Review Paper

Journal of Meat Science
Year 2026, Vol.21 (2)

Impact of High-Pressure Processing on Meat Color Attributes

Rishi Kumar[1*], **Arup Ratan Sen**[1], **Suman Talukder**[1], **Ashim Kumar Biswas**[1] and **Sagar Chand**[1]

[1]Division of Livestock Products Technology, ICAR-Indian Veterinary Research Institute, Izatnagar, Bareilly, Uttar Pradesh 243122, India

***Correspondence:** <chaudharyrishi005@gmail.com>

Submission: 29 April 2026 **Acceptance:** 17 June 2026

DOI: https://doi.org/10.48165/jms.2026.21.02.01

ABSTRACT

Meat color is among the foremost quality indices governing consumer purchasing decisions. Traditional thermal processing often leads to unwanted discoloration in meat, mostly because heat denatures myoglobin and triggers a series of chemical changes. High-pressure processing, or HPP, has emerged as a promising non-thermal alternative. It can inactivate harmful microbes while keeping much of the meat's nutritional value and original taste intact. However, maintaining the desired meat color is a more challenging matter. The impact of HPP on the color of cooked meat depends on exactly how pressure affects myoglobin and myofibrillar proteins, making the underlying interaction complicated. Once pressures reach the 200–600 MPa range, meat tends to get lighter (higher L*) and less red (lower a*). This is caused by pressure accelerating pigment oxidation and light scattering within the meat; these effects vary according to pressure level and duration, processing temperatures, type of muscle, pH values, and product ingredients. The changes in meat color vary depending on whether the meat is heated or high pressure (HP) treated, as thermal processing and high-pressure processing alter meat color via distinct mechanisms. Heat breaks covalent bonds and causes even, widespread protein denaturation. HPP, on the other hand, mainly disrupts non-covalent interactions, so the cooked look it creates stems from a separate mechanism altogether. When it comes to pre-cooked or cured meats, HPP's tendency to cause discoloration drops off. That is because pigments like nitrosylhemochrome, typical in cured meats, are much more stable under high pressure. To maintain meat's appealing appearance the objective is, clean-label solutions, which appear promising. Plant-based antioxidants, smart packaging, and mixing HPP with techniques like cold plasma or mild heat treatments help counteract color loss. This review summarizes existing scientific knowledge and delineates research priorities for enhancing HPP conditions to attain commercially viable color quality in various meat systems.

Keywords: High-pressure processing; Meat color; Myoglobin; Cooked meat; Non-thermal processing; Color stability; Protein denaturation

INTRODUCTION

Meat color is one of the first quality attributes noticed by customers, who often judge the freshness and make buying decisions primarily based on appearance. That makes color one of the biggest factors in whether a product sells (Akhtar and Abrha 2022). In fresh red meat, the bright-red color is primarily attributed to oxymyoglobin, whereas the uniform pink in cured meats reveals the processing was properly done (Sukmanov et al. 2019). Studies confirm this: approximately two-thirds of customers evaluate the level of meat doneness based on its color (Ramanathan et al. 2017). Therefore, maintaining desirable meat color throughout processing and storage is a major challenge for producers.

The cause of color change in cooked meat can be attributed to two primary factors: the heat-induced denaturation of myoglobin along with the Maillard reaction (Djimsa et al. 2017; Hunt et al. 1999; King and Whyte 2006). Myoglobin is the main pigment present in muscle tissue, and it transitions among three forms: deoxymyoglobin (a purplish-red), oxymyoglobin (bright red), and metmyoglobin (brown). Each state exhibits a distinct response to thermal and chemical factors (AMSA 2012). Heat breaks down the globin part, resulting in the release of the heme group and oxidation of the iron from the ferrous (Fe^{2+}) to the ferric (Fe^{3+}) state, leading to the formation of hemichrome. The resulting hemichrome is the pigment primarily responsible for the grey-brown appearance of thoroughly cooked meat (Suman and Joseph 2013).

The primary technique for thermal sterilization or pasteurized foods, may adversely affect product quality by causing colour deterioration, promoting lipid oxidation, and extracting the moisture and hence affecting the appearances and other flavours (Balasubramaniam et al. 2015). The current challenges have pushed the meat industry to explore non-thermal options. High pressure processing (HPP) emerges as the preferred option. HPP increases pressure applied to vacuum-packed meat (100–600 MPa) using water, eliminating pathogens and spoilage microbes without damaging the color-forming pigments like heat does (Bolumar et al. 2020). However, pressure itself can induce a pale, "cooked-like" appearance in fresh red meat, representing a significant barrier to consumer acceptance and wider industrial adoption (Reesman et al. 2022).

Therefore, a thorough understanding of the mechanism underlying HPP-induced color changes is essential for optimizing meat processing applications. This review examines the biochemical and physicochemical factors responsible for HPP-induced color changes in cooked meat, evaluates the influence of processing and product related variables, compares the effect of HPP with those of conventional thermal processing, and discusses emerging strategies for improving color stability.

High-Pressure processing: principles and meat industry relevance

High-pressure processing (HPP) has emerged as an important non-thermal preservation method in the food industry. Globally, meat and meat products account for approximately one-fifth of all HPP applications (Jung and Samson 2018). The technique operates on a basic concept of isostatic pressure transmission whereby pressure is applied uniformly across the entire food, irrespective of size or shape, by means of water or an analogous liquid for transmitting that force (Valdes et al. 2023). According to Le Chatelier's principle, increasing pressures cause the system to move towards molecular configurations that occupy less volume. Consequently, molecular structures compress, and the weak, non-covalent bonds like hydrogen bonds, ionic interactions, and hydrophobic forces may be disrupted. The strong, covalent bonds largely remain intact (Sukmanov et al. 2019; Khalid et al. 2023; Peng et al. 2025).Significant pressure induced changes in proteins generally begin at approximately 200 MPa. At these pressures, muscle proteins begin to unfold, break apart, and subsequently aggregate into altered conformations (Jeong et al. 2023; Szerman et al. 2019). Modifications of myoglobin and myofibrillar proteins affect the meat's color and texture, which are visible and tangible (Bak et al. 2017).

In terms of food safety, HPP offers substantial advantages. It can achieve up to a 99.99% reduction in important foodborne pathogens, including *Listeria monocytogenes* and *Salmonella spp.* while demonstrating greeter energy efficiency than traditional heat-based methods (Ghazali et al. 2025; Jadhav and Choudhary 2024). Nevertheless, HPP is not without limitations. One significant disadvantage is the alteration of meat color, as pressure treatment can induce a paler cooked like appearance in fresh red meat, which discourages certain producers and consumers and restricts wider industrial acceptance.

Fundamentals of meat color and myoglobin chemistry

The visual appearance of meat is governed by the chemical state and relative proportions of myoglobin redox forms Deoxymyoglobin (Fe^{2+}, no ligand) confers the purplish-red color of vacuum-packaged and freshly cut meat, while oxymyoglobin (Fe^{2+}, O_2 ligand) is responsible for the bright-cherry-red colour characteristic of retail display. Metmyoglobin (Fe^{3+}), formed by oxidation of the heme iron to the ferric state, produces the brownish discoloration associated with reduced freshness and diminished consumer appeal (Bak et al. 2017; Hugo et al. 2022).

Color is objectively quantified using the CIE $L^*a^*b^*$ system. Lightness (L^*) increases as protein denaturation and moisture loss enhance light scattering within the muscle matrix. Redness (a^*) is largely determined by the abundance of reduced myoglobin forms and decreases as oxidation to metmyoglobin progresses. Yellowness (b^*) is influenced by lipid oxidation products and pigment alterations that occur during processing (Sazonova et al. 2017). Collectively, these parameters provide a systematic and objective means of monitoring color changes under different processing conditions.

Thermal denaturation of myoglobin occurs progressively over a relatively narrow temperature range (approximately 65-80°C), reflecting sequential unfolding of the globin tertiary structure (Bernofsky et al. 1959; Bowers et al. 1987; Lytras et al. 2000). Denaturation of the globin moiety in ferric myoglobin yields ferrihemochrome, the brown pigment characteristic of fully cooked meat, whereas denaturation of ferrous myoglobin transiently produces ferrohemochrome, a red, unstable intermediate that oxidizes readily to ferrihemochrome during continued heating (King and Whyte 2007). The chemical state of myoglobin in raw meat largely determines the ultimate cooked meat color and is influenced by internal factors such as pH and muscle fiber composition and external factors such as pre-treatment and processing conditions (Mancini and Hunt 2005; Suman and Joseph 2013; Suman and Joseph 2014).

Myoglobin denaturation and CIE L*a*b* parameters changes under HPP technology

Both HPP technology and conventional thermal processes can impart a cooked appearance on the surface of the meat; however, the way they achieve this differs completely. Thermal processing rapidly and uniformly unfolds the globin portion of myoglobin and induces permanent covalent modifications within the proteins. In contrast, HPP mainly breaks apart non-covalent bonds. This causes myoglobin to shift toward a slower, pressure-induced conformational change, a process that can be partially reversed under mild pressure conditions (Sukmanov et al. 2019; Hugo et al. 2022). Myoglobin denaturation has been observed at pressures as low as 100 MPa, and when the pressure increases toward 400 MPa, the effect becomes stronger. At the higher pressure levels, increased heme iron oxidation and protein aggregation are observed (Sukmanov et al. 2019)

These structural disruptions manifest as systematic shifts in CIE *L*a*b** parameters. Lightness (*L**) generally rises within the pressure range of 200-350 MPa due to denaturation and co-precipitation of sarcoplasmic and myofibrillar proteins, which increase surface reflectance and light scattering (Bak et al. 2017; Sazonova et al. 2017; Hugo et al. 2022). Structural modifications including alterations in muscle fiber diameter and myofibrillar organization further contribute to the observed paleness of pressure-treated meat (Szerman et al. 2019). Redness (*a**) typically declines at pressures above 400 MPa as oxymyoglobin and deoxymyoglobin are oxidized to metmyoglobin and as myoglobin co-precipitates with denatured structural proteins (Bak et al. 2017; Hugo et al. 2022; Enkhbold et al. 2025; Kotsoni et al. 2025). An exception to this pattern has been documented in certain poultry systems, where redness increases at intermediate to high pressures (300-600 MPa), potentially reflecting reversible myoglobin renaturation or formation of atypical pink pigments (Sukmanov et al. 2019). Changes in yellowness (*b**) are less consistent and appear to depend on the interaction between lipid oxidation and pigment transformation pathways across different muscle types (Park et al. 2021; Sazonova et al. 2017).

In pre-cooked and cured meats, high-pressure processing causes minimal color changes because cured pigments such as nitrosylhemochrome exhibit greater pressure stability than native myoglobin (Bak et al. 2017; Giménez et al. 2023). Combining HPP with mild heat treatment, such as sous-vide processing, improves color stability, moisture retention, and texture (Yoon et al. 2025).

Processing parameters influencing colorimetric changes

The magnitude and direction of HPP-induced color changes are governed by a complex interplay of processing and intrinsic meat parameters. Pressure intensity exerts a greater influence on color modification than processing temperature within the ranges commonly employed commercially (Sazonova et al. 2017). Actomyosin begins to denature at approximately 200 MPa, whereas myoglobin requires pressures of approximately 400 MPa to undergo substantial denaturation or co-precipitation with structural proteins (Uzunlu and Methven, 2020). Consequently, perceptible reddening loss in beef occurs predominantly at pressures exceeding 400 MPa, whereas at lower pressures the effect on *a**values may be negligible or even marginally positive in certain systems.

Species-specific differences further modulate colorimetric responses. Generally, beef is more sensitive to color discoloration caused by HPP due to higher myoglobin concentrations and higher susceptance to pressure sensitivity of the pigment systems, as observed in comparison with poultry meats (Bak et al. 2017; Sukmanov et al. 2019), but in aquatic species like European hake a mild HPP treatment (150 MPa) was able to improve the color stability in further frozen storage, showing muscle-type dependency (Guerra-Rodríguez et al. 2025).

Intrinsic physicochemical properties of the meat matrix also modulate color outcomes. Muscle tissue with an elevated ultimate pH retains superior color after HPP because proteins remain further from their isoelectric point, reducing their propensity to aggregate and to scatter light (Bak et al. 2017; Sen AR et al. 2009). The addition of curing agents (nitrite), reducing agents (ascorbic acid, erythorbate), or polyphenolic extracts can stabilize myoglobin in reduced forms, thereby mitigating pressure-induced metmyoglobin accumulation (Giménez et al. 2023; Gupta et al. 2018). Finally, temperature modulates color outcomes synergistically with pressure; pressure-assisted thermal processing produces more uniform colour development than HPP conducted at ambient temperature, likely because the combined treatment denatures proteins more completely and reproducibly (Yoon et al. 2025).

Interaction of HPP with other quality attributes

In addition to color modifications, HPP affects other quality attributes include texture, water-holding capacity

(WHC) and lipid oxidative stability, thereby influencing the overall sensory acceptability of the meat. HPP induced Structural alteration in conformation of the myofibrillar proteins result in enhanced protein-protein interactions and stronger gel formation which can improve WHC or binding capacity but may also increases tougher meat (Jeong et al. 2023; Peng et al. 2025). This effect is advantageous because HPP used as an alternative to polyphosphates traditionally used in restructured meat products. However, Pressure treatments above 400 MPa often lead excessive aggregation and cross-linking of the myofibrillar proteins which negatively affects textural qualities such as increasing toughness (Jadhav and Choudhary 2024), especially in chicken breast muscle.

HPP has been reported to accelerate lipid oxidation, particularly at pressures of above 300 MPa (Jadhav and Choudhary 2024; Khalid et al. 2023). Membrane disruption under these conditions may promote the release of pro-oxidant iron from hemoproteins, thereby increasing lipid peroxidation. In the case of beef treated at 500 MPa, it was reported that lipid oxidation, assessed by TBARS values, was higher than the controls during chilled storage (up to 56 days) (Chmiel et al. 2025). However, sensory evaluation revealed that lamb burgers processed at HPP conditions and enriched with plant-derived antioxidants provided satisfactory scores for flavor and overall appearance indicating that when complemented with natural antioxidants, the HPP- treated products retain their consumer acceptability and that the addition of these plant extracts neutralizes the pro-oxidative effect (D Arrigo et al. 2025).

Emerging strategies to mitigate high-pressure processing (HPP)- induced meat discoloration

Current research primarily focuses on combining clean label approaches with complementary processing technologies to mitigate HPP-Induced discoloration. Among the proposed strategies, the incorporation of natural antioxidants has received considerable attention. Cava et al. (2024) reported that combining HPP at 600 MPa with pomegranate peel extract can alleviate meat discoloration, while another study revealed that the incorporation of 5% broccoli by-products to lamb burgers improves oxidative stability and color retention (D Arrigo et al. 2025). These findings demonstrate that plant derived ingredients can function as both natural antioxidant and sustainable functional additives.

Studies have shown that combining high hydrostatic pressure with carvacrol 500-1000 ppm or cold plasma can extend the microbial shelf life of food without impairing its sensory attributes (Ghazali et al. 2025; Hussein et al. 2023). Furthermore, active packaging systems containing oxygen scavengers together with skin packaging have been reported to reduce oxidation and maintain product color during refrigerated storage under moderate hyperbaric pressures (20–200 MPa) (Cava et al. 2024a; Chmiel et al. 2025).

Hyperbaric storage at moderate pressures (20-200 MPa) combined with subzero temperatures is emerging as an alternative to conventional HPP pasteurization, offering extended shelf life with attenuated adverse effects on meat color (Malinowska-Pańczyk and Mazur 2024).

CONCLUSION

HPP represents a scientifically validated and commercially relevant technology for producing safe meat products with superior retention of nutritional and sensory quality relative to conventional thermal processing. Pressure-induced discoloration in fresh red meat remains the primary challenge associated with HPP. However, this constraint is substantially reduced in pre-cooked and cured systems, where nitrosylhemochrome and related stable pigments confer pressure resistance. Strategic optimization of pressure thresholds, particularly by avoiding pressures exceeding 400 MPa in the products with limited color tolerances, combined with targeted incorporation of natural antioxidants and complementary non-thermal treatments, provides clear and practical pathways for maintaining acceptable color while ensuring microbial safety. Future research should focus on developing species-specific predictive models linking pressure parameters to colorimetric outcomes across diverse muscle types and on investigating hybrid processing strategies, such as HPP-Cold plasma and pressure-assisted sous-vide processing, to enhance color stability and textural quality across a wide range of commercially relevant meat products.

COMPETING INTERESTS

The authors declare no known competing financial or personal interests that might influence the work reported herein.

ETHICS STATEMENT

Not applicable.

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How to Cite this Article: Kumar R., Sen A.R., Talukder S., Biswas A.K., Chand S.. (2026). Impact of High-Pressure Processing on Meat Color Attributes. *J. Meat Sci.*, ***21***(2), 1-6. https://doi.org/10.48165/jms.2026.21.02.01