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Review Article

Pre and Post-Slaughter Factors Affecting Meat Quality: A Comprehensive Review

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Abstract

Meat quality significantly impacts consumer acceptance, nutritional value, and commercial viability, and it is influenced by a complex interplay of factors occurring both before and after animal slaughter. The current review comprehensively discusses critical pre-slaughter and post-slaughter elements that shape the overall quality of meat products, outlining strategies to mitigate negative impacts and maximize product quality. Pre-slaughter factors such as animal handling and stress management profoundly influence meat attributes including tenderness, color, juiciness, and overall palatability. Improper handling can lead to increased stress responses in animals, resulting in physiological and biochemical changes detrimental to meat quality. The review emphasizes best practices in handling methods and facilities design aimed at minimizing animal stress, highlighting their roles in ensuring optimal meat characteristics. Nutritional influences prior to slaughter also play a pivotal role in determining meat quality. The review delves into how specific dietary components and feeding regimes can affect muscle composition, fat distribution, and metabolic profiles in animals, subsequently influencing tenderness, flavor, and shelf-life stability of the meat. Slaughter methods are another critical area explored in this review. The paper examines various slaughter techniques, comparing their effectiveness in preserving meat quality and ethical considerations. It further details how proper stunning and bleeding protocols can minimize animal suffering and reduce physiological stress responses, thereby enhancing meat quality. Post-slaughter factors, particularly storage conditions, strongly determine meat's shelf life, safety, andsensory properties. The review analyzes the impacts of temperature management, packaging techniques, aging processes, and preservation technologies. It underscores that careful control and optimization of these factors can prevent microbial spoilage, lipid oxidation, and protein degradation, thus preserving meat quality throughout distribution and consumption phases. The review synthesizes existing research to provide practical recommendations for producers and processors to effectively manage pre- and post-slaughter conditions. Adopting these best practices can significantly enhance meat quality, improve consumer satisfaction, and bolster industry profitability.

Introduction

Meat quality significantly determines consumer satisfaction and economic value. Quality parameters such as tenderness, juiciness, flavor, and shelf-life are affected by multiple factors occurring during pre-slaughter handling, slaughter processes, and post-slaughter management. These collective efforts underscore the growing reliance on interdisciplinary approaches for enhancing meat quality, food safety, and animal productivity. Recent research has significantly contributed to the understanding of various aspects of meat quality and animal production, including the use of probiotics (Azad et al., 2022; Mia et al., 2024), freezing impacts on organ meat (Akhter et al., 2022; Sharker et al., 2024; Rabbi et al., 2024; Yasmin et al., 2022), and meat adulteration detection using NIRS and chemometric analysis (Hashem et al., 2024a). Furthermore, studies have explored innovative technologies like machine learning and AI for improving livestock management and meat safety evaluation (Mia et al., 2025; Sarker et al., 2024). Additional reviews have addressed heat stress (Mia et al., 2023), poultry processing (Hashem et al., 2024b), and cutting-edge technology meat quality and meat preservation techniques. These collective efforts underscore the growing reliance on interdisciplinary approaches for enhancing meat quality, food safety, and animal productivity.

High-quality meat production is vital not only for consumer acceptance and market competitiveness but alsofor maintaining nutritional integrity and ensuring food safety standards (Rebezov et al., 2024). Consumers increasingly demand consistent meat products with desirable sensory attributes, driving producers and researchers to better understand and control the multitude of factors influencing meat quality. Before slaughter, numerous intrinsic and extrinsic factors significantly impact meat characteristics (Poveda-Arteaga et al., 2023).Intrinsic factors include the animal’s breed, age, sex, genetics, and physiological status, which inherently influence meat tenderness, marbling, and overall sensory experience. Extrinsic factors such as animal handling practices, transportation conditions, environmental stressors, and nutrition further contribute to variation in meat quality. Stress experienced by animals before slaughter can trigger biochemical changes, including glycogen depletion, altered pH values, and the onset of rigor mortis, ultimately compromising meat tenderness, juiciness, and overall palatability. During the slaughter process, conditions such as the method of stunning, bleeding efficiency, and carcass processing practices play crucial roles in defining the subsequent quality of meat. Proper stunning and efficient bleeding not only align with ethical considerations but also significantly influence muscle metabolism and meat characteristics. Inadequate procedures during this phase can lead to defects such as Pale, Soft, Exudative (PSE) meat or Dark, Firm, Dry (DFD) meat, both of which negatively affect consumer acceptance and market value (Botha, 2021). After slaughter, post-mortem management practices, including chilling, aging, packaging, and storage, become critical determinants of meat quality (Ahmed et al., 2025; Álvarez et al., 2022). Optimal chilling and storage conditions are necessary to reduce microbial growth, extend shelf-life, and preserve sensory attributes such as texture and flavor (Rabiepour et al., 2024). Post-slaughter aging processes can further enhance tenderness and flavor through controlled enzymatic breakdown of muscle tissues. Consequently, effective control and management of these factors help producers consistently deliver high-quality, safe and desirable meat products to consumers. Considering these complex interactions, it is essential for meat producers, processors, and industry stakeholders to thoroughly understand the pre-slaughter, slaughter, and post-slaughter factors affecting meat quality. This comprehensive review aims to analyze these factors systematically, discuss their specific impacts on meat quality parameters, and suggest best practices and strategies to optimize overall meat product quality.

Pre-Slaughter Factors

Pre-slaughter factors are conditions and practices that affect animals before they are slaughtered, and they have a significant impact on meat quality (Álvarez et al., 2009). These factors can influence stress levels, muscle metabolism, and ultimately the chemical, physical, and sensory properties of meat (Table 1). Here are the main pre-slaughter factors affecting meat quality:

Table 1: Influence of Pre-Slaughter Factors on Meat Quality Attributes

Factors	Quality Attribute Affected	Recommendations	References
Breed/Genetics	Marbling, Tenderness	Select breeds suited for the desired meat quality traits.	Grigoletto et al. (2020)
Nutrition	Tenderness, Flavor, Juiciness	Balanced diet, optimal feeding strategies	Van Wymelbeke et al. (2020)
Age & Sex	Tenderness, Fat deposition	Younger animals, appropriate sex management.	Suchacki et al. (2023)
Stress Management	Color, Texture	Improved handling, shorter transport duration.	Gou et al. (2021)
Fasting Duration	Meat Safety, Contamination	Optimal fasting duration (12-24 hours).	Xue et al. (2020)

Animal Genetics and Breed

Animal genetics and breed play a crucial role in determining the quality of meat (Sakowski et al., 2022). Here's a breakdown of how genetic factors influence various meat attributes such as (Figure 1)

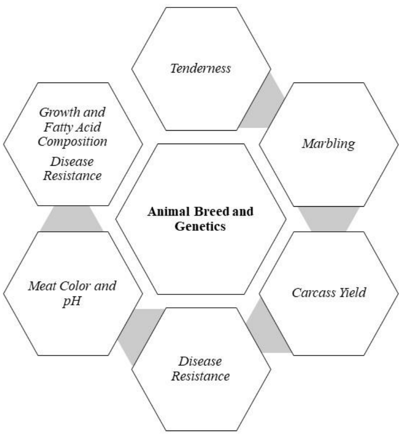

Figure 1: Pre-Slaughter Factor of Animal Breed and Genetics.

Tenderness: Genetics influence muscle fiber composition, which affects tenderness (Fuku et al., 2019). Breeds with a higher proportion of fine muscle fibers (e.g., Angus cattle) generally produce more tender meat. The ability of muscles to break down collagen (a protein that makes meat tough) is also inherited, and breeds with lower collagen content yield more tender cuts.

Marbling: Marbling refers to the fat interspersed within muscle tissue, which enhances flavor and juiciness (Chen et al., 2019). Some breeds, particularly those bred for high-quality beef like Wagyu, have a genetic predisposition to develop more marbling. Marbling is a desirable trait in meat as it contributes to the tenderness, flavor, and mouthfeel, which are key factors in consumer preferences.

Carcass Yield: Different breeds have varying levels of muscle and fat deposition, which affect the carcass yield (the percentage of edible meat obtained from the carcass) (Chacko-Kaitholil et al., 2024). Genetic factors influence how efficiently an animal can convert feed into muscle mass. Breeds like Charolais, known for high growth rates, often yield higher carcass weights and better muscle-to-fat ratios, impacting the overall meat output.

Meat Color and pH: Genetics influence muscle color, which is an important quality factor in meat (Poveda-Arteaga et al., 2023). The presence of specific genes can lead to different levels of myoglobin (the protein responsible for meat's red color) in the muscles. Moreover, genetic factors affect the post-mortem pH of the meat, which influences meat tenderness and water retention capacity. A lower pH often results in meat that is more tender and juicier.

Disease Resistance: The genetic robustness of an animal can affect its overall health and meat quality. Animals that are genetically resistant to diseases tend to have higher quality meat because they experience less stress and fewer health-related issues that could otherwise impact meat characteristics (e.g., off-flavors or spoilage) (Liu et al., 2022b).

Growth and Fatty Acid Composition: The genetic makeup of an animal also influences the fat composition of its meat (Fuku et al., 2019). Breeds like Duroc pigs are known for producing meat with a higher intramuscular fat content, which is associated with better flavor (Li et al., 2023). On the other hand, leaner breeds may have less fat, affecting flavor but potentially making the meat more desirable in health-conscious markets. It also determines the animal's growth rate and the proportion of fat deposits (Zhang et al., 2019). Some breeds are genetically predisposed to grow faster, which can lead to early harvesting, while others may develop higher levels of healthy fatty acids (omega-3 and omega-6). These differences influence the overall health benefits and consumer preferences for certain types of meat. Overall, the breed and genetic makeup of an animal affect all aspects of meat quality, from tenderness and flavor to overall yield and nutritional profile. Selective breeding can help enhance these traits, catering to specific consumer preferences and market demands

Nutrition and Feeding Practices

Nutrition and feeding practices play a pivotal role in shaping the chemical composition and sensory attributes of meat (Rodrigues et al., 2024). By influencing factors like muscle protein, fat content, and the accumulation of specific micronutrients, nutrition directly affects meat's flavor, tenderness, and overall quality. The protein content in the muscle tissues is determined by the amino acids available in the diet (Church et al., 2020). Animals fed a balanced diet, especially one rich in essential amino acids, build muscle proteins like actin and myosin more efficiently. These proteins contribute to meat's texture and tenderness. Excessive protein intake, however, may not significantly improve muscle growth and could lead to excess nitrogenous waste accumulation on the other hand the type and amount of dietary fats are key determinants of intramuscular fat (marbling) content in meat. Fatty acids from dietary sources are deposited in the muscle tissue, and the type of fatty acid (saturated, monounsaturated, or polyunsaturated) influences the sensory properties of the meat. Unsaturated fats (from grains, oilseeds, or fish oils) are often incorporated into the meat, improving flavor and juiciness. Saturated fats (from grass-fed animals) tend to accumulate in muscle fibers, contributing to a firmer texture. The fatty acid profile in meat is largely dictated by the animal's diet. For example: Omega-3 fatty acids, found in flaxseeds or fish-based diets, are often incorporated into meat tissues, contributing to healthier meat and improving flavor by reducing off-flavors. Omega-6 fatty acids (from grains or corn) may lead to an increased proportion of linoleic acid, affecting the meat's overall fatty acid profile and texture.

On the other hand, Feeding practices help to development of different flavors and volatile compounds formation such as Lipid oxidation, influenced by dietary fat intake, produces volatile compounds like aldehydes, ketones, and alcohols. These compounds play a major role in meat flavor, particularly during cooking. Diets rich in certain antioxidants (e.g., vitamins E and C, found in certain plant-based diets) help reduce lipid oxidation, preserving flavor and enhancing the meat's quality (Manessis et al., 2020). A diet high in unsaturated fats increases the risk of oxidative rancidity, whereas feeding animals antioxidants (like vitamin E) reduces oxidative stress, maintaining desirable flavors on the other hand the Maillard reaction, which occurs during cooking, is a chemical reaction between reducing sugars and amino acids. The availability of amino acids from dietary protein influences the Maillard reaction, which contributes to the browning and flavor development in cooked meat (Liu et al., 2022a). The composition of the amino acid profile, particularly glutamate, can also enhance savory (umami) flavors, making the meat more flavorful. The type of feed an animal receives can also impact muscle fiber composition. High-protein diets with a balanced amino acid profile encourage the development of Type I muscle fibers (slow-twitch fibers) that are associated with tenderness. In contrast, animals on a high-energy, low-protein diet may develop more Type II muscle fibers (fast-twitch fibers), which are less tender. The diet's impact on glycogen storage is also significant. Glycogen, a carbohydrate, is stored in muscle cells and acts as the primary source of energy during muscle contraction. Following slaughter, glycogen is converted to lactic acid, which influences the pH of the meat. A lower pH (due to high glycogen levels) results in more tender meat because the muscle proteins (like myosin) remain in a more relaxed state. Conversely, a high-energy diet that causes rapid muscle growth may lead to insufficient glycogen stores, resulting in higher pH post-mortem and tougher meat. Feed with micronutrients like vitamins (e.g., vitamin A, E, and C) and minerals (e.g., zinc, selenium) from the diet contribute to the chemical stability and oxidative stress levels in meat. For example, vitamin E acts as an antioxidant and can delay lipid oxidation, improving the flavor stability of the meat during storage. Proper micronutrient intake, including zinc and magnesium, is vital for maintaining enzymatic activities post-mortem. Enzymes like calpains and cathepsins, which break down muscle proteins, are influenced by the animal's diet and play a key role in meat tenderness. Adequate mineral and vitamin levels ensure that these enzymes function effectively, leading to optimal meat quality after slaughter. Diets that promote better hydration (e.g., diets high in fresh forage) can improve water holding capacity (WHC), which is a key factor in determining meat juiciness. High-quality forage or a balanced ration helps the muscle retain more water, leading to juicier meat. Water retention is crucial for preventing muscle proteins from squeezing out water during cooking, thereby improving the texture and sensory properties of the meat. Stress Reduction through Diet on Meat Quality: Stress during the pre-slaughter period can negatively affect meat quality by increasing the levels of catecholamines (stress hormones like adrenaline) in the animal's bloodstream. These hormones lead to an increase in muscle glycogen depletion, resulting in a rapid pH drop post-mortem, which causes the meat to be tough and dry (Matarneh et al., 2023). Feeding strategies that reduce stress, such as balanced energy intake, adequate fiber, and relaxation-inducing feed additives, can mitigate these negative effects on meat quality. In summary, nutrition and feeding practices influence meat quality through a complex network of biochemical pathways that affect muscle growth, fat deposition, flavor, tenderness, and water retention. The appropriate balance of energy, protein, and micronutrients in an animal's diet supports the optimal formation of muscle proteins, marbling, and flavor compounds, leading to higher-quality meat that meets consumer preferences for tenderness, juiciness, and flavor. Careful dietary management, with an emphasis on controlling fatty acid profiles, antioxidant intake, and micronutrient balance, is essential to achieving these outcomes.

Animal Age and Sex

The age and sex of an animal have significant effects on the chemical and physical properties of meat, influencing tenderness, flavor, marbling, and overall meat quality (Pogorzelska-Przybyłek et al., 2020). These factors impact muscle composition, fat deposition, protein structure, and enzyme activity, all of which play crucial roles in determining meat characteristics. Below is a detailed, chemistry-based discussion of how animal age and sex influence meat quality. Muscle Development and Protein Cross-linking: As animals age, muscle fibers undergo changes that affect their texture and tenderness. In younger animals, the muscle fibers are finer and more delicate, and the amount of collagen (a connective tissue protein) is relatively low. Collagen fibers in younger animals are also more soluble and easier to break down. However, as animals age, the muscles develop more Type I (slow-twitch) fibers and Type II (fast-twitch) fibers, which increase in size and contribute to the meat's firmness. Older animals tend to have a higher proportion of collagen cross-links, which are formed through enzymatic reactions during the aging process. These cross-links make the collagen fibers tougher and less soluble, resulting in meat that is more resistant to tenderization. As a result, the meat from older animals typically requires more time to break down collagen and become tender during cooking. In younger animals, the calpain and cathepsin enzymes, responsible for muscle protein breakdown, are more active in post-mortem muscle tissues. These enzymes degrade proteins like myosin and actin, which improves the tenderness of the meat (Shang et al., 2022). In contrast, the activity of these enzymes decreases in older animals, leading to less efficient breakdown of muscle proteins and, therefore, tougher meat. On the other hand Fat Deposition and Marbling, as animals grow older; they tend to accumulate more fat, particularly in the muscle tissue. The fatty acid composition of this fat varies with age: Younger animals typically deposit a higher proportion of unsaturated fatty acids, which are softer and contribute to a more desirable texture and juiciness in the meat. These fats are also healthier for consumers due to their lower content of saturated fat. In contrast, older animals accumulate more saturated fatty acids, which are firmer and can affect the flavor and texture of the meat. Higher levels of saturated fat can lead to meat that has a firmer texture, and in some cases, an undesirable waxy mouthfeel. Adipocyte Development and Fat Distribution: Fat deposition is largely regulated by the development of adipocytes (fat cells) (Schumacher et al., 2022). In younger animals, adipocyte growth is slower, and fat is deposited mostly around internal organs and under the skin. As animals age, fat becomes more uniformly distributed across the muscles as intramuscular fat (marbling), which enhances flavor and tenderness. This marbling results from the infiltration of fat into the muscle fibers, making the meat juicier and more flavorful. Older animals tend to have more pronounced marbling than younger animals.

Sexual Dimorphism and Muscle Development: Male and female animals exhibit differences in muscle development due to the influence of sex hormones (e.g., testosterone, estrogen) (Alexander et al., 2022). Male animals typically have more muscle mass and less fat than females, resulting in leaner meat with a firmer texture. Testosterone, in particular, promotes the growth of muscle fibers, leading to meat that may be less tender due to the increased muscle density and the greater amount of connective tissue. Females tend to have more intramuscular fat due to the influence of estrogen, which encourages fat deposition in the muscles. This fat contributes to marbling, improving the flavor and tenderness of the meat. Female animals also tend to develop a softer, less fibrous texture in their muscles compared to males, which can make their meat more tender, particularly in younger animals. Castration (Influence of Gender on Meat Quality): In many livestock operations, male animals are castrated to prevent the production of excessive testosterone, which can lead to a tougher texture and stronger flavors (due to the presence of certain volatile compounds). Castrated males (steers) tend to have better meat quality in terms of tenderness, flavor, and fat content compared to intact males. Castration reduces the impact of testosterone, resulting in meat that has a more desirable balance of muscle and fat, and is generally more tender. Fatty Acid Profiles: The dietary fats and sex hormones influence the types of fats deposited in the meat. Male animals tend to have a higher muscle-to-fat ratio, with more lean meat and less fat. This can lead to a drier, leaner cut of meat, which might be less flavorful and less juicy than meat from female animals, which tend to have more fat and marbling. Female meat tends to have a higher proportion of monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA), which contribute to a more tender texture and a milder, less gamey flavor compared to meat from intact males. Male meat, especially from uncastrated males, often has a higher proportion of saturated fats, which are firmer and less desirable in terms of mouthfeel and flavor. Meat flavor is influenced by both age and sex through the chemical breakdown of proteins and lipids. In younger animals, the meat tends to have a milder, more delicate flavor, as fewer volatile compounds (such as aldehydes and ketones) are produced during cooking. Older animals, with their more developed muscles and higher fat content, often produce more intense flavors during cooking due to the greater breakdown of lipids and proteins, which can result in stronger, more complex flavors. Sexual differences in flavor are also notable. Male meat, particularly from uncastrated males, may have a more pronounced musky or gamey flavor due to the presence of and roster one, a compound produced by the testes, which can give the meat an undesirable taste. Female and castrated male animals (steers) generally have a more neutral flavor profile, making their meat more appealing to a wider range of consumers. In summary, both animal age and sex have profound chemical impacts on meat quality. Age affects tenderness, fat content, and the rate of collagen cross-linking, while sex influences muscle development, fat deposition, and flavor profiles through hormonal and biochemical processes. Young animals typically produce tenderer, milder-flavored meat, while older animals provide more mature flavors and tougher textures due to increased collagen and fat content. Sex differences further contribute to variations in muscle composition, fat distribution, and flavor characteristics, with females generally producing meat that is more tender and marbled, while males may produce leaner, firmer cuts with stronger flavors.

Handling and Transport Stress

Transportation and handling stress are critical pre-slaughter factors that significantly impact meat quality, leading to defects such as Dark, Firm, and Dry (DFD) meat and Pale, Soft, and Exudative (PSE) meat (Prasad, 2023). These defects are primarily the result of glycogen depletion and altered biochemical processes in muscle cells during stressful conditions. We know, Glycogen, the stored form of glucose in muscle cells, is the primary energy source for muscle activity. Under normal conditions, muscles use glycogen to produce energy for contraction and other cellular processes. However, during transportation and handling, animals often experience stress (e.g., physical movement, noise, temperature extremes), which activates the sympathetic nervous system and releases stress hormones such as epinephrine (adrenaline) and norepinephrine. Stress hormones stimulate glycogen breakdown in the liver and muscles to release glucose, which provides immediate energy. This leads to a depletion of muscle glycogen stores before slaughter. Glycogen depletion significantly affects muscle metabolism after slaughter, as it reduces the amount of glycogen available for conversion to lactic acid during post-mortem rigor mortis. After slaughter, muscles undergo rigor mortis, a process in which muscle fibers contract due to the depletion of ATP (adenosine triphosphate). In normal muscle, lactic acid is produced from the breakdown of glycogen, which lowers the muscle's pH and facilitates the transition from a relaxed to a rigid state. The drop in pH is also essential for enhancing meat tenderness, as lower pH helps to weaken muscle proteins, especially myosin and actin, which are involved in muscle contraction. However, in stressed animals, the rapid depletion of glycogen leads to an insufficient production of lactic acid, and as a result, the muscle's pH does not drop enough or drops too slowly post-mortem. This can lead to two primary meat defects, Pale, Soft, and Exudative (PSE) Meat: Characteristics of PSE Meat: PSE meat is characterized by paleness, softness, and exudation (release of moisture from the meat). This defect typically arises from severe stress prior to slaughter, which leads to a rapid depletion of glycogen. The insufficient production of lactic acid during rigor mortis results in a higher pH than normal. High Muscle pH (6.0 to 6.5): In PSE meat, the pH remains elevated (around 6.0 to 6.5) immediately after slaughter, leading to poor water retention capacity. This is because the muscle proteins (mainly myosin and actin) do not undergo proper post-mortem denaturation. As a result, the muscle fibers retain water, making the meat more prone to exudation (leaking of water). The pH drop is delayed due to the lack of lactic acid production, causing the meat to have a pale, watery appearance and a soft texture that is undesirable in terms of both appearance and consumer preference. The soft texture in PSE meat arises because the higher pH prevents proper protein denaturation. This causes the muscle fibers to remain too relaxed, resulting in a mushy consistency. Additionally, the excess water retention due to insufficient protein cross-linking leads to moisture loss during cooking, further impacting the texture and sensory experience of the meat. Dark, Firm, and Dry (DFD) Meat: DFD meat is characterized by dark color, firm texture, and dryness. This defect typically occurs when animals undergo prolonged or severe stress, particularly when they are fasted or deprived of water before transport. In this scenario, the animal's muscle glycogen stores are depleted before slaughter, and as a result, the meat exhibits a number of unfavorable characteristics. In DFD meat, glycogen depletion is so severe that, post-mortem, there is little or no glycogen available for conversion into lactic acid. This results in insufficient acidification (pH does not drop enough), leaving the muscle pH much higher than in normal meat (around 6.0 to 7.0). The lack of lactic acid results in poor protein denaturation, which means that actomyosin cross-links (formed between actin and myosin) are not properly broken down, leading to a firm, chewy texture (Hussain et al., 2024). Dark Color and Water Loss: The elevated pH in DFD meat also causes myoglobin (the protein responsible for meat color) to remain in its oxygenated form, which gives the meat a dark red or purplish appearance (Ijaz et al., 2020). Additionally, DFD meat tends to have lower water-holding capacity due to improper protein denaturation, which makes the meat dry and prone to shrinkage during cooking.

Physiological and Biochemical Changes Leading to PSE and DFD Meat

Physiological and biochemical pathways illustrating the impact of pre-slaughter stress on muscle metabolism leading to Pale, Soft, Exudative (PSE) meat and Dark, Firm, Dry (DFD) meat. Acute stress results in rapid glycogen depletion with sufficient lactic acid production, causing a rapid pH decline and protein denaturation, characteristic of PSE meat. In contrast, chronic stress leads to severe glycogen depletion with inadequate lactic acid formation, resulting in high ultimate pH and water retention, characteristic of DFD meat (Figure 2). Stress causes the activation of the sympathetic nervous system, which leads to the release of stress hormones like epinephrine (Pondeljak et al., 2020). These hormones cause muscle glycogen to be rapidly metabolized into glucose, which is used for immediate energy (Figure 2).

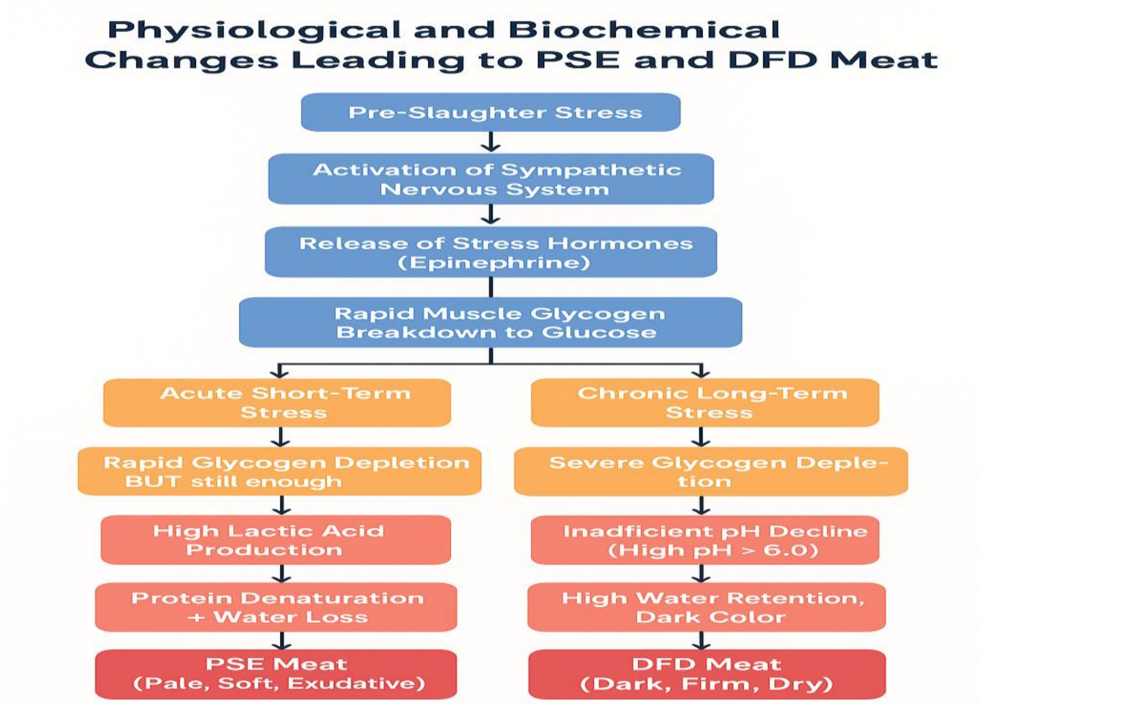

Figure 2: Pre-slaughter stress affects muscle glycogen and pH decline, leading to the development of PSE orDFD meat.

However, if this stress continues for a prolonged period, muscle glycogen is depleted before slaughter. This depletion causes the subsequent changes in muscle biochemistry. In stressed animals, the energy crisis leads to inadequate lactic acid production in the muscle cells. This affects the post-mortem pH decline, which is crucial for tenderization and the development of desirable meat quality. Acute stress normally responsible for PSE meat. In PSE meat, the rapid glycogen depletion means there is enough lactic acid to lower the pH, while in DFD meat, the lack of glycogen leads to insufficient lactic acid formation, causing the pH to remain high. Reducing Stress, to minimize the occurrence of PSE and DFD meat, animal handling and transportation procedures must be carefully managed. Reducing transport time, minimizing noise, avoiding overcrowding, providing water and feed during transport, and using calm handling techniques can help alleviate stress. In particular, pre-slaughter fasting should be minimized to prevent significant glycogen depletion. Ensuring that animals are well-fed and hydrated prior to slaughter helps maintain adequate glycogen levels in the muscles. Adequate glycogen stores promote proper lactic acid production, ensuring normal pH decline post-mortem and enhancing meat quality by preventing both PSE and DFD defects. In conclusion, handling and transport stress can lead to two significant meat quality defects: PSE and DFD meat, both caused by the depletion of glycogen and its subsequent effects on muscle metabolism. Stress-induced depletion of glycogen results in abnormal pH levels, affecting the denaturation of muscle proteins, water retention, and overall meat texture. By managing animal handling, transportation conditions, and minimizing pre-slaughter fasting, the risks of these defects can be reduced, ultimately improving meat quality and consumer satisfaction.

Fasting period before slaughter

Fasting before slaughter is a critical pre-slaughter management practice that significantly impacts both the quality and safety of meat (Driessen et al., 2020). By reducing gut contents and depleting glycogen stores, fasting plays a pivotal role in ensuring proper post-mortem muscle metabolism. Glycogen serves as the primary energy source for muscle activity, and its depletion before slaughter promotes a controlled post-mortem pH decline. This pH decline is essential for proper protein denaturation, which leads to meat tenderness and improved water retention, ultimately enhancing juiciness and texture. In addition to its effects on muscle metabolism, fasting helps reduce the amount of digestive material in the gastrointestinal tract, which minimizes the risk of microbial contamination during slaughter. By reducing the potential for pathogen leakage into the carcass, fasting ensures that the meat remains safer for human consumption and less prone to spoilage. However, if fasting is not properly managed, excessive glycogen depletion can lead to insufficient lactic acid production, which results in Dark, Firm, and Dry (DFD) meat. In DFD meat, the pH remains elevated post-mortem, leading to tougher meat with poor water retention, dry texture, and darker coloration. Additionally, improper fasting can impact fatty acid metabolism, affecting flavor development and the balance of marbling in the meat. Thus, a balanced fasting period is crucial for achieving optimal meat quality by ensuring proper glycogen depletion, reducing microbial risks, and promoting desirable meat attributes such as tenderness, juiciness, and flavor.

Post-Slaughter Factors

Post-slaughter factors play a crucial role in determining the final quality, safety, and consumer acceptability of meat. The slaughter method influences early post-mortem biochemical reactions, affecting the rate of pH decline, color stability, and tenderness development. Proper carcass handling and cooling are essential to regulate temperature and prevent cold shortening or excessive drip loss, thereby preserving water-holding capacity and texture. Controlled chilling facilitates optimal lactic acid production and prevents microbial growth (Figure 3).

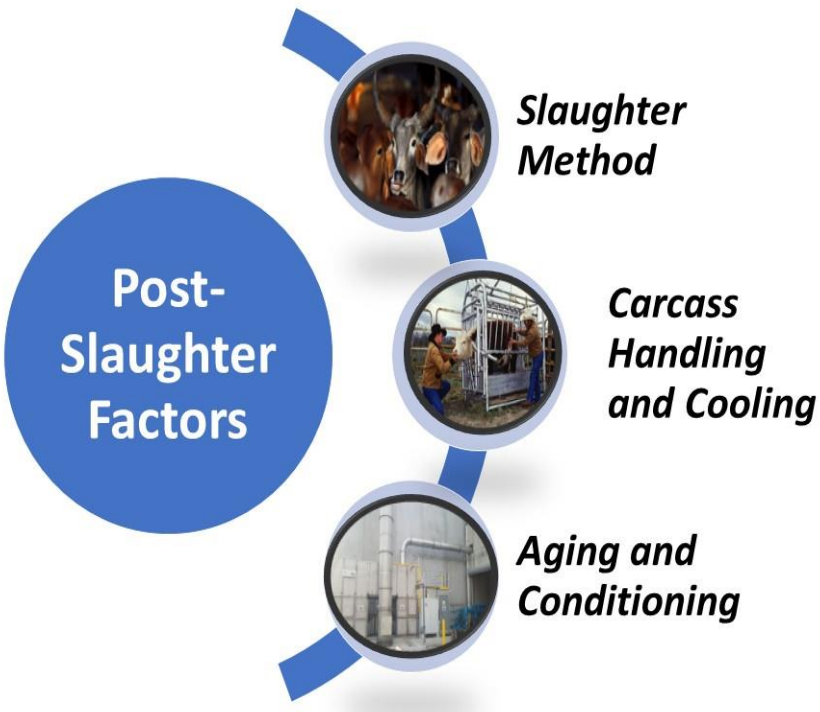

Figure 3: Main Post Slaughter factors in meat quality.

Aging and conditioning promote enzymatic proteolysis of muscle fibers, improving tenderness, juiciness, and flavor development over time. Furthermore, storage temperature and packaging methods such as vacuum or modified atmosphere packaging (MAP) help maintain oxidative stability, minimize contamination, and extend shelf life. Therefore, effective management of post-slaughter practices ensures the desired meat quality attributes, including tenderness, color, water-holding capacity, and overall sensory characteristics, while enhancing consumer satisfaction and market value (Table 2).

Table 2: Influence of Post-Slaughter Factors on Meat Quality Attributes

Factors	Quality Attribute Affected	Recommendations	References
Slaughter Method	pH decline, Color, Tenderness	Use humane slaughter methods to reduce stress and optimize pH decline.	Terlouw et al., 2021
Carcass Handling & Cooling	Water-holding capacity, Drip loss, Oxidation	Apply rapid but controlled chilling to prevent cold shortening and spoilage.	Savell et al., 2005
Electrical Stimulation	Tenderness, pH decline	Apply immediately post-mortem to accelerate rigor mortis and improve texture.	Polidori & Vincenzetti, 2017
Aging & Conditioning	Tenderness, Flavor	Implement optimal aging time depending on species (7–14 days in beef).	Hernandez et al., 2023
Packaging Method	Color stability, Oxidation, Shelf life	Use vacuum or modified atmosphere packaging to delay lipid oxidation.	Śmiecińska & Daszkiewicz, 2021
Storage Temperature	Microbial load, Oxidation, Color stability	Maintain chilled storage (0–4°C) or frozen storage (−18°C) to retain quality.	Abdel-Naeem et al., 2021

Slaughter Method

The method of slaughter plays a crucial role in determining the quality of meat by directly influencing both physiological processes and biochemical reactions in muscle tissue (Terlouw et al., 2021). Humane and effective stunning, followed by proper slaughtering techniques, significantly reduce the animal's stress levels, which in turn affects the post-mortem biochemical changes in the muscles. Stress before slaughter can lead to undesirable meat defects, such as Pale, Soft, and Exudative (PSE) meat or Dark, Firm, and Dry (DFD) meat, due to the improper depletion of glycogen and a lack of efficient lactic acid production. Effective stunning ensures that the animal is rendered unconscious, minimizing the stress response, which prevents the excessive release of stress hormones like epinephrine and norepinephrine, that would otherwise deplete glycogen stores rapidly and alter muscle metabolism. Proper stunning and bleeding techniques also facilitate adequate blood removal from the muscle tissue, which is important for both meat safety and quality. Blood retention in the muscle can promote microbial growth and negatively affect meat color, texture, and shelf life. Furthermore, ensuring proper muscle relaxation by reducing stress during slaughter allows for a smoother transition into rigor mortis, where muscle proteins like actin and myosin undergo optimal denaturation and degradation, improving meat tenderness. Proper bleeding ensures that glycogen stores are used more efficiently, promoting the formation of lactic acid and a controlled pH drop, which contributes to optimal meat texture. If the slaughter method is suboptimal or stressful, muscle fibers contract prematurely, leading to a higher pH post-mortem and affecting the water-holding capacity (WHC), resulting in meat that is less tender, dry, and less flavorful (Ayaz et al., 2024). Therefore, humane and effective slaughtering practices are essential for ensuring that biochemical processes like pH decline, glycogen depletion, and muscle protein denaturation proceed correctly, which ultimately enhances meat tenderness, juiciness, and overall sensory attributes.

Carcass Handling and Cooling

Carcass handling and cooling post-slaughter are critical factors in determining meat quality, as they influence both microbial safety and biochemical processes that affect tenderness (Álvarez et al., 2022). After slaughter, meat is highly susceptible to microbial growth, which can lead to spoilage and contamination. Rapid cooling of the carcass is essential to reduce the muscle temperature quickly, inhibiting bacterial growth by lowering the temperature below the danger zone (4-60°C), where microorganisms thrive (Van-wyk, 2024). Cooling also helps in stabilizing the pH of the meat, which is important for controlling texture and preventing the development of off-flavors. However, excessively fast chilling can cause cold shortening, a phenomenon where the muscles contract too quickly due to low temperatures. This results in a high pH, which prevents proper muscle relaxation and increases rigor mortis intensity, leading to tough meat with poor water-holding capacity (WHC). Cold shortening occurs because the muscles, still full of energy reserves, undergo rapid contraction before the post-mortem ATP depletion allows for proper relaxation. This reduces the tenderness of the meat and affects its overall texture. On the other hand, gradual chilling at controlled temperatures, typically around 2-4°C, allows for proper muscle relaxation and the breakdown of myofibrillar proteins (such as myosin and actin) during rigor mortis, resulting in meat that is tender, juicy, and flavorful. Optimal cooling also aids in the hydrolysis of proteins through the action of calpains and cathepsins, enzymes that break down muscle fibers, further contributing to tenderness. Therefore, while rapid cooling is crucial for preventing spoilage and maintaining safety, it is essential to regulate the chilling process to avoid cold shortening and ensure that biochemical processes, such as muscle relaxation and protein breakdown, occur properly, ultimately resulting in high-quality, tender meat.

Aging and Conditioning

Aging and conditioning play a pivotal role in improving meat tenderness and overall quality by facilitating the enzymatic breakdown of muscle proteins and collagen (Joo et al., 2023). After slaughter, meat undergoes a biochemical process known as post-mortem aging, where enzymes like calpains, cathepsins, and collagenases naturally degrade muscle fibers, leading to increased tenderness. These enzymes, present in the muscle tissue, initiate the breakdown of myofibrillar proteins (e.g., myosin and actin) and collagen, which is the primary connective tissue protein responsible for meat toughness. As collagen breaks down into smaller peptides, the meat becomes tenderer, and its texture improves. The duration of aging is crucial—short aging times (a few days) may result in only limited enzymatic activity, while longer aging periods (up to several weeks) allow more extensive protein degradation, resulting in significantly more tender meat. The method of aging, whether dry aging or wet aging, also influences meat quality. Dry aging involves hanging the carcass in a controlled environment with low humidity, which allows moisture to evaporate from the meat, concentrating its flavor and increasing tenderness due to the enzymatic breakdown. During dry aging, the exposure to air allows the meat to develop complex, nutty, and rich flavors, though it results in some weight loss due to moisture evaporation. In contrast, wet aging, where meat is vacuum-sealed in bags to retain moisture, prevents weight loss but allows for tenderness enhancement without the intense flavor concentration seen in dry aging. Both aging methods rely on the natural enzymatic processes to improve tenderness; however, the choice of method depends on the desired flavor intensity, texture, and moisture content of the final product. Additionally, the temperature at which aging occurs (typically between 0-4°C) is critical, as higher temperatures can promote bacterial growth, while lower temperatures might slow down the enzymatic breakdown, preventing the full tenderization process. Proper aging, therefore, is essential for achieving meat with an ideal balance of tenderness, flavor, and juiciness, as the controlled enzymatic activity contributes to the breakdown of muscle fibers and collagen, enhancing the sensory qualities that consumers seek in high-quality meat.

Packaging and Storage

Packaging and storage are crucial factors in maintaining meat quality after slaughter by influencing microbial growth, oxidation, and overall freshness (Nethra et al., 2023). The primary goal of packaging is to extend the shelf-life of meat while preserving its sensory attributes such as color, texture, and flavor. Vacuum packaging (VP) and modified atmosphere packaging (MAP) are two commonly used methods that effectively improve meat quality by altering the atmospheric conditions around the meat to prevent spoilage and deterioration (Ząbek et al., 2021). Vacuum packaging involves sealing meat in an airtight bag, which removes oxygen, a key factor in the growth of aerobic bacteria and the oxidation of unsaturated fatty acids in meat. By eliminating oxygen, vacuum packaging helps prevent microbial contamination and oxidative rancidity, which can lead to off-flavors and undesirable changes in color and texture. Furthermore, the absence of oxygen inhibits the growth of spoilage microorganisms such as Pseudomonas and Listeria, thereby extending meat freshness. On the other hand, modified atmosphere packaging alters the composition of gases within the package, typically by increasing carbon dioxide and decreasing oxygen levels. This change slows down the growth of spoilage bacteria and the metabolic processes that lead to the deterioration of meat quality, while maintaining the red color of meat by stabilizing myoglobin in its oxygenated form. MAP can also help reduce lipid oxidation, which is responsible for the development of rancid flavors and the degradation of fats. By controlling the gas environment, MAP not only helps maintain the meat's color and flavor but also extends its shelf-life, especially in fresh meat and pre-cooked products. Both vacuum packaging and MAP, when combined with proper refrigeration, help to delay microbial spoilage and oxidation processes. Additionally, temperature control during storage is vital, as cold storage slows down microbial activity and the enzymatic breakdown of muscle proteins, which otherwise could lead to undesirable changes in texture, flavor, and juiciness. Thus, the appropriate choice of packaging method whether vacuum packaging or MAP along with proper storage conditions, plays a critical role in ensuring that meat maintains its quality over time, preserving its freshness, flavor, and safety for consumers.

Interaction between pre and post-slaughter factors

The interaction between pre- and post-slaughter factors is a complex and dynamic process that significantly influences meat quality, and understanding the synergy between these factors is essential for achieving a consistently high-quality product. Pre-slaughter conditions such as animal handling, diet, stress levels, fasting, and transportation set the stage for the post-mortem biochemical processes that determine the final characteristics of the meat (Sardi et al., 2020). For example, stress before slaughter can lead to the activation of the sympathetic nervous system, releasing stress hormones like epinephrine and norepinephrine, which cause a rapid depletion of muscle glycogen (Birhanu, 2020). This depletion directly impacts lactic acid production post-slaughter, which is essential for a proper pH decline and muscle relaxation. In turn, insufficient lactic acid production can result in poor meat texture and defects like Pale, Soft, and Exudative (PSE) or Dark, Firm, and Dry (DFD) meat, depending on the extent of glycogen depletion and subsequent pH rise. The post-slaughter factors such as humane stunning, proper slaughter techniques, carcass handling, and cooling interact with these pre-slaughter conditions to either alleviate or exacerbate these biochemical issues (Njoga et al., 2023). For example, humane stunning ensures that the animal is unconscious and free from stress at the time of slaughter, preventing the surge of stress hormones that could lead to detrimental changes in muscle metabolism (Sazili et al., 2023). Proper bleeding during slaughter ensures effective removal of blood from the carcass, reducing microbial growth and preventing the development of off-flavors and spoilage. In addition, cooling immediately after slaughter is essential to control microbial contamination by reducing temperature to levels that slow down bacterial growth. However, overly rapid chilling can lead to cold shortening, where muscle fibers contract too quickly due to a low temperature, resulting in tougher meat (James & James, 2010). Thus, the timing and rate of cooling must be controlled to allow for optimal muscle relaxation and to prevent excessive shrinkage of muscle fibers, which would affect tenderness and water-holding capacity. Aging post-slaughter further interacts with the pre-slaughter conditions by allowing the natural breakdown of muscle proteins and collagen through the activity of calpains and cathepsins, enzymes that help improve meat tenderness (Shi et al., 2021). The duration and method of aging whether dry aging or wet aging also depend on the quality of the animal before slaughter. For example, animals that are well-handled, properly fed, and not stressed will have more optimal glycogen levels and healthier muscle tissues, making them better candidates for aging methods that enhance tenderness and flavor. Dry aging, where meat is exposed to air in a controlled environment, leads to moisture loss, concentrating flavors and enhancing umami characteristics, while wet aging, which is done under vacuum in a sealed environment, retains moisture but can enhance tenderness by allowing for enzymatic action without the flavor concentration. Furthermore, packaging plays a significant role in preserving the biochemical integrity of meat after slaughter. Vacuum packaging and modified atmosphere packaging (MAP) are designed to maintain optimal conditions for meat by preventing oxidation, which is crucial for preventing oxidative rancidity and off-flavors that degrade the meat's sensory qualities. MAP, for example, alters the atmospheric composition around the meat by replacing oxygen with gases such as carbon dioxide and nitrogen, slowing down the growth of spoilage microorganisms and extending shelf-life while maintaining myoglobin in its oxygenated form, preserving the red color of fresh meat. Vacuum packaging, on the other hand, removes oxygen completely, reducing microbial activity and preserving the integrity of fats, which can otherwise become rancid when exposed to oxygen. Both methods, when combined with appropriate storage temperature (typically between 0-4°C), reduce microbial contamination and prevent spoilage, ensuring that meat retains its flavor, texture, and color over time. In summary, the interaction between pre- and post-slaughter factors is a complex yet essential aspect of meat production that governs its final quality (Figure 4).

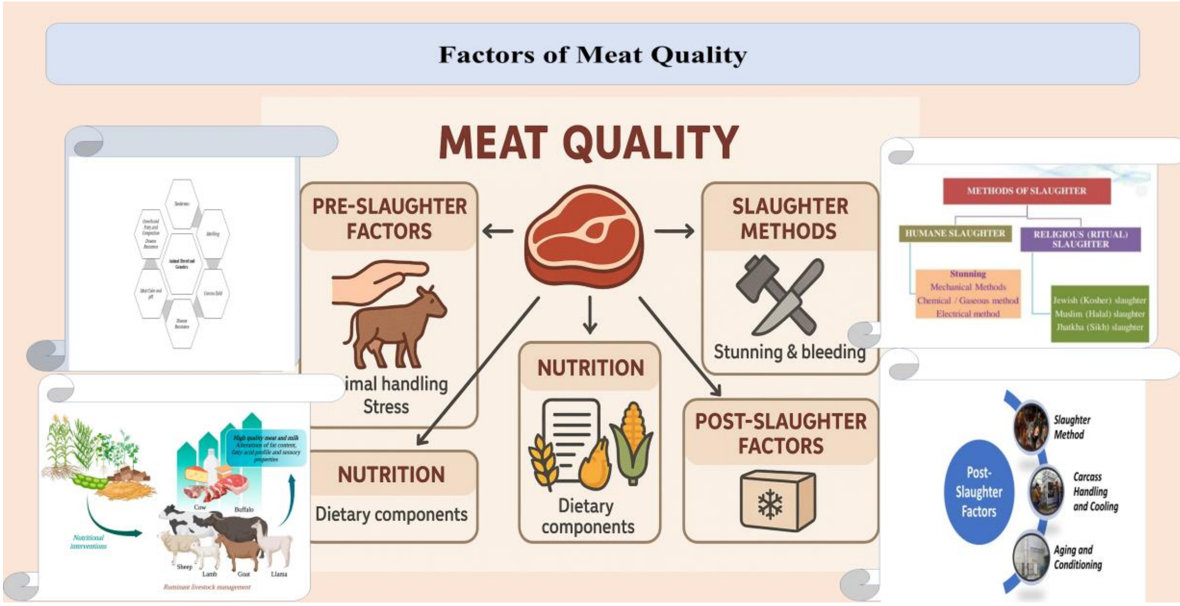

Figure 4: Factors that affect the meat quality.

Effective pre-slaughter management including animal handling, stress reduction, proper feeding, and fasting lays the foundation for optimal post-mortem biochemical processes, such as muscle relaxation, protein degradation, and collagen breakdown, which directly impact tenderness, texture, and flavor. Proper post-slaughter handling, cooling, aging, and packaging methods then work in synergy with these pre-slaughter conditions to preserve and enhance the meat's quality by minimizing microbial growth, oxidative spoilage, and undesirable texture changes. Integrated management strategies that ensure consistency between these factors are key to producing meat with desirable sensory attributes, ensuring it is safe, flavorful, tender, and juicier, with a longer shelf life.

Conclusion

This comprehensive review underscores the intricate and multifactorial nature of meat quality, highlighting the profound influence of both pre-slaughter and post-slaughter factors on the final product. The integration of animal genetics, nutritional management, stress reduction, and optimal handling practices prior to slaughter plays a pivotal role in shaping the biochemical and physiological foundation that governs meat quality. Factors such as muscle fiber composition, glycogen levels, and fat deposition, influenced by genetics and diet, dictate key quality attributes like tenderness, flavor, marbling, and juiciness. Moreover, the reduction of stress through humane slaughtering and handling methods mitigates the adverse biochemical changes, such as accelerated glycogen depletion and altered pH levels, that contribute to defects like Pale, Soft, and Exudative (PSE) or Dark, Firm, and Dry (DFD) meat. Post-slaughter, the careful management of carcass handling, cooling, aging, and packaging techniques remains critical for preserving the biochemical integrity of meat. Rapid cooling reduces microbial proliferation and oxidation, but overly aggressive chilling can induce cold shortening, undermining meat tenderness. Aging processes, particularly when coupled with optimal temperature and humidity control, enhance tenderness and flavor through enzymatic degradation of muscle proteins and collagen. Furthermore, innovative packaging technologies, such as vacuum and modified atmosphere packaging (MAP), prevent oxidative spoilage and microbial growth, thereby extending shelf life while preserving sensory attributes like color, texture, and flavor. The synergistic interactions between pre- and post-slaughter factors are essential for producing meat that not only meets but exceeds consumer expectations in terms of quality. A holistic and integrated management approach, ensuring optimal conditions throughout the meat production process, is paramount for enhancing the consistency, safety, and sensory appeal of meat. These findings provide a foundation for future advancements in meat science, emphasizing the need for continued innovation in both pre-slaughter management and post-slaughter preservation strategies to meet the evolving demands of the global market for high-quality meat products.

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Conflict of Interest

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