Review Article

Journal of Advanced Veterinary Research
(2026) Volume 16, Issue 4, 602-610

Optimizing meat tenderness and flavor through novel processing techniques

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ARTICLE INFO

Recieved: 01 April 2026

Accepted: 01 June 2026

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Keywords:

Meat tenderness, Meat flavor, Non-thermal processing, Marination, Enzymatic treatment, High-pressure processing.

ABSTRACT

Texture and flavor are the primary sensory attributes that determine meat quality and consumer acceptance. Tenderness directly influences chewing comfort, whereas flavor arises from complex interactions among proteins, lipids, and volatile compounds during processing and consumption. However, conventional heat-based processing methods often reduce sensory quality due to excessive protein denaturation and the loss of aroma-forming compounds. Therefore, the development of innovative processing techniques has become increasingly important to improve meat quality in an efficient and sustainable manner. This review aims to evaluate and synthesize recent findings on emerging processing techniques that have the potential to optimize meat tenderness and flavor, with particular emphasis on texture–flavor interactions and their implications for sensory quality. The review was conducted through a systematic search of scientific literature from reputable databases, with articles selected based on their relevance to tenderization mechanisms, flavor formation, and sensory impacts on meat products. The findings indicate that innovative approaches, such as controlled enzymatic treatments, non-thermal technologies, and the combination of mechanical methods with modern physical processes, can selectively modify muscle tissue structure. These modifications enhance the release of taste and aroma compounds during consumption without compromising nutritional stability and food safety. Furthermore, integrated processing strategies demonstrate synergistic effects in maintaining juiciness and quality consistency during storage and cooking. Overall, modern meat processing technologies offer significant opportunities for the meat industry to produce products with superior sensory quality, meet consumer preferences for more natural products, and open new directions for future research in process optimization and value-added meat product innovation.

Introduction

Meat quality is a critical factor that determines consumer preference and acceptance of meat products (Cardona *et al.*, 2023). Among the various quality attributes, tenderness and flavor are widely recognized as the most influential sensory parameters, as they directly shape the overall eating experience (Forde and Graaf, 2022). Tenderness determines the ease of chewing, whereas flavor represents a complex combination of taste, aroma, and oral sensations generated during consumption (Wolinska-Kennard *et al.*, 2025). Meat products with a tender texture and well-balanced flavor profile are generally associated with high quality, freshness, and greater economic value in the market (Yamini *et al.*, 2025).

However, achieving an optimal balance between tenderness and flavor remains challenging, particularly when conventional processing techniques are applied (Hossain *et al.*, 2025). Traditional methods that rely heavily on intensive heat treatment often lead to myofibrillar protein denaturation, muscle fiber toughening, and reduced water-holding capacity (Gong *et al.*, 2024). These changes not only negatively affect the desired texture but also promote the loss of volatile compounds that are essential for the development of characteristic meat aroma (Bleicher *et al.*, 2022). Furthermore, excessive thermal processing may reduce nutritional value and produce inconsistent sensory attributes, especially in meat cuts with varying structural characteristics (Zhang *et al.*, 2023a).

With the growing consumer demand for high-quality, safe, and minimally processed meat products, innovative processing approaches have gained increasing attention (Inguglia *et al.*, 2023). Various emerging techniques have been developed to modify muscle tissue structure in a more controlled manner without compromising key sensory characteristics (Lang *et al.*, 2024). Non-thermal technologies, controlled mechanical methods, selective enzymatic treatments, and combinations of multiple processing techniques have been reported to enhance meat tenderness while maintaining or even improving flavor profiles (Hossain *et al.*, 2025). These approaches operate through more targeted mechanisms, including the disruption of myofibrillar fibers, loosening of the collagen matrix, improved water retention, and optimized release of flavor compounds during consumption (Zhang *et al.*, 2024).

Advances in meat processing technologies also provide new opportunities to better understand the dynamic relationship between texture and flavor (Xu *et al.*, 2024). Structural changes in meat not only influence mechanical properties but also modulate the release of taste and aroma compounds within the oral cavity (Ilić *et al.*, 2022). Consequently, flavor perception is determined not solely by chemical composition but also by how meat texture interacts with mastication and saliva during consumption (Conti *et al.*, 2025). Understanding these interactions is therefore crucial for the development of meat products capable of delivering consistent and superior sensory experiences (Jang and Lee, 2024).

From an industrial perspective, the implementation of modern processing techniques has the potential to improve production efficiency, reduce reliance on synthetic additives, and support the development of value-added products (Dinani and Van Der Goot, 2023). Moreover, more precise processing approaches align with the growing trends of sustainability and clean-label production, which increasingly influence consumer purchasing decisions (Chen *et al.*, 2022). Nevertheless, the adoption of these emerging technologies still faces several challenges, including

ISSN: 2090-6277/2090-6269/

investment requirements, process parameter optimization, and adaptation to industrial-scale production. Based on these considerations, the objective of this review article is to examine and analyze various innovative meat processing techniques that have the potential to optimize tenderness and flavor, elucidate the mechanisms underlying texture–flavor interactions, and evaluate their implications for sensory quality and consumer acceptance as a foundation for the development of high-quality meat products in the future.

Method

The preparation of this review article was based on a systematic literature search conducted to identify, evaluate, and synthesize research findings related to the optimization of meat tenderness and flavor through innovative processing techniques. The literature search was performed using several reputable scientific databases, including PubMed, Scopus, Web of Science, and Google Scholar, in order to ensure broad and relevant source coverage. The search strategy employed a Boolean combination of keywords, including terms such as meat tenderness, meat flavor, novel processing techniques, non-thermal processing, enzymatic treatment, marination, aging, and high-pressure processing. Keyword adjustments were made according to the indexing characteristics of each database to maximize the retrieval of relevant articles.

Inclusion criteria were established to ensure the quality and relevance of the selected sources. Eligible studies consisted of English-language scientific publications, including original research articles and review papers, published within the last ten years. Studies addressing various types of red meat and poultry and evaluating mechanical, enzymatic, chemical, or non-thermal processing techniques in relation to meat texture and/or flavor were prioritized. Conversely, articles that had not undergone peer review, brief reports lacking clear experimental data, and studies that did not focus on the sensory quality aspects of meat were excluded from the analysis. Following the selection process, the chosen articles were qualitatively analyzed with particular emphasis on the mechanisms of the technologies, processing parameters, and their effects on meat tenderness, aroma, and flavor profiles. This approach enabled a comprehensive and critical synthesis of the available evidence, thereby providing an up-to-date overview of the development of meat processing technologies and their potential applications within the meat industry.

Novel techniques for improving meat tenderness

Meat tenderness is strongly influenced by muscle tissue structure and protein–collagen interactions. Consequently, various innovative processing techniques have been developed to modify these structural characteristics in a controlled manner without compromising sensory and nutritional quality (Roy and Bruce, 2024). Table 1 summarizes several innovative processing techniques used to enhance meat tenderness, categorized according to the type of method, principal mechanisms of action, and their effects on muscle tissue structure and sensory quality. Figure 1 illustrates the three principal pillars of meat tenderization techniques developed in response to the strong influence of muscle tissue structure and protein–collagen interactions on meat tenderness.

Mechanical techniques

Mechanical techniques represent a physical approach widely used to improve meat tenderness through the direct modification of muscle tissue structure (Li *et al*., 2022). These methods operate by applying external forces that cause the disruption of myofibrillar fibers and the loosening of the collagen matrix, thereby significantly reducing the resistance of the tissue during mastication. Unlike chemical or thermal treatments,

Table 1. Innovative techniques for improving meat tenderness and their mechanisms of action.

Method category	Processing technique	Primary mechanism of action	Impact on muscle structure	Implications for sensory quality	Source
Mechanical	Tumbling	Repeated pressure and friction that disrupt myofibrillar organization and enhance tissue permeability	Loosening of muscle fibers and more uniform distribution of fluids	Increased tenderness and juiciness without significant flavor alteration	(Azmi *et al*., 2023)
	Blade tenderization	Physical cutting of muscle fibers and connective tissue	Collagen disruption and reduction in shear force	Improved tenderness, although contamination risk must be controlled	
	Ultrasonication	Microcavitation that modifies protein and collagen structures	Tissue loosening and enhanced water-holding capacity	Softer texture while maintaining natural flavor characteristics	
Enzymatic	Papain	Hydrolysis of collagen and myofibrillar proteins	Intensive degradation of connective tissue	Highly effective for collagen-rich meat, with risk of over-tenderization	(Abril *et al*., 2023; Fayaz *et al*., 2024)
	Bromelain	Selective proteolysis of myofibrillar proteins	Softening of muscle fibers without excessive collagen degradation	Balanced texture and enhanced umami perception	
	Ficin	Specific proteolytic activity with greater control	Targeted modification of muscle tissue	Controlled tenderization and improved sensory stability	
Non-thermal	High-pressure processing (HPP)	Selective protein denaturation through high hydrostatic pressure	Reorganization of myofibrils and collagen structures	Increased tenderness while retaining flavor and nutrients	(Rathod *et al*., 2022; Li *et al*., 2025)
	Pulsed electric field (PEF)	Cell membrane permeabilization and activation of endogenous enzymes	Release of intracellular components and tissue relaxation	Softer texture without significant flavor changes	
	Cold plasma	Surface modification of proteins by reactive species	Localized structural alterations in muscle tissue	Tenderization accompanied by improved microbiological safety	
Marination / Chemical	Organic acids	pH reduction and partial protein denaturation	Weakening of collagen and muscle fiber bonds	Increased tenderness, with potential moisture loss if excessive	(Guo *et al*., 2024a; Tomar *et al*., 2025)
	Salt (NaCl)	Increased solubility and hydration of myofibrillar proteins	Expansion of muscle structure and improved water retention	Enhanced juiciness and improved texture	
	Sodium bicarbonate	Increased pH away from the isoelectric point of proteins	Electrostatic repulsion between filaments	Softer and more stable texture, although flavor balance must be controlled	

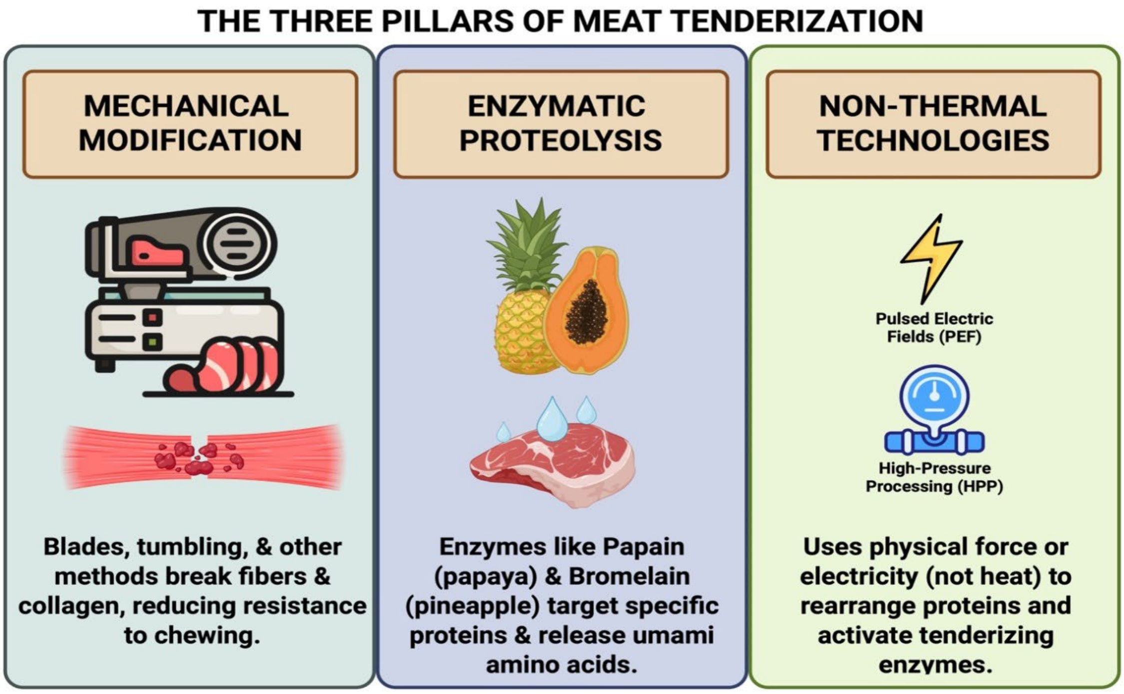

Figure 1. The three pillars of meat tenderization techniques

mechanical techniques generally do not involve alterations in the chemical composition of meat, allowing its natural sensory characteristics to remain largely preserved (Guo and Greaser, 2022).

Tumbling is one of the most commonly applied mechanical techniques, particularly in the meat processing industry (Drachuk *et al.*, 2025). The mixing process within a rotating drum generates repeated pressure and friction on muscle tissues, leading to the disorganization of myofibrillar structures and increased tissue permeability (Banerjee *et al.*, 2023). This effect not only reduces meat toughness but also improves the distribution of fluids and additives, such as marinades or enzymes, thereby contributing to a more uniform tenderization effect (Abril *et al.*, 2023).

Blade tenderization operates through the penetration of sharp blades into muscle tissue, mechanically cutting muscle fibers and dense connective tissues (Tomar *et al.*, 2025). This technique is particularly effective for meat cuts with high collagen content, where the physical disruption of connective tissue directly reduces shear force and enhances chewability (Roy and Bruce, 2024). However, due to its invasive nature, the application of blade tenderization requires strict hygienic control (Sun *et al.*, 2025).

Ultrasonication represents a more advanced mechanical approach that utilizes high-frequency sound waves (Ma *et al.*, 2025a). The cavitation phenomenon generated during this process leads to the formation and collapse of microbubbles within muscle tissues, contributing to the loosening of protein structures and the release of collagen (Li *et al.*, 2024a). As a result, improvements in tenderness and water-holding capacity can be achieved without causing significant changes in flavor (Sheng *et al.*, 2025). Overall, mechanical techniques offer an effective and relatively rapid solution for improving meat texture, particularly when combined with other processing methods (Alfaifi *et al.*, 2023).

Enzymatic treatments

Enzymatic treatment represents an effective biochemical approach to improving meat tenderness through targeted proteolysis of muscle proteins and connective tissue (Azmi *et al.*, 2023). Proteolytic enzymes such as papain, bromelain, and ficin are widely used due to their ability to hydrolyze peptide bonds in myofibrillar proteins and collagen, thereby loosening the muscle structure and making the meat easier to chew (Fayaz *et al.*, 2024). Papain, derived from papaya latex, is known for its high activity toward collagen, making it particularly effective for cuts with a high connective tissue content (Choudhary *et al.*, 2025). Bromelain from pineapple tends to be more selective toward myofibrillar proteins, whereas ficin exhibits a more specific proteolytic pattern, providing flexibility in controlling the degree of tenderization (Wang *et al.*, 2025).

The primary mechanism of enzymatic treatment involves the breakdown of structural proteins such as actin, myosin, and collagen into peptide fragments and free amino acids (Nikolaeva *et al.*, 2024). This process reduces the structural integrity of muscle tissue and decreases the shear force of meat, while simultaneously generating compounds that contribute to the development of umami flavor (Hossain *et al.*, 2025). In addition to its effects on texture, protein degradation also enhances the ability of meat to absorb and retain water as well as marinating compounds, indirectly improving juiciness and overall sensory attributes (Alam *et al.*, 2024).

The effectiveness of enzymatic treatment is strongly influenced by enzyme concentration, treatment duration, and processing temperature (Kabir and Ju, 2023). Insufficient enzyme concentrations may result in minimal tenderization, whereas excessive levels can lead to over-degradation of proteins and an overly soft texture (Cao *et al.*, 2023a). Treatment time must be optimized to allow sufficient enzymatic activity without causing excessive structural breakdown (Wang *et al.*, 2022). Temperature also plays a critical role because enzyme activity depends on a specific thermal range; excessively high temperatures can cause enzyme denaturation and reduce proteolytic efficiency (Yang *et al.*, 2023). Therefore, careful control of processing parameters is essential for the successful application of enzymatic treatment to produce meat with optimal texture and balanced sensory quality (Hussain *et al.*, 2024).

Non-thermal technologies

Non-thermal technologies have emerged as innovative approaches in meat processing due to their ability to modify muscle tissue structure without exposure to high temperatures that may compromise sensory and nutritional quality (Li *et al.*, 2025). These approaches operate through physical and electrochemical mechanisms that target myofibrillar proteins, collagen, and cell membranes, resulting in more controlled textural modifications (Xu *et al.*, 2024). Among the most extensively studied non-thermal technologies are high-pressure processing (HPP), pulsed electric field (PEF), and cold plasma (Rathod *et al.*, 2022).

High-pressure processing applies uniform hydrostatic pressure throughout the entire meat matrix, leading to the selective denaturation of structural proteins and the reorganization of the collagen matrix (Peng *et al*., 2025). This pressure disrupts non-covalent interactions in myofibrillar proteins, such as hydrogen bonds and hydrophobic interactions, making the protein structure more flexible and the muscle fibers more susceptible to deformation (Zhang *et al*., 2023b). As a result, shear force is reduced and tenderness is improved, while water-holding capacity and flavor compounds are largely preserved (Li *et al*., 2024b).

Pulsed electric field operates by delivering high-voltage electrical pulses that induce permeabilization of muscle cell membranes (Asadipour *et al*., 2023). This process facilitates the release of endogenous enzymes and intracellular ions involved in the degradation of myofibrillar proteins (Wang *et al*., 2024). Additionally, the disruption of membrane integrity enhances the diffusion of water and soluble compounds, contributing to the relaxation of the muscle structure and improvement of texture without altering the natural flavor characteristics of the meat (Guo *et al*., 2024a).

Cold plasma utilizes ionized gas at low temperatures that generates reactive species, including free radicals and charged ions (Kumar *et al*., 2024). These reactive species can modify surface bonds of proteins and lipids, causing localized alterations in muscle tissue structure that support the tenderization process (Huang *et al*., 2025). The advantage of cold plasma lies in its ability to improve tenderness while simultaneously exerting antimicrobial effects, thereby enhancing both textural quality and food safety (Nwabor *et al*., 2022).

Marination and chemical modifications

Marination and chemical modification represent important strategies in meat processing aimed at improving texture and sensory quality through alterations in the chemical environment within muscle tissue (Alam *et al*., 2024). This approach primarily functions by modulating pH and the interactions of myofibrillar proteins, thereby influencing water-holding capacity and overall meat tenderness (Sulaiman *et al*., 2025). Common marination agents include organic acids, salts, and pH-regulating compounds such as sodium bicarbonate (Yang *et al*., 2022).

Organic acids, such as citric acid and lactic acid, reduce the pH of muscle tissue and induce partial denaturation of myofibrillar proteins (Yu *et al*., 2024). This alteration disrupts the secondary and tertiary structures of proteins, making muscle fibers more flexible and easier to deform during mastication (Xie *et al*., 2023a). In addition, acidic conditions can weaken collagen cross-links, contributing to reduced rigidity of connective tissue. However, excessive pH reduction may decrease water-holding capacity; therefore, the concentration and duration of marination must be carefully controlled (Rolandelli and Eeckhout, 2025).

Salt (NaCl) acts through ionic and osmotic mechanisms that influence the hydration of myofibrillar proteins (Zhu *et al*., 2025). Chloride ions increase protein solubility by disrupting electrostatic interactions between filaments, causing proteins to swell and bind more water (Cao *et al*., 2023b). The resulting increase in water-holding capacity directly enhances meat juiciness and tenderness while reducing fluid loss during storage and cooking (Sheng *et al*., 2025).

Sodium bicarbonate functions by increasing the pH of meat away from the isoelectric point of myofibrillar proteins (Zou *et al*., 2022). Under these conditions, the negative charges on proteins increase, generating electrostatic repulsion that expands the muscle tissue structure and improves water-holding capacity (Xie *et al*., 2023b). This effect produces a more tender and stable texture, although its use must be carefully controlled to prevent undesirable changes in flavor (Xu *et al*., 2023a).

Novel techniques for enhancing meat flavor

Meat flavor is formed through complex interactions among proteins, lipids, and volatile compounds. Consequently, various innovative processing techniques have been developed to optimize the formation and stability of flavor without compromising the natural sensory quality of meat (Fu *et al*., 2022). Table 2 summarizes several innovative approaches for enhancing meat flavor, including biological processes (aging and fermentation), non-thermal technologies, and the use of smoke, spices, and bioactive compounds. Figure 2 illustrates innovative strategies for meat flavor development and the formation of flavor precursors.

Aging and fermentation

Aging is a postmortem process aimed at optimizing the sensory quality of meat through the activity of endogenous enzymes (Joo *et al*., 2023). Two main approaches commonly applied are dry-aging and wet-aging, each producing distinct flavor characteristics (Xu *et al*., 2023b). In dry-aging, meat is stored under controlled temperature, humidity, and airflow conditions, allowing water evaporation and the concentration of flavor components (Ribeiro *et al*., 2025). The proteolytic activity of endogenous enzymes, such as calpains and cathepsins, leads to the degradation

Table 2. Innovative techniques for enhancing meat flavor and their formation mechanisms.

Approach category	Technique / method	Primary mechanism of flavor formation	Flavor compounds affected	Impact on sensory quality	Source
Biological	Dry-aging	Endogenous enzymatic proteolysis accompanied by moisture evaporation	Peptides, free amino acids, and volatile compounds	More intense and complex aroma, although associated with weight loss	(Xu *et al*., 2023b; Hossain *et al*., 2025)
	Wet-aging	Proteolysis under vacuum conditions with moisture retention	Amino acids and Maillard reaction precursors	Enhanced umami taste and efficient for industrial applications	
	Fermentation	Microbial proteolytic and lipolytic enzyme activity	Free amino acids, free fatty acids, and characteristic volatiles	Distinctive, complex, and controllable flavor profile	
Non-termal	Ultrasonic-assisted marination	Microcavitation enhances diffusion of flavor compounds into muscle tissue	Salts, amino acids, and aromatic compounds	More homogeneous and intensified flavor distribution	(Bakri *et al*., 2026)
	High-pressure processing (HPP)	Protein conformational modification and activation of endogenous enzymes	Aroma precursors and volatile compounds	Richer natural flavor with improved nutrient retention	
Smoke, spices, and bioactives	Smoking	Interaction of phenolic compounds with proteins and lipids	Phenols, aldehydes, and organic acids	Stable characteristic aroma and inhibition of off-flavor formation	(Das *et al*., 2023; Hossain *et al*., 2025)
	Spices and herbs	Modulation of protein–lipid reactions and antioxidant activity	Terpenoids, flavonoids, and sulfur-containing compounds	Increased flavor complexity and fresher aroma	
	Natural bioactive additives	Interaction with protein–lipid matrices influencing flavor development	Volatile compounds and flavor precursors	More balanced flavor profile and improved sensory stability	

of myofibrillar proteins and collagen into peptides and free amino acids, which serve as key precursors of flavor (Zhang *et al*., 2024). This process results in a more complex and intense aroma profile, although it is accompanied by product weight loss (Tang *et al*., 2024).

In contrast, wet-aging is performed by storing meat in vacuum packaging that limits contact with air (Yu *et al*., 2026). This condition preserves moisture content and reduces weight loss, making it more efficient for industrial applications (Fathi *et al*., 2022). Although the resulting flavor concentration is generally lower than that of dry-aged meat, wet-aging still supports the formation of peptides and amino acids through internal proteolysis (Chmiel, 2024). These compounds contribute to the enhancement of umami taste and serve as important substrates in aroma-forming reactions during cooking, such as the Maillard reaction (Ma *et al*., 2025b).

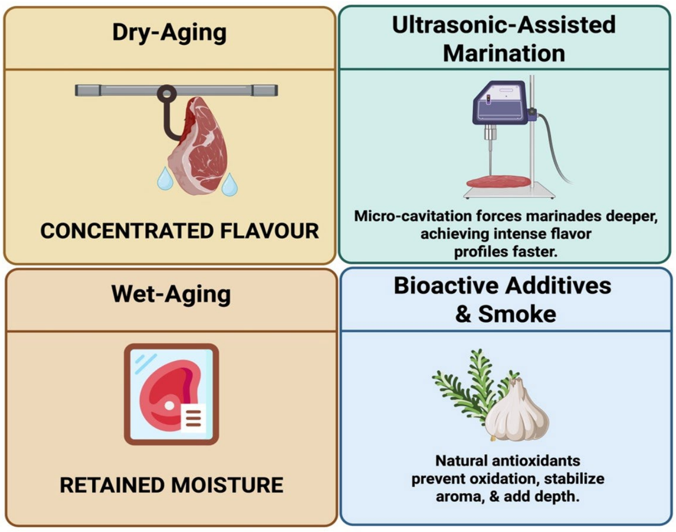

Figure 2. Innovative strategies for flavor development and flavor precursors

Fermentation represents an additional approach that utilizes selected microorganisms to enrich the flavor profile of meat through more targeted biochemical transformations (Hossain *et al*., 2025). Fermentative microorganisms produce proteolytic and lipolytic enzymes that accelerate the degradation of proteins and lipids into simpler compounds, including amino acids, free fatty acids, and various volatile compounds (Sun *et al*., 2022). The interaction of these degradation products generates diverse flavor precursors, enabling the development of distinctive aroma and taste characteristics that cannot be achieved through conventional aging alone (Wang *et al*., 2023). By controlling microbial strains and fermentation conditions, this process can be directed to produce consistent flavor profiles with high added value (An *et al*., 2023).

Non-thermal flavor enhancement

Non-thermal approaches for enhancing meat flavor have gained increasing attention due to their ability to optimize flavor formation and retention without damaging heat-sensitive sensory components (Khalid *et al*., 2023). One of the most widely studied techniques is ultrasonic-assisted marination, which utilizes high-frequency ultrasonic waves to accelerate the diffusion of marinade solutions into muscle tissues (Guo *et al*., 2024b). The cavitation phenomenon generated during ultrasonication leads to the formation and collapse of microbubbles, thereby increasing tissue permeability and expanding the diffusion pathways for flavor compounds (He *et al*., 2022). This mechanism facilitates a more homogeneous distribution of amino acids, salts, and aromatic compounds, resulting in greater flavor intensity within a shorter marination time compared with conventional methods (Hossain *et al*., 2025).

In addition, high-pressure processing (HPP) has demonstrated significant potential in meat flavor development through controlled modifications of protein structure (Xu *et al*., 2023a). High hydrostatic pressure alters the conformation of myofibrillar proteins and collagen, thereby increasing the accessibility of flavor precursors to endogenous enzymes (Peng *et al*., 2025). These conditions facilitate biochemical reactions involved in the formation of complex aromatic compounds while simultaneously preserving volatile compounds that are easily lost during thermal processing (ElGamal *et al*., 2023). Consequently, HPP not only contributes to improved tenderness but also enriches the natural aroma and taste characteristics of meat (Alam *et al*., 2024).

The primary advantage of non-thermal approaches lies in their ability to maintain nutrient integrity and sensory profiles during processing and storage (Sawale *et al*., 2024). Optimization of process parameters, such as ultrasonic intensity and pressure level, is essential to achieve a balance between flavor development, quality stability, and food safety (Urango *et al*., 2022). Therefore, non-thermal technologies offer a strategic opportunity for the development of meat products with more consistent, natural, and high-value-added flavor profiles (Ali *et al*., 2022).

Smoke, spices, and bioactive additives

The application of smoke, spices, and bioactive additives represents a strategic approach to shaping and enhancing the flavor profile of meat through complex physicochemical mechanisms (Hossain *et al*., 2025). Phenolic compounds, aldehydes, and organic acids generated during the smoking process can interact with myofibrillar proteins and lipid fractions in meat, forming non-covalent interactions that contribute to aroma stability and distinctive flavor characteristics (Qian *et al*., 2024). These interactions not only intensify the smoky flavor but also inhibit lipid oxidation, thereby reducing the formation of off-flavor compounds during storage (Zhang *et al*., 2024).

Spices and herbs, such as garlic, pepper, ginger, and rosemary, contain bioactive compounds including terpenoids, flavonoids, and sulfur-containing compounds that are capable of modulating chemical reactions within the meat matrix (Orimaye *et al*., 2024). These compounds can associate with proteins and lipids, influencing the release of volatile compounds during cooking and consumption (Shahidi and Hossain, 2022). In addition, the natural antioxidant activity of spices helps maintain the stability of unsaturated fatty acids, thereby preserving aroma freshness and the complexity of meat flavor (Bellucci *et al*., 2022).

The incorporation of bioactive additives, including plant extracts and natural functional compounds, also contributes to the development of a more balanced flavor profile (Nieto *et al*., 2023). Interactions between these additives and proteins may influence the microstructure of muscle tissue, indirectly modulating flavor perception through changes in texture and the retention of flavor compounds (Chen *et al*., 2023). Overall, the use of smoke, spices, and bioactive ingredients not only enriches the aroma and taste of meat but also improves sensory stability and product quality, making this approach highly relevant for the development of value-added meat products (Sen *et al*., 2022).

Texture-flavor interplay

Texture and flavor in meat interact dynamically, whereby changes in tenderness resulting from processing can modulate the release of flavor compounds and directly influence sensory perception and consumer acceptance (Kurniawan *et al*., 2026). Figure 3 illustrates this dynamic interaction between meat texture and flavor, highlighting how processing-induced modifications in tenderness affect the release of flavor compounds and ultimately shape sensory perception and consumer acceptance.

How tenderization can affect taste perception

The tenderization process not only improves the texture of meat but also has direct implications for the perception of taste and aroma during consumption (Joo *et al*., 2023). Structural changes in muscle tissue resulting from the disruption of myofibrillar fibers and the loosening of the collagen matrix enhance the ability of meat to release flavor compounds during mastication (Roy and Bruce, 2024). More tender meat requires lower chewing force, allowing the release of intracellular fluids and volatile compounds to occur more rapidly and evenly in the oral cavity, thereby intensifying the perception of savory taste and the characteristic aroma of meat (Zhang *et al*., 2024).

Furthermore, tenderization involving the degradation of myofibrillar proteins generates peptides and free amino acids that serve as major precursors of flavor (Azmi *et al*., 2023). These compounds contribute directly to enhanced umami taste and also participate in aroma-forming reactions during cooking, such as the Maillard reaction and Strecker degradation (Chen *et al*., 2025). Consequently, an optimal degree of tenderization can enrich flavor complexity without requiring the addition of external flavoring agents (Hossain *et al*., 2025).

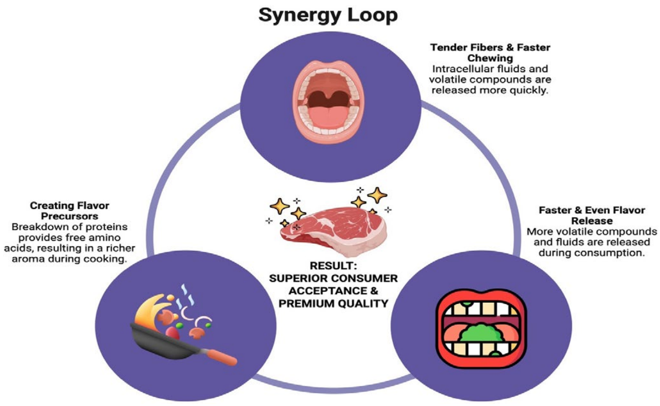

Figure 3. The synergy: How texture unlocks flavor

Tenderization also influences the interaction between proteins and lipids, which are key components in meat flavor formation (Fu *et al*., 2022). The loosening of protein structures increases the mobility of lipids and fat-soluble volatile compounds, thereby facilitating more efficient aroma release (Chen *et al*., 2024). At the same time, improved water-holding capacity resulting from tenderization helps retain flavor compounds during cooking, preventing excessive aroma loss (Sheng *et al*., 2025).

From a sensory perspective, meat with a higher level of tenderness is often associated with superior flavor quality by consumers, even when the basic chemical composition is similar (Xie *et al*., 2023b). This indicates that flavor perception is determined not only by the quantity of flavor compounds but also by how meat texture modulates their release and perception during consumption (Hossain *et al*., 2025). Therefore, controlled tenderization strategies are an important element in the development of meat products with superior and consistent flavor profiles (Xu *et al*., 2023b).

Synergistic effect of the combination of processing methods

The combination of various meat processing methods has increasingly been applied to exploit synergistic effects that cannot be achieved by a single technique (Wang *et al*., 2026). The integration of mechanical, enzymatic, and non-thermal approaches enables gradual and controlled modification of muscle structure, thereby improving tenderness and flavor development more efficiently (Li *et al*., 2025). This approach minimizes the need for extreme treatments, such as high-temperature processing or excessive enzyme concentrations, which may compromise sensory quality (Dai *et al*., 2024).

For example, the application of mechanical techniques such as tumbling or blade tenderization can increase the accessibility of protein substrates to proteolytic enzymes, allowing enzymatic activity to occur more uniformly and effectively (Azmi *et al*., 2023). The initial loosening of muscle tissue also accelerates the penetration of marinades and flavor compounds, resulting in a more homogeneous distribution of taste (Nie *et al*., 2025). When combined with non-thermal technologies, such as high-pressure processing or pulsed electric field treatment, the tenderization effect is further enhanced through protein structural modifications and the activation of endogenous enzymes without degrading volatile compounds (Abril *et al*., 2023).

Synergistic effects are also evident in sensory stability and product quality during storage (Kurniawan *et al*., 2026). The combination of methods can improve water-holding capacity and flavor retention, thereby reducing the loss of moisture and aroma during cooking (Sheng *et al*., 2025). In addition, integration with non-thermal technologies contributes to improved microbiological safety, which indirectly helps preserve flavor quality and texture over a longer shelf life (Saputra *et al*., 2026).

Impact on consumer acceptability and sensory quality

The application of innovative meat processing techniques has a significant influence on consumer acceptability through improvements in key sensory attributes, including tenderness, juiciness, aroma, and flavor (Xu *et al*., 2023b). Controlled modifications of muscle tissue structure and protein–lipid composition enhance ease of mastication and promote the release of flavor compounds during consumption, thereby directly improving perceived product quality (Chen *et al*., 2023). Consumers tend to associate tender meat with balanced aroma and flavor with freshness and premium value, regardless of the cut type or cooking method used (Cardona *et al*., 2023).

Sensory quality is also influenced by the ability of processing technologies to maintain the stability of flavor and texture during storage and cooking (Khalid *et al*., 2023). Non-thermal technologies and integrated treatments have been shown to reduce the loss of volatile compounds and intracellular fluids, thereby preserving flavor intensity and juiciness (Zia *et al*., 2024). This retention of quality contributes to the consistency of the sensory experience, which is an important factor in shaping consumer preference and loyalty (Bing *et al*., 2024).

Beyond fundamental sensory attributes, consumer acceptability is increasingly influenced by perceptions of naturalness and product safety (Curran, 2022). Processing techniques that minimize excessive heating and the use of synthetic additives support the development of a more natural flavor profile while preserving nutritional value (Singh *et al*., 2023). This aligns with modern consumer trends that demand high-quality meat products that are safe, minimally processed, and nutritionally preserved (Samad *et al*., 2025).

Challenges and future perspectives

Although innovative meat processing techniques demonstrate significant potential in improving sensory quality, their implementation still faces various technical and economic challenges, which simultaneously create opportunities for further research and the development of value-added products.

Limitations of new techniques

Although innovative meat processing techniques offer significant improvements in tenderness and flavor, their implementation still faces several limitations that must be critically considered (Sun *et al*., 2025). One of the primary challenges is the relatively high investment and operational costs, particularly for non-thermal technologies such as high-pressure processing, pulsed electric field, and cold plasma (Souza *et al*., 2025). The need for specialized equipment, substantial energy consumption, and maintenance expenses can limit widespread adoption, especially among small and medium-sized enterprises (Gennitsaris *et al*., 2023).

From an industrial-scale perspective, many emerging techniques still exhibit limitations in terms of production capacity and integration with existing processing lines (Kurniawan *et al*., 2026). Processes such as ultrasonication or precision enzymatic treatments require strict control of operational parameters; thus, scaling up may introduce variability in outcomes and reduce product quality consistency (Córdova *et al*., 2022). Furthermore, adapting these technologies often requires modifications to the production workflow, which may affect both time efficiency and operational costs (Castiglione *et al*., 2024).

Sensory stability during storage is also an important concern (Kurniawan *et al*., 2026). Some innovative techniques may trigger further changes in protein and lipid structures, potentially affecting texture and flavor profiles over time (Khalid *et al*., 2023). The interactions among processing methods, packaging systems, and storage conditions are not yet fully understood, which means that fluctuations in sensory quality may still occur (Ingale *et al*., 2025). Therefore, process optimization and long-term evaluation are necessary to ensure that the initial improvements in product quality can be maintained throughout the product's shelf life.

Potential for further research

Future research on innovative meat processing should be directed toward exploring combinations of technologies capable of producing synergistic effects on tenderness, flavor, and overall quality stability. The integration of mechanical, enzymatic, and non-thermal techniques has the potential to enhance processing efficiency while reducing the need for excessive intensity of single treatments (Khalid *et al*., 2023). However, the mechanisms underlying the interactions among these treatments still require in-depth investigation, particularly in understanding the structural responses of muscle proteins and collagen across different meat types and cuts.

The assessment of long-term effects also represents a critical focus for future studies. Most existing research remains limited to evaluating initial quality immediately after processing, while changes in texture, flavor, and physicochemical properties during prolonged storage have not been fully characterized. The dynamics of protein and lipid degradation, as well as the stability of volatile compounds, should be systematically examined to ensure that the initial improvements in quality can be maintained throughout the product's shelf life.

In addition, food safety considerations must become an integral component in the development of new processing technologies. Combinations of treatments that modify tissue structure and cellular permeability may influence microbial growth and the formation of reactive compounds. Therefore, future research should investigate the interactions among processing technologies, meat microbiota, and packaging systems to ensure that improvements in sensory quality do not compromise product safety and reliability. Such a holistic approach is expected to support the development of innovative, safe, and sustainable meat processing technologies.

Implications for innovation in functional or premium meat products

The application of innovative meat processing techniques offers significant opportunities for the development of functional and premium meat products with more controlled quality characteristics (Kurniawan *et al*., 2026). Targeted modifications of protein and lipid structures not only enhance tenderness and flavor but also enable the retention and stabilization of bioactive components, such as functional peptides, essential amino acids, and natural antioxidant compounds (Abdo *et al*., 2024). Consequently, meat can be regarded not merely as a source of protein but also as a food matrix with additional functional value.

In the context of premium products, non-thermal technologies and precision treatments support the formation of distinctive, consistent, and reproducible sensory profiles (Zia *et al*., 2024). The ability to control texture, juiciness, and aroma release allows product differentiation based on the overall consumption experience rather than solely on the type of raw material or meat cut. This approach is particularly relevant for high-value market segments that emphasize quality, authenticity of flavor, and minimal processing (Xu and Falsafi, 2024).

Furthermore, processing innovations provide flexibility in the formulation of functional meat products tailored to the needs of modern consumers, such as low-sodium, high-protein, or bioactive compound–enriched products (Yamini *et al*., 2025). With proper process optimization, improvements in functional value can be achieved without compromising sensory quality or food safety (Hossain *et al*., 2026). Overall, the integration of innovative processing technologies plays a strategic role in promoting diversification and enhancing the competitiveness of functional and premium meat products in the global market (Sun *et al*., 2025).

Conclusion

Various innovative processing techniques have been proven effective in optimizing meat tenderness and flavor through controlled modifications of muscle tissue structure, myofibrillar proteins, and lipid components. Mechanical, enzymatic, and chemical approaches, as well as non-thermal technologies, can enhance tenderization, improve the distribution of flavor-forming compounds, and maintain sensory stability without compromising nutritional value. In addition, the application of aging, fermentation, and the use of smoke, spices, and bioactive compounds contribute significantly to the development of more complex and balanced flavor profiles.

From an industrial perspective, the integration of these techniques offers substantial opportunities for the development of high-value meat products that meet consumer demands for superior sensory quality, consistency, and authentic flavor characteristics. Future research should therefore focus on optimizing combinations of technologies, gaining a deeper understanding of the underlying molecular mechanisms, and evaluating the feasibility of industrial-scale applications to support sustainable innovation in modern meat processing.

Acknowledgement

The author would like to thank Universitas Airlangga for supporting this study.

Conflict of interest

The authors have declared no conflict of interest.

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