According to the study of Destefanis et al. (2008), the shear force values found in this study suggest that the evaluated beef may be considered tough. Based on consumer perceptions, Destefanis et al. (2008)'s study classified beef with WBSF values greater than 52.68 N (5.37 kg) as tough beef, and according to Ertbjerg and Puolanne (2017), the sarcomere length of 1.4 µm found in this study is considered a shortened sarcomere. Reduced carcass or muscle weight could be leading to sarcomere shortening in both chilling environments.

Meat color is influenced by intrinsic factors such as genetics and sex as well as environmental factors, including diet, preslaughter management, and chilling conditions (Malheiros et al., 2020). Usually, consumers prefer bright cherry-red beef over darker cuts, which can be caused by ultimate pH above 6. The dynamic chilling environment examined in this study resulted in reduced redness, yellowness, and chroma of the meat and yet they were within the range considered acceptable by the consumers. In the literature review performed by Holman and Hopkins (2021),

consumer thresholds for beef color were compiled from different studies, which showed acceptable color when $L^* > 31.4$; $a^* > 14.5$; $b^* > 6.3$; hue > 22.5; and chroma > 17.4. Even though consumers' color preferences can be affected by demographic factors (Zhang et al., 2021), the color parameters in this study are within those standard values. Understanding the acceptable standard for beef color is important for ensuring quality in the beef industry.

Holdstock et al. (2023) evaluated the effect of conventional (2°C) and fast chilling, by removing the subcutaneous fat, on the color and quality characteristics of the LT. Their work showed the same pattern found in this study for most of the parameters at 2 d postmortem. Carcasses subjected to the faster rate of temperature decline had lower values of a^*, b^*, and chroma; lower proportion of OMb; and increased DMb. However, they did not find differences in intramuscular pH decline rate between treatments on 0.75, 3, and 24 h postmortem.

Atypical dark beef, as described by Holdstock et al. (2014), exhibits characteristics such as dark red or purple color and tougher meat while still maintaining an ultimate pH below 6.0. This condition is not well characterized in the literature, and there is little investigation evaluating its effects on yield and eating quality (Mahmood et al., 2017). Comparing meat quality parameters between normal grade, atypical, and typical dark-cutting grade, Holdstock et al. (2014) observed that atypical dark-cutting grade carcasses had lower carcass weight than normal grade. Even though they did not evaluate the chilling environment, smaller or less muscled carcasses can be chilled more rapidly than heavier ones. So, the chilling rate can also be a potential cause for atypical dark-cutting despite sufficient glycolytic potential to produce a normal ultimate pH (Mahmood et al., 2017).

The dynamic chilling environment with a higher DMb percentage than the conventional chilling environment could lead to lower color stability and shorter shelf life due to the formation of a brown color, which is unappealing to consumers. Meat containing high levels of DMb is highly susceptible to oxidation. In the presence of oxygen, DMb reacts with oxygen radicals and reactive oxygen species, which causes rapid oxidation of DMb to MMb, even though the purple color of DMb may not be visible due to the excess of oxygen on the meat surface (King et al., 2023). Furthermore, lower temperature conditions during the early postmortem period preserve mitochondrial respiratory activity, which increases the proportion of DMb (Mancini and Ramanathan, 2014).

The rate of temperature decline in carcasses can be influenced by even slight changes in cooler temperatures, which primarily impact meat pH and color. The increase in beef carcass weight in recent decades has resulted in a broader range of HCW (Djimsa et al., 2022). Because of that, beef processing facilities have been seeking alternatives to achieve faster chilling rates and cool carcasses to the desirable deep tissue temperatures within 24 h postmortem. However, accelerating the chilling rate for lighter carcasses with minimum fat cover can affect meat quality parameters (Djimsa et al., 2022). Our study provides insights into the effects of chilling rate on meat quality, enabling us to inform industry practices to optimize meat processing for consistent quality outcomes. For example, temperature decay rate could be increased after 2.5 h postmortem, which was the time necessary for the carcass reach the pH of 6 in the conventional chilling environment.

Conclusions

The variation in chilling rate evaluated in this study impacted meat pH, color, and tenderness as the dynamic chilling treatment resulted in a tendency toward higher ultimate pH levels, less intense red color, and higher shear force value. Thus, establishing a chilling protocol based on the assessment of meat quality parameters is crucial to meet market demands, particularly considering that meat color is a primary factor affecting consumer purchase decisions.

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