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**Review Article**

# Relation among meat pH, color and tenderness- A review

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## Abstract

The quality of meat depends on postmortem biochemical changes where pH plays a vital role in determining visual appearance and eating quality. This review aims to explore the interrelations among meat pH, color, and tenderness, focusing on how variations in muscle pH affect these key qualities. A rapid pH drop at high carcass temperatures can lead to pale, soft, exudative (PSE) meat while an insufficient drop may cause dark, firm, dry (DFD) meat. Both cases are undesirable. Color of meat mainly depends on the chemical state of myoglobin, which is sensitive to changes in pH that affect muscle structure and oxygen levels. Tenderness is also affected by pH because it has impact on the action of natural proteolytic enzymes like calpains and the strength of muscle fibers. Optimal tenderness and color can be obtained when the ultimate pH is between 5.6 and 5.9. Insights of this article can help meat industry to improve processing methods and enhance consumer satisfaction.

## Introduction

In recent times, the quality of milk and meat production has grown in importance in addition to its quantity. The issue has arisen from heightened consumer awareness and demand for food with certain dietary or health attributes (Brunso et al., 2005). Consumers generally evaluate meat quality based on visual appearance, with color serving as the most significant predictor of freshness and acceptability during purchase (Mancini and Hunt, 2005). Any deviation from the expected lean color can lead to consumer disappointment and reduced purchasing intent. Numerous factors influence beef color and its stability, many of which are related to muscle metabolism, including ultimate pH (Zhang et al., 2018), myoglobin content (Wang et al., 2021), mitochondrial content and function (McKeith et al., 2016; Ramanathan et al., 2021) and 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 (Murshed et al., 2014). Consumers are always interested to pay a premium for beef with guaranteed tenderness. Among different intrinsic factors, ultimate pH (Grayson et al., 2016) contributes 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, 2020b) and tenderness (Antonelo et al., 2020; Gagaoua et al., 2019; King et al., 2019; Picard et al., 2018). Among the meat quality traits pH, color, and tenderness are interdependent and play vital roles in consumer preference and processing characteristics. Postmortem biochemical processes, particularly the rate and degree of pH decline, significantly influence the structural and sensory characteristics of meat.

Therefore, understanding the interrelationship between pH, color, and tenderness is essential for improving beef quality and meeting consumer expectations (Siddiqua et al., 2018; Hossain et al., 2023). 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 which occur in the muscle during the postmortem period (Lawrie and Ledward, 2006).

Following slaughter, the cessation of blood circulation halts oxygen supply, forcing muscle cells into anaerobic metabolism called glycolysis. Due to glycolysis lactic acid forms and accumulates that leads to a decline in muscle pH from ~7.2 to values between 5.4 and 5.5 (Marsh, 1954). 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; glycogen storage at slaughter, ambient temperature, animal stress and handling etc. The degree of pH reduction after death largely depends on the amount of muscle glycogen present at the time of slaughter. Glycogen serves as the principal substrate for anaerobic glycolysis, which persists post-mortem and results in lactic acid accumulation, thereby lowering muscle pH.

When animals have adequate glycogen, the pH generally drops to around 5.5 within 24 hours Animals with poor glycogen levels, due to extended stress or fasting, experience restricted glycolysis, leading to an elevated final pH and the production of darker, drier meat, widely known as DFD (Dark, Firm, Dry) meat (Warriss, 2010).

The muscle temperature after death influences the rate of glycolysis and enzyme activity. Elevated ambient temperatures accelerate metabolic responses, resulting in pH decline while the carcass remains warm, potentially causing protein denaturation and leading to PSE (Pale, Soft, Exudative) meat in pigs and poultry. Conversely, low temperatures may slow glycolysis and postpone pH fall and produce the pale color of meat (Kim et al., 2014).

Prior to slaughter stress on animal due to transportation, rough handling or unknown environment causes catecholamines and cortisol release which stimulate the breakdown of glycogen for energy. In case of acute stress glycogen is broken quickly which can result in PSE meat. Chronic stress causes glycogen stores to gradually be depleted, which leads to inadequate lactic acid formation, a high final pH, and DFD meat (Gregory and Grandin, 2007).

Rapid pH decline while the carcass temperature remains high can lead to protein denaturation and pale, soft, exudative (PSE) meat, particularly in pigs (Kim et al., 2014). 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 and Nurul, 2011).

Postmortem glycolysis leads to lactic acid buildup, lowering muscle pH. Deviations from the normal ultimate pH result in DFD (dark, firm, dry) or PSE (pale, soft, exudative) meat, both considered undesirable (Kim et al., 2014).

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 primary quality attribute perceived by consumers and serves as a preliminary visual cue for assessing meat freshness and quality. It is predominantly influenced by the chemical state of myoglobin called as primary pigment responsible for meat color, which is directly affected by muscle pH (Mancini and Hunt, 2005; Varnam and Sutherland, 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 and Sutherland, 1995).

Muscle pH plays a central role in determining meat color by affecting myoglobin chemistry and muscle protein structure. A rapid decline of pH after death 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, 2006; 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 and 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, 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, tenderness and water-holding capacity. 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 degree 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 (Figure 1) (Dong et al., 2020).

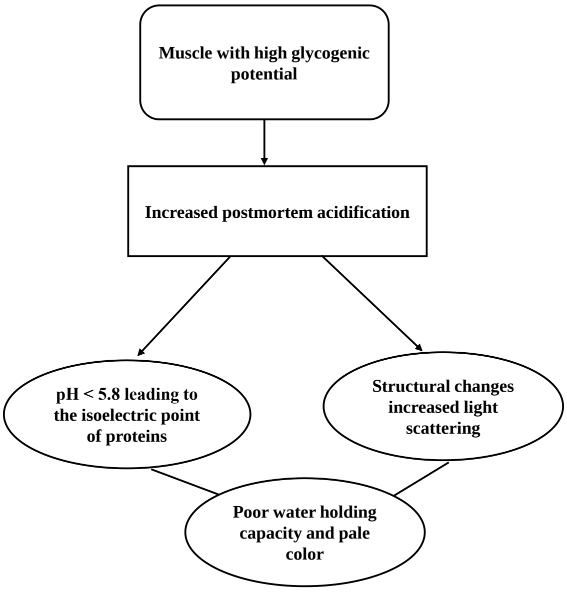


**Figure 1.** Relation between meat pH and color (Adopted and modified from Dong et al., (2020).

## Relationship between pH and tenderness

Meat tenderness is widely recognized as the most important factor influencing meat palatability and consumer satisfaction (Marchello and Dryden,1968; Lásztity, 2009). However, it remains one of the most challenging traits to predict accurately, due to the complex interaction of numerous factors (Thu, 2006). 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 (Montgomery and Leheska, 2008). Beef tenderness is influenced by a variety of intrinsic factors including the ultimate pH of muscle (Maddock et al., 2005; Grayson et al., 2016).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 | Contribution to Meat Quality | References |
|---|---|---|---|---|
| **μ-Calpain** | 5.8–6.2 | Degrades myofibrillar proteins | High Tenderness | Blewniewski et al., 2011 |
| **m-Calpain** | 6.5-8.0 | Supports late-phase proteolysis | Moderate | Kaur et al., 2021 |
| **Cathepsins** | 4.5–5.5 | Active in acidic lysosomes | Low-moderate | Kaur et al., 2020 |
| **Caspases** | 6.5–7.0 | Apoptosis-related proteolysis | Moderate | van Raam and Salvesen, 2013 |

This Table 1 summarizes the major proteolytic enzymes contributing to postmortem tenderization in meat and how their activity is modulated by ultimate pH.

According to Koohmaraie and Geesink (2006), when pH remains near to neutral, activating calpains, which are calcium-dependent proteases responsible for degrading myofibrillar proteins and improve tenderization. The μ-calpain enzyme system, critical for postmortem proteolysis, 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 and Lonergan, 2005). Cathepsins, a group of lysosomal enzymes (particularly cathepsins B, D, H, and L), are optimally active in the acidic range of pH (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 but are generally inactivated by the acidic postmortem environment (Herrera-Mendez et al., 2006).

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 (Petracci et al., 2015). 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).

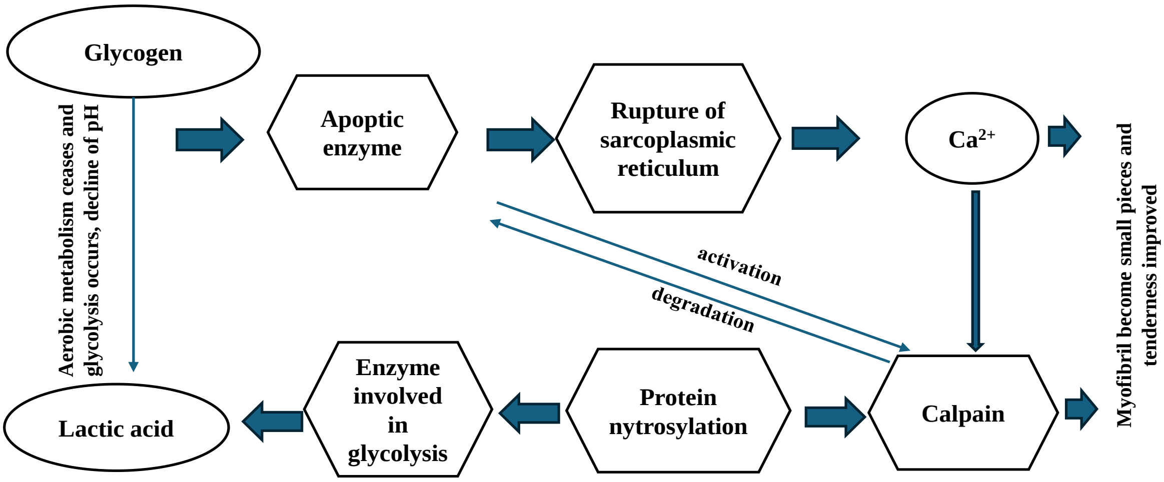


**Figure 2.** Relationship between meat pH and tenderness (Adopted and modified from (Dong et al., 2022).

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 demonstrated that after slaughter the aerobic metabolism stops so that the glycogen stored in muscle is broken down and forms lactic acid that lowers the meat pH of the muscle. The rate and degree of pH reduction directly affect the enzymes related to meat tenderization. The apoptosis enzymes are active in early postmortem. It causes limited degradation of myofibrillar protein (Huang et al., 2011) by activation of calpain enzyme with the presence of calcium ion which releases from the rupture of sarcoplasmic reticulum. Furthermore, protein nitrosylation influences the enzymes involved in glycolysis and the rate of pH decline (Liu et al., 2016). These phenomena are related to myofibrillar breakdown and causes meat tenderization.

## Relationship among pH, color, and tenderness

Meat pH serves as a central factor linking meat color and tenderness. Meat with an intermediate ultimate pH (~5.6) typically exhibits acceptable color and tenderness. Though the processes are different these traits are adversely affected by both low and high pH values. Cooper et al., (2025) stated that a correlation exists between lean color stability and meat tenderness. Additionally, variations in meat tenderness and color stability among animals are affected by muscle metabolism. It has been reported that increasing the rate and extent of pH decline within the normal range can make meat more tender (Jones and Tatum, 1994; Eilers et al., 1996 ) and improve lean meat color (Zhang et al., 2018).

Among different types of muscle from 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).

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 (Watanabe et al., 1996; Huff-Lonergan and Lonergan, 2005).

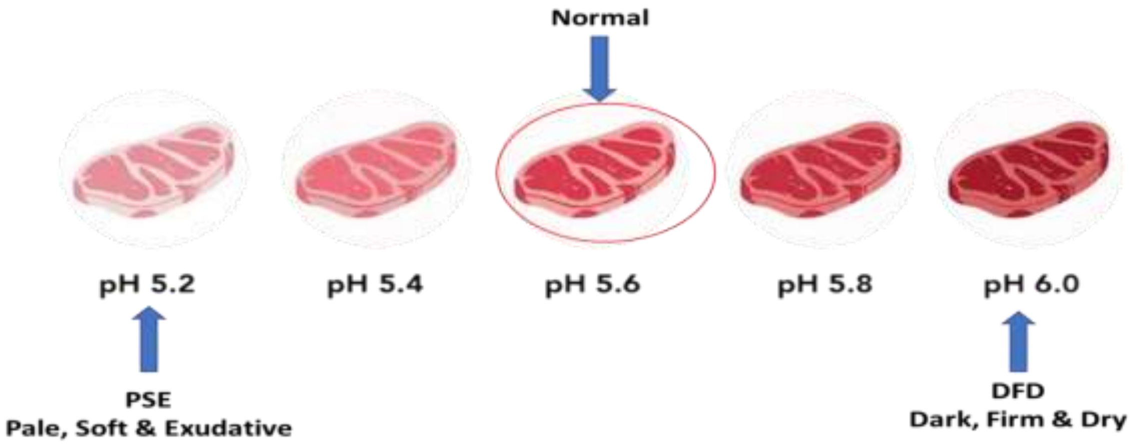


**Figure 3**. The color of meat at various pH levels (Adopted and modified from Asian Agribiz, 2024).

**Table 2**. Interrelationship among pH, color, and tenderness

| Ultimate pH Range | Color ($L^*$) | Tenderness | Reference |
|---|---|---|---|
| **≤ 5.6** | Pale (high $L^*$) | Improved | |
| **5.6-5.9** | Desirable | Optimal (preferred by consumers) | Jankowiak et al., 2021 |
| **≥ 6** | Dark (low $L^*$) | Lower | |

Meat with ultimate pH 5.6-5.9 showing desirable meat color and optimal tenderness which is preferred by consumers (Table2). 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. Among different species there is variation in meat color and tenderness due to meat pH including different influencing factors (Table 3)

**Table 3.** Variation in meat color and tenderness among different species

| 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 and Pegg, 2001 |
| **Pork** | Genetic susceptibility to PSE (Pale, Soft, Exudative) condition | Rapid postmortem pH drop leads to excessive protein denaturation, resulting in pale color, poor water-holding capacity and soft texture | Huff-Lonergan and Lonergan, 2005 |
| **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., 2015 |

## Conclusions

Meat 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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