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[1]Department of Animal Science, Bangladesh Agricultural University, Mymensingh-2202, Bangladesh
[2]Department of Animal Nutrition, Bangladesh Agricultural University, Mymensingh-2202, Bangladesh

***Corresponding Author:**

MA Hashem
E-mail: hashem_as@bau.edu.bd

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Review Article

Relation among meat pH, color and tenderness- A review

PR Sristi[1], NR Das[1], A Akhter[2], NM Kaniya[2], MA Hashem[1*]

Abstract

Meat quality is fundamentally influenced by postmortem biochemical changes, with pH decline playing a central role in determining both visual appeal and eating satisfaction. This review explores the interrelationships among meat pH, color, and tenderness, focusing on how variations in muscle acidification impact these key quality traits. A rapid pH decline at high carcass temperatures can result in pale, soft, exudative (PSE) meat, while an insufficient drop may lead to dark, firm, dry (DFD) meat—both of which are undesirable. Meat color is primarily governed by the chemical state of myoglobin, which is sensitive to pH-induced changes in muscle structure and oxygenation. Tenderness is likewise influenced by pH, as it affects the activity of endogenous proteolytic enzymes like calpains and the structural integrity of muscle fibers. Optimal tenderness and color are generally achieved when the ultimate pH ranges between 5.5 and 5.8. Extremely low or high pH values impair enzyme function and protein integrity, leading to poor textural and visual quality. This paper also highlights recent advancements in molecular biology and omics technologies that offer new insights into predicting and controlling meat quality through pH regulation. Understanding these complex relationships can help the meat industry refine processing techniques and improve consumer satisfaction.

Introduction

Recently not only the quantity but also the quality of produced milk and beef has become increasingly important. That situation has resulted from the increased consciousness and demand of consumers who expect food characterized by special dietetic or health properties (Brunso et al., 2005). Meat quality is primarily assessed by consumers based on visual appearance, with color being the most important indicator of freshness and acceptability at the point of purchase (Mancini and Hunt, 2005). Any deviation from the expected lean color can lead to consumer rejection and reduced purchasing intent. Numerous factors influence beef color and its stability, many of which are associated with muscle metabolism, including ultimate pH (McKeith et al., 2016; Zhang et al., 2018), myoglobin content (Wang et al., 2021), mitochondrial abundance and function (McKeith et al., 2016; Mitacek et al., 2019; Ramanathan et al., 2021), metmyoglobin-reducing activity (Bekhit and Faustman, 2005). The complex interactions among these metabolic factors necessitate further investigation to fully understand their combined effects on beef lean color and stability.

While color is critical at the point of purchase, tenderness remains a key determinant of consumer satisfaction during consumption. Consumers have consistently shown a willingness to pay a premium for beef with guaranteed tenderness. Intrinsic factors such as ultimate pH (Grayson et al., 2016) all contribute to tenderness development. However, these variables alone cannot fully explain the variability observed in beef tenderness, highlighting the need for deeper understanding of the underlying mechanisms.

Recent advancements in proteomics and metabolomics have enabled the identification of specific molecular markers associated with meat quality traits. These approaches have revealed that certain proteins and metabolites, involved in a wide array of biological pathways, are closely linked to both color stability (Canto et al., 2015; Nair et al., 2016; Nair et al., 2018; Ramanathan et al., 2020a; Ramanathan et al., 2020b) and tenderness (Antonelo et al., 2020; Gagaoua et al., 2019; King et al., 2019; Picard et al., 2018). Meat quality traits such as pH, color, and tenderness are interdependent and play vital roles in consumer preference and processing characteristics. Postmortem biochemical processes, particularly the rate and extent of pH decline, significantly influence the structural and sensory characteristics of meat (Purslow et al., 2020).

Therefore, understanding the interrelationship between pH, color, and tenderness is essential for improving beef quality and meeting consumer expectations. The aim of this review paper is to comprehensively explore the interrelationship among meat pH, color, and tenderness, focusing on the biochemical, physiological, and technological factors that influence these quality attributes. By analyzing how postmortem muscle pH affects meat appearance and texture, the paper seeks to enhance understanding of meat quality development and provide insights for improving animal handling and meat processing strategies to ensure consistent and desirable meat products.

Meat pH refers to the measure of acidity or alkalinity of muscle tissue after the animal has been slaughtered. It is a critical indicator of meat quality, influenced primarily by the biochemical changes that occur in the muscle during the postmortem period (Lawrie & Ledward, 2006). Following slaughter, the cessation of blood circulation halts oxygen supply, forcing muscle cells into anaerobic metabolism. Glycolysis leads to the accumulation of lactic acid and a decline in muscle pH from ~7.2 to values between 5.4 and 5.8 within 24 hours (Lawrie & Ledward, 2006). The rate and final value of this pH decline play a critical role in meat quality.

This pH decline is time-sensitive and influenced by factors such as: The extent of pH decline postmortem largely depends on the amount of muscle glycogen present at the time of slaughter. Glycogen is the primary substrate for anaerobic glycolysis, which continues after death and leads to lactic acid accumulation, thereby reducing muscle pH. If animals have adequate glycogen, the pH typically drops to around 5.5 within 24 hours. However, animals with depleted glycogen (due to prolonged stress or fasting) undergo limited glycolysis, resulting in a higher ultimate pH and darker, drier meat—commonly referred to as DFD (Dark, Firm, Dry) meat (Warriss, 2010).

Postmortem muscle temperature affects the rate of glycolysis and enzyme activity. High ambient temperatures accelerate metabolic reactions, leading to rapid pH decline while the carcass is still warm, which may cause protein denaturation, resulting in PSE (Pale, Soft, Exudative) meat in pigs and poultry. Conversely, low temperatures may slow glycolysis and delay pH fall, affecting the meat's color and water-holding capacity (Lawrie & Ledward, 2006).

Stress prior to slaughter—due to transport, rough handling, fighting, or unfamiliar environments—triggers the release of catecholamines and cortisol, which stimulate glycogen breakdown for energy. If the stress is acute, it can lead to rapid glycogen use and subsequent PSE meat. If the stress is chronic, glycogen stores are depleted over time, causing insufficient lactic acid production, resulting in high ultimate pH and DFD meat (Gregory & Grandin, 2007).

Muscles are composed of different fiber types: Type I (slow-twitch, oxidative) and Type II (fast-twitch, glycolytic). Type II fibers contain more glycogen and have higher glycolytic capacity, thus contributing to a faster and more pronounced pH decline postmortem. In contrast, muscles with more Type I fibers have slower glycolysis, leading to a gradual pH drop and potentially different meat characteristics in terms of tenderness, color, and water retention (Kim et al, 2014).

Rapid pH decline while the carcass temperature remains high can lead to protein denaturation and pale, soft, exudative (PSE) meat, particularly in pigs (Petracci & Cavani, 2012). Conversely, insufficient pH drop (high ultimate pH > 6.0) may result in dark, firm, dry (DFD) meat due to reduced WHC and limited proteolysis (Adzitey & Nurul, 2011).

Postmortem glycolysis leads to lactic acid buildup, lowering muscle pH. Normal ultimate pH (pHu) for meat is around 5.5–5.8. Deviations result in DFD (dark, firm, dry) or PSE (pale, soft, exudative) meat, both considered undesirable (Zhou et al., 2017; Mancini & Hunt, 2005).

According to Lancaster et al. (2020), beef samples with higher pHu tend to have greater water retention and lower cooking loss. This is because higher pHu preserves myofibrillar structure and reduces protein denaturation.

Relationship Between pH and Meat Color

Color is the first quality attribute perceived by consumers and serves as a primary visual cue for assessing meat freshness and quality. It is predominantly influenced by the chemical state of myoglobin, the primary pigment responsible for meat color, which is directly affected by muscle pH (Mancini & Hunt, 2005; Varnam et al., 1995). Depending on oxygen availability, myoglobin exists in different forms: deoxymyoglobin (purple) in oxygen-poor environments, oxymyoglobin (bright red) in oxygen-rich conditions, and metmyoglobin (brown) when oxidized this last form is generally perceived as lower quality (Varnam et al., 1995).

Muscle pH plays a central role in determining meat color by affecting myoglobin chemistry and muscle protein structure. A rapid postmortem pH decline causes denaturation of sarcoplasmic proteins, reducing water holding capacity and increasing light scattering, which leads to pale meat color; a condition known as PSE (pale, soft, exudative) (Toldrá et al., 2006; Hunt et al., 2016; Khliji et al., 2016). At low pH, limited oxygen diffusion and greater protein denaturation enhance light reflectance, resulting in higher L values* (lightness) and a paler appearance (Qiao et al., 2001).

In contrast, high ultimate pH (pHu) limits oxygen penetration and supports the formation of deoxymyoglobin or metmyoglobin, giving the meat a darker hue (Mancini & Hunt, 2005). Additionally, a relatively slower or moderate pH decline helps maintain color stability by supporting better enzymatic function and oxygen binding in muscle tissues (Toldrá et al., 2006).

The quantitative assessment of meat color typically involves parameters such as L (lightness), a (redness), and b* (yellowness)**. A negative correlation between pHu and L values* has been observed in pork and poultry, confirming that higher pH results in darker meat (Qiao et al., 2001). Jankowiak et al. (2021) further demonstrated that both initial pH (pH_{45}) and ultimate pH (pHu) significantly influence meat quality traits such as color, water-holding capacity, and tenderness. Specifically, lower pH_{45} values are associated with PSE conditions paler and softer meat with reduced pigment content while higher pH_{45} values result in darker, firmer meat with greater pigment concentration. A strong negative correlation ($r = -0.566$, $p < 0.01$) between pH_{45} and L* value further supports this relationship.

Overall, the rate and extent of postmortem acidification are critical determinants of meat color and visual quality, with faster pH decline typically leading to undesirable pale coloration, and slower decline contributing to better color retention and quality (Hunt et al., 2016).

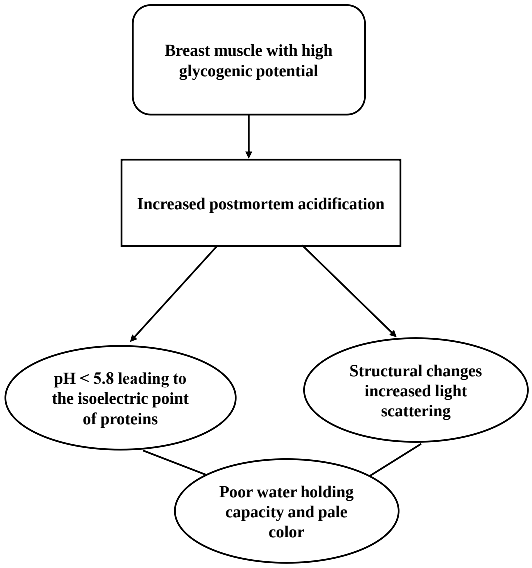

Figure 1: Relation between meat pH and color.

Relationship Between pH and Tenderness

Meat tenderness is widely recognized as the most important factor influencing meat eating quality and consumer satisfaction (Marchello and Dryden et al., 1987; Lásztity, 1990). However, it remains one of the most challenging traits to predict accurately, due to the complex interaction of numerous factors (Dinh, 2008). Both pre-slaughter and post-slaughter conditions influence tenderness, including muscle contraction during rigor mortis, the amount and structure of connective tissue, and the activity of endogenous proteolytic enzymes, particularly calpains and cathepsins (Jennifer 2008). Beef tenderness is impacted by a variety of intrinsic factors such as the ultimate pH of muscle (Grayson et al., 2016; Maddock et al., 2005).

Tenderness is a multidimensional trait involving not just the initial bite (incisor tenderness) but also overall chewing experience, which is shaped by factors such as fiber cohesiveness, friability, softness, chew count, and the presence of residual connective tissue (Juárez et al., 2010). These physical attributes collectively contribute to meat's texture and mouthfeel, which are directly affected by pH through its regulation of muscle structure, enzyme activity, and water retention.

Table 1. Postmortem Enzymes Involved in Meat Tenderness at Different pH Levels

Enzyme	Optimal pH	Role in Tenderization	Inhibition at Extreme pH	Contribution to Meat Quality
μ-Calpain	5.8–6.2	Degrades myofibrillar proteins	↓ Activity <5.5 or >6.5	↑ Tenderness
m-Calpain	~7.0	Supports late-phase proteolysis	↓ Activity <6.0	Moderate
Cathepsins	4.5–5.5	Active in acidic lysosomes	↓ Activity >5.8	Low-moderate
Caspases	6.5–7.2	Apoptosis-related proteolysis	↓ Activity <6.0	Under investigation

This table summarizes the major proteolytic enzymes contributing to postmortem tenderization in meat and how their activity is modulated by ultimate pH.

According to Koohmaraie & Geesink (2006), tenderization is optimal when pH falls to approximately 5.6–5.8, activating calpains, which are calcium-dependent proteases responsible for degrading myofibrillar proteins. The μ-calpain enzyme system, critical for postmortem proteolysis, shows peak activity at pH 6.0–6.5, with reduced function at excessively low or rapidly declining pH values. m-Calpain, although structurally similar to μ-calpain, requires higher calcium concentrations and is less active at the acidic conditions that typically develop postmortem (Huff-Lonergan & Lonergan, 2005). Cathepsins, a group of lysosomal enzymes (particularly cathepsins B, D, H, and L), are optimally active in the acidic range of pH 4.5–5.5 (Sentandreu et al., 2002). These enzymes may contribute to tenderization especially under conditions of muscle stress or prolonged cold storage where lysosomal membranes degrade, allowing cathepsins to interact with myofibrillar proteins. Caspases, traditionally associated with apoptosis, are now being explored in meat science for their role in initiating proteolysis immediately after slaughter. These enzymes function in a slightly alkaline range (pH 6.5–7.2) but are generally inactivated by the acidic postmortem environment (Herrera-Mendez et al., 2006).

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A rapid postmortem pH decline, especially when carcass temperatures remain high, can lead to heat shortening and protein denaturation, reducing the effectiveness of calpains and ultimately resulting in tougher meat (Morgan et al., 1991; Petracci et al., 2019). Conversely, very high ultimate pH (pHu) can also hinder calpain activity due to limited calcium ion mobility, which impairs proper tenderization. Therefore, a moderate rate of pH decline is considered most favorable for the development of tenderness (Zhang et al., 2018).

The ultimate pH also has a notable impact on both meat tenderness and water-holding capacity (WHC). Higher pHu values are often associated with reduced drip loss but increased shear force (WBSF), indicating tougher meat. Jankowiak et al. (2021) reported a strong positive correlation between pHu and shear force ($r = 0.517$, $p < 0.01$), suggesting that meat becomes less tender at higher pH. On the other hand, low pHu contributes to increased drip loss, lower WHC, and softer, paler meat.

In summary, both the early postmortem pH (e.g., pH_{45}) and ultimate pH (pHu) are key determinants of pork tenderness and overall meat quality. While pH_{45} is more strongly associated with meat color and initial postmortem biochemical changes, pHu exerts a more significant influence on technological traits such as tenderness and WHC (Jankowiak et al., 2021).

Achieving optimal tenderness thus depends on maintaining a controlled and moderate pH decline, allowing for effective enzymatic action and preservation of muscle structure.

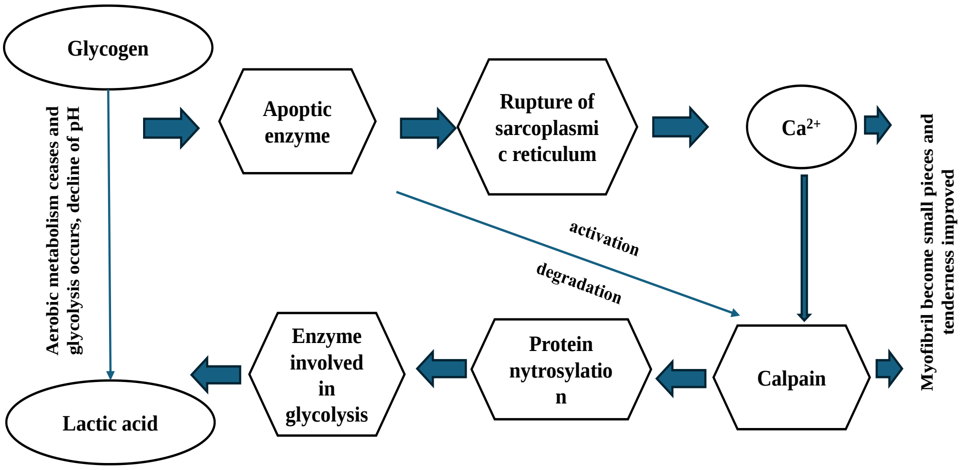

Figure 2: Relationship between meat pH and tenderness.

Relationship among pH, Color, and Tenderness

pH serves as a central factor linking color and tenderness. Meat with an intermediate ultimate pH (~5.6) typically exhibits acceptable color and tenderness. Both extremely low and high pH values negatively impact these traits, though the mechanisms differ. Cooper et al., (2025) that relationships exist between tenderness and lean color stability. Moreover, animal variation in both tenderness and color stability is influenced by muscle metabolism. Increasing the rate and extent of pH decline, within the normal range, has been reported to improve tenderness (Eilers et al., 1996; Jones and Tatum, 1994) and lean color (Zhang et al., 2018).

Compared to other muscles on the carcass, the semimembranosus (SM) muscle begins at the highest temperature and takes longer to dissipate heat. Hannula and Puolanne (2004). According to Mohrhauser et al. (2014), slower postmortem temperature reductions cause faster pH declines, indicating that temperature and pH are not independent variables. Additionally, meat that is lighter in color and has less protein functionality due to higher pH combined with delayed temperature drops has a reduced ability to store water (Jacob and Hopkins, 2014). The cause of the discoloration seen in the SM at the area nearest the femur bone is myoglobin denaturation brought on by high temperatures and low pH levels, which also causes enzyme denaturation and may result in tenderness problems (Kim et al., 2010).

This figure illustrates the simultaneous effect of ultimate pH on two critical meat quality traits: color (L*) and tenderness (shear force) in beef. The data represents a theoretical model derived from empirical studies in meat science literature. Color (L)* peaks around pH 5.8, producing bright red, consumer-acceptable meat. At lower or higher pH, meat appears pale (PSE) or dark (DFD), respectively. Tenderness (inverse of shear force) is optimal near pH 5.8–6.0, where proteolytic enzyme activity is favorable. At extremes (below 5.5 or above 6.3), meat becomes tougher due to limited enzymatic breakdown or altered fiber structure.

Studies have reported that beef samples with pH <5.5 tend to be lighter in color but tougher due to heat-induced shortening, whereas samples with high pH (>6.0) are darker and less tender due to reduced enzymatic degradation (Huff-Lonergan & Lonergan, 2005; Watanabe et al., 1996).

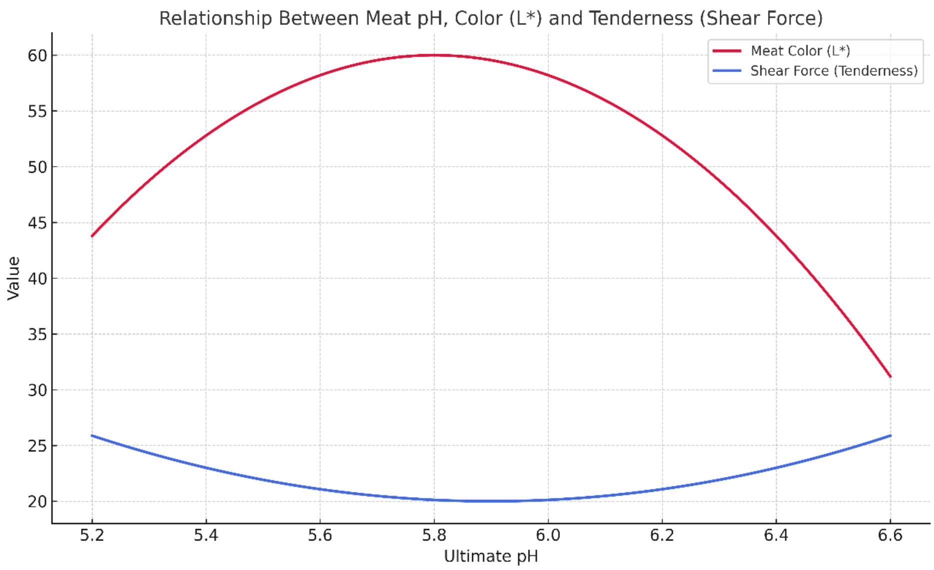

Figure 3. Combined Influence of ultimate pH on Meat Color (L*), Tenderness (Shear Force) in beef.

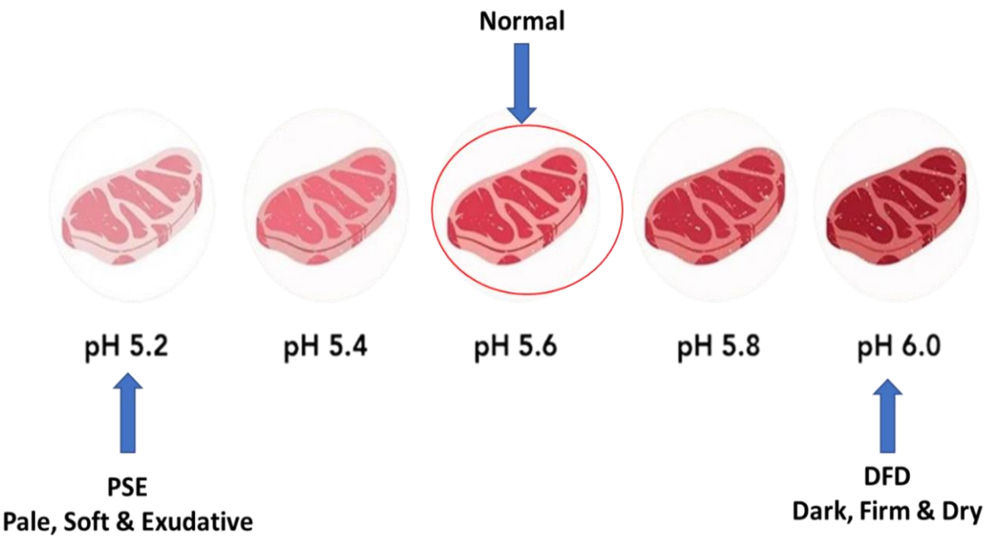

Figure 4: The colour of meat at various pH levels. With the upper control threshold for the ultimate pH at 5.8, meat with an ultimate pH equal or greater than this is classified as dry, firm and dark (DFD).

Table 1: The events causing PSE and DFD meat

PSE meat	DFD meat
Acute stress	Chronic stress
Rapid initial acidification	Reduced glycogen
Low initial pH at high carcass	High ultimate pH temperature
Proteins denature	Proteins do not denature
Low water-holding capacity	High water-holding capacity
'Bound' water lost	Water held by proteins
Muscle fibres separate	Fibres tightly packed
Large extracellular space	Small extracellular space
Light scattering high	Light scattering low
Surface appears pale	Surface dark
Low pH promotes Mb oxidation	O2 diffusion inhibited by closed structure
Reduction in absorption of green	O2 used up by high cytochrome light by Mb activity
Meat looks less red	MbO2 layer thin and underlying Mb (purple) shows through

Source: (Warriss, 2010).

Table 2: Interrelationship among pH, Color, and Tenderness

pH Range	Color (L*)	Tenderness
≤ 5.4	Pale (high L*)	Reduced (protein denaturation)
5.5–5.8	Desirable	Optimal
≥ 6.0	Dark (low L*)	Juicier and more tender early

According to Morrow et al. (2019), high-pH meat had lower shear force values, indicating improved tenderness, while Listrat et al. (2016) emphasized the structural influence of muscle fibers in supporting WHC and tenderness.

Table 3: Differences of meat ccolor

Meat Type	Influencing Factors	Effect of pH on Color and Tenderness	Reference
Beef	Muscle fiber type and postmortem metabolism	pH decline affects protein denaturation and sarcomere shortening, influencing tenderness and meat color stability	Boles et al., 2018
Pork	Genetic susceptibility to PSE (Pale, Soft, Exudative) condition	Rapid postmortem pH drop leads to excessive protein denaturation, resulting in pale color, soft texture, and poor water-holding capacity	Lonergan et al., 2015
Poultry	Chilling rate and muscle pH	Faster pH decline combined with slow chilling enhances protein denaturation, negatively affecting tenderness and causing pale coloration	Petracci et al., 2019

Conclusions

pH plays a pivotal role in determining meat color and tenderness by influencing postmortem biochemical pathways and structural integrity. Maintaining an optimal pH decline during rigor mortis is essential for achieving desirable meat quality. Understanding these relationships can guide producers and processors in managing pre- and post-slaughter conditions to enhance meat quality traits.

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