Journal of Meat Science
Year 2025 (June), Volume-20, Issue-1
ISSN 0975-5209 (Print)
ISSN 2581-6616 (Online)

Harnessing Omics Technologies for Meat Biomarker Discovery

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ARTICLE INFO

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(Rajendran Thomas)
Received 2025-02-27; Accepted 2025-05-30

doi10.48165/jms.2025.20.01.8

ABSTRACT

Meat quality, safety, and postmortem aging processes have all been transformed by the use of omics technology in meat science. The function of metabolomics, proteomics, metagenomics, lipidomics, transcriptomics, and multiomics techniques in locating biomarkers linked to characteristics of meat quality, such as flavor, texture, shelf life, and tenderness, is examined in this study. While proteomics identifies important protein alterations during postmortem aging, metabolomics sheds light on small-molecule metabolites that impact meat quality. Characterizing the microbial communities that affect meat safety and deterioration is made easier with the help of metagenomics. While transcriptomics reveals changes in gene expression after slaughter, lipidomics clarifies lipid oxidation and flavor development. A comprehensive understanding of the molecular connections influencing meat quality is provided by multiomics integration. This review also discusses the omics of postmortem meat aging, focusing on metabolic pathways that affect softness and water-holding ability, including glycolysis, proteolysis, and apoptosis. Mass spectrometry and high-throughput sequencing developments have made it possible to precisely identify biomarkers, which has aided in the creation of predictive models for evaluating the quality of meat. There is also discussion of difficulties including economic constraints, standardization, and data integration. In the end, precision agriculture and customized processing methods using omics-driven technologies have enormous potential to maximize meat production, improve food safety, and raise consumer happiness.
Keywords: Meat quality, Biomarkers, Post-mortem meat changes, Omics approaches, Food safety

INTRODUCTION

Meat science has been revolutionized by the intervention of omics technologies, which provide previously unheard-of insights on meat quality, traceability, authenticity, and food safety. These cutting-edge analytical techniques include metagenomics, lipidomics, proteomics, metabolomics, transcriptomics, genomics etc. and offer a thorough comprehension of the molecular and biochemical mechanisms underpinning the creation and processing of meat. In order to ensure meat authenticity and stop fraudulent techniques like species mislabelling, genomics makes possible the identification of species-specific DNA markers. Gene expression patterns in muscle tissues are revealed by transcriptomics, which provides hints about the characteristics of meat that affect its quality, including colour, flavour, and tenderness. Proteomics, the study of proteins aids in the detection of possible allergens or pollutants that may jeopardize food safety as well as biomarkers linked to characteristics of meat quality and post-mortem alterations (Ramanathan et al. 2020). With their relative emphasis on small molecules and lipids, metabolomics and lipidomics offer comprehensive profiles of the biochemical makeup of meat, offering information on its nutritional value, sensory qualities, and signs of spoiling. The development of strong traceability systems is made easier by various omics technologies working together is ensuring the accountability and transparency in the meat supply chain (Munekata et al. 2021). Through the integration of multi-omics data, scientists can tackle intricate problems in meat science, including improving product quality, reducing the danger of adulteration or foodborne infections, and optimizing production methods. As these technologies develop further, they have the potential to significantly improve safe and sustainable meat production, satisfying customer demands for premium, genuine, and ethically sourced goods (Hwang et al. 2023).

Omics approaches in biomarker discovery

Meat industry is increasingly using omics techniques to improve the production and quality of meat. In cattle, genomics aids in the identification of genetic markers linked to desired characteristics such as growth efficiency, marbling, and tenderness. The texture and flavor of meat are influenced by gene expression patterns that are revealed by transcriptomics during muscle growth and post-mortem procedures (Munekata et al. 2021). By analyzing the protein profiles found in muscle tissues, proteomics finds biomarkers for qualities like color stability and water-holding capacity. Metabolomics examines how an animal's metabolism changes, relating stress and nutrition to the texture and flavour of meat. The study of epigenomics looks at how environmental elements, like as diet and management techniques, affect meat quality and gene expression. Targeted breeding and management practices are made possible by integrative multi-omics, which offers a thorough understanding of the molecular pathways driving meat qualities (Ramanathan et al. 2023). These methods are very useful for raising the caliber of beef, pork, and poultry in order to satisfy consumer demands for high-end goods. Data integration, expense, and converting research results into useful farming applications are among the difficulties. Notwithstanding these obstacles, omics technologies are revolutionizing animal science and opening the door to the production of high-quality, sustainable meat (Laville et al. 2009). Through the optimization of animal health, nutrition, and genetics, omics techniques guarantee higher-quality meat, increasing its nutritional and economic worth.

Genomics

Genomics the study of the complete set of genome of an individual. Finding important gene networks and pathways, as well as potential genes, that underlie the genetic regulation of phenotypes is one of the advantages of functional genomics. By combining genetic analysis with expression phenotypes, a process known as genetic genomics, it is possible to identify regulatory networks that govern the coordinated expression of genes and map DNA variation that influences the expression of mRNA (Mullen, 2006). In the meat industry, genomics, the study of an organism's whole genome has proven to be a crucial tool for identifying biomarkers associated with certain characteristics and ailments (D'Alessandro et al. 2013). The uses of genomics biomarkers in meat research are described in detail below.

Enhancing meat quality traits In order to detect genetic differences that affect important meat quality attributes including flavour, marbling, and tenderness, genomic biomarkers are essential. For instance, meat tenderness is directly correlated with genes like calpastatin and calpain, but marbling and juiciness are influenced by markers linked to fatty acid metabolism (Thompson et al. 2003). Animal farmers can reliably generate high-quality meat products by choosing animals with advantageous genetic characteristics. This strategy benefits the meat business in addition to increasing customer satisfaction (Hocquette et al. 2006). Overall, genetic biomarkers are revolutionizing the evaluation and improvement of meat quality.

Improving breeding efficiency Breeders can detect and choose superior animals early on based on their genetic potential by using genomic biomarkers. This lessens the need for laborious, conventional phenotypic selection techniques, which frequently need for waiting for the animal to reach adulthood. Producers can hasten the development of desired features by integrating genetic information into breeding operations (Goll et al. 2003). Faster genetic advancement and more productive cattle production result from this. Breeding programs consequently become more productive and economical.

Optimizing growth and production Genomic biomarkers aid in the identification of genes linked to livestock muscle development, feed conversion, and growth efficiency. Better growth rates and greater meat production can result from breeding animals with advantageous genetic markers. This lowers the environmental impact of meat production while simultaneously increasing productivity (Gagaoua, 2022). Producers can sustainably supply the rising demand for meat by maximizing these qualities. Thus, genomic tools are essential to ensuring cattle production is both economic and efficient.

Animal wellbeing and resistance to disease Genomic indicators play a crucial role in detecting genetic variants associated with livestock disease resistance. Producers can create healthier herds that need f.ewer medical treatments by choosing animals with these indicators. This encourages sustainable farming methods and lessens the need for antibiotics. Better meat quality and increased productivity are additional results of improved animal health (Magalhães et al. 2019). In general, the development of robust and disease-resistant livestock populations is aided by genetic biomarkers.

Stress tolerance and welfare Animals under stress may produce meat that is dark, firm, and dry (DFD), among other problems. By identifying genetic variants linked to stress tolerance, genomic biomarkers facilitate the selection of animals that are more resilient to environmental stressors. This guarantees constant meat quality while simultaneously enhancing animal welfare (Mullen.2006). Producers can increase profitability and productivity by lowering stress-related losses. Thus, genomic tools promote moral and environmentally friendly animal management techniques.

Traceability and authenticity Meat products may be reliably traced from farm to table using genomic biomarkers. Producers can confirm the provenance and validity of beef by examining genetic markers, guaranteeing supply chain transparency. This increases customer confidence and bolsters the market for goods sourced responsibly. Additionally, traceability aids in the detection and resolution of problems such as food theft (Gagaoua 2022). All things considered, genetic indicators improve the meat industry's dependability and integrity.

Proteomics

In meat research, proteomics, the extensive study of proteins has become a potent instrument for comprehending and enhancing meat safety, quality, and production effectiveness. Specific proteins or protein profiles known as proteomics biomarkers shed light on an animal's post-mortem alterations, muscle growth, and stress reactions (Banerjee et al. 2022). Researchers can find important proteins linked to characteristics like softness, colour stability, and water-holding capacity by examining these biomarkers. This information makes it possible to create plans to improve the quality of meat and streamline processing methods (Sidira et al. 2024). The uses of proteomics biomarkers in meat research are described in detail below.

Improving meat tenderness Proteomics biomarkers aid in the identification of proteins that affect meat softness and are involved in muscle contraction and breakdown, such as caspases and calpains (Gagaoua 2022). Researchers can forecast and regulate the tenderness of meat products by examining post-mortem proteolytic changes. The aging and processing conditions are optimized with the help of this data. Because of this, producers are able to provide meat that is consistently tender, which increases customer satisfaction (Sidira et al. 2024). Therefore, proteomics is essential to guaranteeing the quality of premium meat.

Enhancing colour stability One important element affecting consumers' decisions to buy is the colour of the meat. Proteins like myoglobin and antioxidant enzymes that impact colour stability during storage are revealed by proteomics biomarkers. Producers can create plans to preserve desired meat colour by comprehending these protein interactions. Optimizing storage and packaging conditions is part of this. Increased colour stability lowers waste and increases shelf life (Banerjee et al. 2022; Jagadeesh et al. 2017). Therefore, proteomics is crucial to preserving beef products' aesthetic appeal.

Understanding post mortem changes Proteomics biomarkers shed light on the metabolic alterations, including as glycolysis and protein breakdown, that take place in muscle following slaughter. Texture, flavour and shelf life are all impacted by these changes in meat quality. Researchers can improve the circumstances for slaughter and processing by examining post-mortem proteomes. This lowers variability in meat products and guarantees constant quality (Capozzi et al. 2017). A useful technique for comprehending and managing post-mortem procedures is proteomics.

Detecting meat authenticity and adulteration Proteomics indicators are utilized to identify adulteration and confirm the authenticity of meat products. Cuts, species, and processing techniques can all be identified by specific protein profiles (Sidira et al. 2024). This increases consumer trust and guarantees openness in the beef supply chain. Additionally, proteomics aids in spotting dishonest tactics like adding subpar meat. Proteomics improves the integrity of the meat sector by guaranteeing authenticity (Afzaal et al. 2022).

Improving nutritional quality Protein content and amino acid profiles are two examples of the nutritional makeup of meat that can be inferred from proteomics biomarkers. Breeding for desired traits and improving animal diets are examples of this. Better nutritional value satisfies consumer preferences for more healthful food options (Afzaal et al. 2022). Thus, the production of meat that is high in nutrients is supported by proteomics.

Enhancing food safety Pathogens and spoilage organisms in meat products are found using proteomics biomarkers. Researchers are able to create quick detection techniques by recognizing particular bacteria proteins. This guarantees the meat's quality and safety all the way through the supply chain. Additionally, proteomics aids in the development of control methods and an understanding of microbial resistance (Capozzi et al. 2017). Improved food safety lowers financial losses while safeguarding consumer health.

Detection of meat quality Biomarkers related to various traits of meat such as tenderness, colour, texture, water holding capacity can be identified by proteomic analysis. For example proteins associated with meat tenderness such as actin, myosin can be identified as the biomarker for meat tenderness (Gagaoua 2022). Similarly, for softness of meat calpins and calpastain can act as the biomarker, to detect the volatile compounds associated with specific flavour of meat which gets bound to specific kinds of proteins can act as the biomarker for flavour.

Pathogen Identification Food borne pathogens can be identified using the proteomic technology. These pathogens can be used as parkers for detection of meat spoilage and these markers make it possible to create sensitive and quick pathogen detection techniques. Though the food processing techniques the pathogens and toxins cannot be destroyed but can be identified if the proteins responsible for these changes can get identified which could be used as the protein biomarker for the specific trait (Gagaoua 2022). Example, certain assays for identifying Listeria monocytogenes in meat processing settings can be developed by focusing on its distinct proteins.

Metabolomics

It is the study of the total metabolic profile of a biological system. It is generally a method of functional genomics (Shulaev 2006). Metabolomics is crucial in locating biomarkers for contamination, freshness, and quality of meat. In meat science, metabolomics, the study of small molecules or metabolites in biological systems has emerged as a useful tool for understanding and improving meat quality, safety, and production efficiency. Metabolomics biomarkers, which are specific metabolites or metabolic profiles, offer insights into the biochemical processes that influence meat qualities like flavour, tenderness, and shelf life (Zhang et al. 2021). By analysing these biomarkers, researchers can identify key metabolic pathways and develop strategies to optimize meat quality, supporting sustainable and ethical meat production and satisfying consumer demands for high-quality products (Muroya et al. 2020). The following are the uses of metabolomics biomarkers in meat science explained in detail.

Meat flavour enhancement Metabolomics biomarkers identify metabolites like volatile chemicals, peptides, and amino acids that are linked to flavour formation. Through examining these metabolites, scientists can get insight into the molecular mechanisms underlying the production of appealing flavours. The purpose of this data is to optimize processing conditions and feeding schedules. Market value and customer happiness both rise with improved flavour characteristics (Capozzi et al. 2017). Thus, metabolomics is essential to enhancing meat's sensory appeal.

Meat tenderness and texture improvement Metabolomics biomarkers detect metabolites including lactate and nucleotides that are involved in muscle metabolism and post-mortem alterations. By altering muscle pH and proteolysis, these metabolites affect the texture and softness of meat. Researchers are able to predict and regulate tenderness by examining metabolic patterns (Sidira et al. 2024). Improving storage and aging conditions is part of this. The eating experience and customer acceptance of beef products are both improved by increased softness.

Meat authenticity and adulteration detection Metabolomics biomarkers are utilized to identify adulteration and confirm the authenticity of meat products. Cuts, species, and processing techniques can all be identified by specific metabolic signatures (Muroya et al. 2020). This increases consumer trust and guarantees openness in the beef supply chain. Additionally, metabolomics aids in spotting dishonest tactics like adding subpar meat. Metabolomics improves the integrity of the meat sector by guaranteeing authenticity (Sidira et al. 2024).

Stress monitoring The quality of meat can be adversely affected by stress in animals before to slaughter, resulting in problems such as dark, firm, and dry (DFD) meat. Cortisol, glucose, and other stress-related metabolites are identified by metabolomics biomarkers. Producers can evaluate animal wellbeing and apply stress-reduction techniques by keeping an eye on these biomarkers. This guarantees that livestock are treated ethically and enhances the quality of the meat (Zhang et al. 2021). Thus, metabolomics promotes both product quality and animal welfare.

Food safety enhancement Meat products are analyzed for contaminants and spoilage microbes using metabolomics indicators. The identification of particular microbial metabolites allows researchers to create quick detection techniques. Throughout the supply chain, this guarantees the meat's safety and quality (Shulaev 2006). Additionally, metabolomics aids in the comprehension of microbial resistance and the creation of management plans. Improved food safety lowers financial losses while safeguarding the health of consumers.

Transcriptomics

Transcriptomics is the study of the total transcriptome viz. the total set of RNA in a particular organism. For transcriptomic study the identification of transcripts and analysing the gene expression at the transcriptional level is very important (Bassey et al. 2021). These approaches help in developing novel biomarkers by acting as powerful tool for understanding complex biological system (Pedrotty et al. 2021). Transcriptomics basically focuses on RNA molecules including mesanger RNA (mRNA), transfer RNA (tRNA), ribosomal RNA (rRNA), some non coding RNA (ncRNA) and small RNAs (sRNA) (Bassey et al. 2021). RNA sequencing or gene expression microarrays are used in transcriptomic investigations to measure the amount of each transcript expressed in a group of experimental samples (Pedrotty et al. 2021). The link between genotype and phenotype in a biological system is mostly represented by the mRNAs which makes them very important (Bassey et al. 2021). Transcriptomics is essential for comprehending the relationships between gene expression patterns and the safety and quality of meat. The key applications of transcriptomics biomarkers in meat science, explained in details below.

Meat quality assessment Gene expression profiles can help in identifying the biomarkers associated with meat tenderness and texture. For example, the potential tenderness of meat can be indicated by expression of potential genes like calpin and calpastatin which regulates post-mortem proteolysis of meat. Studies on tenderness prediction reveals that heat shock proteins are potential biomarkers for meat tenderness detection (Guo et al. 2022). The identification of transcripts related to production of volatile compounds and lipid metabolism can lead to the identification of biomarker responsible for aroma.

Meat safety and pathogen detection Transcriptomic analysis by identifying RNA transcripts specific to certain pathogens such as *E.coli*, salmonella etc. can help in pathogen detection. Transcriptomics can also help in identifying the expression of antibiotic resistance gene in the microorganisms present in the meat and meat products which can help to manage and mitigate the spread of the antibiotic resistance strain through the infected meat or meat products. These resistance genes can further be identified as antibiotic resistance biomarker (Bassey et al. 2021).

Understanding muscle development Gene expression patterns linked to animal muscle growth and development are revealed by transcriptomics biomarkers. Researchers can determine the genes that affect muscle mass, fibre type, and composition by examining these patterns. Breeding plans are optimized using this data to increase the quantity and quality of meat produced. Tender and well-marbled meat is produced with the help of improved knowledge of muscle growth (Zhang et al. 2021). Thus, transcriptomics is essential for increasing the productivity of meat production.

Meat tenderness enhancement Transcriptomics biomarkers aid in the identification of genes that affect meat tenderness through post-mortem proteolysis, including caspases and calpains. Researchers can forecast and regulate the softness of meat products by examining gene expression profiles. Improving the circumstances for slaughter and aging is part of this. Increased softness raises market value and customer delight (Guo et al. 2022). Therefore, transcriptomics is crucial to guaranteeing the quality of premium meat.

Enhancing the marbling and fat content of meat Transcriptomics biomarkers shed light on how meat's marbling and fat deposition are genetically regulated. Researchers can uncover important genes involved in lipid metabolism by examining patterns of gene expression. In order to optimize marbling, breeding and feeding techniques are developed using this knowledge. Meat with improved marbling has more flavour and juiciness. Thus, transcriptomics facilitates the generation of premium beef products with marbling (Bassey et al. 2021).

Stress and welfare indicator By identifying the genes that gets expressed due to stress which leads to the degradation of meat quality and reduction of yield can be identified as stress biomarker for the particular breed. These can enhance animal wellbeing which will ultimately raise the quality of the meat (Sidira et al. 2024). For example, heat shock protein (HSP) expression that is caused by stress can be tracked as a biomarker of animal welfare.

Metagenomics

Metagenomics is the culture independent genetic analysis of microbial community. In this approach, microbial DNA is extracted straight from the ambient sample, this technology has the ability to access the full range of microorganisms, including the majority that have not been cultivated in a laboratory. Metagenomic study can be performed by two approaches, one is sequence based approach and the other is functional approach in which metagenomic libraries are constructed (Allan 2014). The key applications of metagenomics biomarkers in meat science are explained in details below.

Metagenomics in meat quality assessment The biomarkers associated with meat quality, can be identified using the metagenomic approaches as it identifies the microbes present in the ambient sample so the microbial species responsible for meat spoilage or which contributes to enhance flavour can be identified by this approach and some of the specific species can be recognized as biomarker for that specific trait. For example, lactic acid bacteria enhance the flavour and spoilage bacteria like pseudomonas species and *Pseudomonas fragi* are responsible for off odour and off flavour of meat. Clostridium species responsible for the production of large amount of gas in vacuum packed meat (Hultman et al. 2020).

Meat safety and pathogen detection Metagenomic approaches can detect and identify pathogenic DNA such as E.coli, Salmonella etc. even at low abundance and can ensure early detection and intervention by the pathogenic microbe in the supply chain. These studies also can stop spreading of antibiotic resistance bacteria in the meat supply chain by identifying the presence of antibiotic resistance bacteria in the meat sample by removing it from the supply chain (Allan 2014).

Identification of meat authenticity Metagenomics approach can be a powerful tool to detect meat authenticity by detecting the species specific DNA in some cases. It can also be used to identify microbial markers by identifying some specific DNA sequences at processed meat products (Muñoz-Martinez et al. 2025).

Microbiome and Animal Health Microbial markers related to animal health and welfare can get identified by the metagenomic approaches. It can also help in identifying the meat quality by monitoring the environmental impact on meat by identifying the microbial population in the soil, water (Hultman et al. 2020).

Enhancement of fermented meat products Information on the microbial communities that ferment foods like salami and sausages can be found through metagenomics biomarkers. By examining these communities, scientists can find helpful microorganisms that enhance flavor and preservation, like Lactobacillus and Staphylococcus. This data is utilized to guarantee constant quality and optimize fermentation procedures. Improved fermentation enhances meat products' safety and sensory qualities (Poirier et al. 2023). Thus, metagenomics promotes the creation of premium fermented foods.

Gut microbiota assessment of animal Meat quality, growth, and animal health are all impacted by the intestinal microbiota of livestock, which can be studied using metagenomics biomarkers. Through microbial community analysis, scientists can find advantageous microorganisms that enhance disease resistance and nutrient absorption. Management techniques and animal feeds are optimized with the use of this data. Meat quality and production both increase with intestinal health (Abril et al. 2024). Therefore, metagenomics is crucial to the production of animals in a sustainable manner.

Understanding microbial resistance Metagenomics biomarkers shed light on the genetic underpinnings of antibiotic resistance in microorganisms linked to meat. Researchers can monitor the growth of resistant strains and create control plans by examining resistance genes. Optimizing the use of antibiotics in animal production is part of this. Public health and food safety are enhanced by decreased antibiotic resistance (Poirier et al. 2023). Thus, metagenomics promotes ethical and sustainable meat production.

Optimization of processing environment Microbial communities in meat processing facilities can be monitored with the use of metagenomics biomarkers. Researchers can find contamination sources and put specific cleaning procedures in place by examining these communities. This lowers the chance of spoiling and the spread of pathogens. Consistent meat safety and quality are guaranteed by optimal processing conditions (Muñoz-Martinez et al. 2025). Thus, metagenomics is a useful tool for preserving hygienic practices in the production of meat.

Multi-omics-approaches

Meat science has been transformed by multiomics, the fusion of several omics technologies, including transcriptomics, proteomics, metabolomics, metagenomics, and genomes. Researchers can obtain a thorough grasp of the biological mechanisms influencing meat quality, safety, and production efficiency by integrating data from several methods (Wang, J. et al. 2023). The development of focused techniques to maximize meat qualities is made possible by multiomics biomarkers, which offer insights into the connections between genes, proteins, metabolites, and microbial populations. This all-encompassing strategy meets consumer demands for premium products while promoting ethical and sustainable beef production (Afzaal et al. 2022). The main uses of multiomics biomarkers in meat science are described in detail below.

Systems biology By integrating genomes, proteomics, metabolomics, and transcriptomics, scientists may build intricate models of the biological mechanisms influencing the safety and quality of meat. Biomarker discovery is more accurate and reliable using this systems biology method. For example, Integrative analysis can provide a comprehensive picture of the factors impacting meat quality by revealing how genetic variants (genomics) affect protein expression (proteomics) and metabolite levels (metabolomics) (Hultman et al. 2020).

Meat quality trait enhancement Multiomics biomarkers combine information from proteomics, metabolomics, transcriptomics, and genomes to pinpoint important variables affecting meat quality characteristics as flavour, marbling, and tenderness. Through examining these relationships, scientists can create methods to maximize the quality of meat. This entails enhancing processing conditions and choosing animals with desired genetic features (Hultman et al. 2020; Wang et al. 2023). Improved meat quality boosts market value and customer happiness. Therefore, multiomics is essential to the delivery of high-quality beef products.

Improvement of animal health and welfare A comprehensive understanding of the molecular mechanisms governing animal health and stress reactions is offered by multiomics biomarkers. Researchers can find biomarkers linked to stress tolerance and disease resistance by combining information from metabolomics, transcriptomics, and genomes. Animal welfare is enhanced and health therapies are developed using this knowledge (Hwang et al. 2023). Improved productivity and meat quality are the results of improved animal health. Sustainable and moral cattle production methods are supported by multiomics.

Ensuring meat safety and self-life Multiomics biomarkers track microbial communities and meat product deterioration processes by combining information from metagenomics, proteomics, and metabolomics. By examining these relationships, scientists can create methods to manage infections and increase shelf life. Optimizing storage and packaging conditions is part of this. Improved shelf life and food safety cut waste and boost productivity (Perrotta et al. 2017). Meat products are safe and fresh because to multiomics.

Understanding post-mortem changes To investigate the biochemical alterations that take place in muscle following slaughter, multiomics biomarkers combine information from transcriptomics, proteomics, and metabolomics. Researchers can enhance the quality of meat by examining these changes and optimizing processing settings. This involves managing elements such as lipid oxidation, proteolysis, and p^H. A better comprehension of post-mortem procedures guarantees constant meat quality (Wei et al. 2022). For meat processing to be optimized, multiomics is therefore crucial.

Authenticity and adulteration detection of meat To confirm the authenticity of meat products and identify adulteration, multiomics biomarkers integrate information from proteomics, metabolomics, and genetics. Species, cuts, and processing techniques can be identified by researchers by examining several layers of biological data. This increases consumer trust and guarantees openness in the beef supply chain. Additionally, multiomics aids in the detection of dishonest behaviour (Wei et al. 2022). Multiomics improves the integrity of the meat sector by guaranteeing authenticity.

Livestock management Personalized livestock management—in which each animal is tracked and treated according to its distinct genomic, proteomic, metabolomic, and transcriptome profiles—can be made possible using multi-omics techniques. Meat quality and production can be maximized in this way (Perrotta et al. 2017). Example: Meat quality and feed efficiency in individual animals can be enhanced by customized feeding plans based on metabolomic profiles. Details of different types of biomarkers in meat and their applications are placed in table 1.

Table 1: Different types of meat biomarkers and their applications

Field of omics	Biomarker type	Concerned attribute	Reference
Proteomics	Quality Biomarkers	Tenderness Indicators	Banerjee, R. et al. 2022
		Freshness Marker	Wei et.al. 2022
		Colour Stability	Munekata, et al. 2021; Hwang et al. 2023
	Authenticity Biomarkers	Species Identification	Wang et al. 2023
		Breed and Origin Verification	Afzaal et. al. 2022
	Safety Biomarkers	Pathogen Detection	Pedrotty et al. 2021
		Contaminant Identification	Hultman et al. 2020; Muñoz-Martinez et al. 2025
	Processing Biomarkers	Oxidation Markers	Magalhães et al. 2019; Mullen 2006
		Curing and Smoking Indicators	Allan 2014
	Nutritional Biomarkers	Nutrient Content	Lamri et. al. 2023
Metabolomics	Quality Biomarkers:	Tenderness Indicators	Shulaev 2006;
		Freshness Marker	Zhang et al. 2021
		Flavor Compounds	Sidira et al. 2024
			Capozzi et al. 2017
	Authenticity Biomarkers	Species Identification	Abril et al. 2024
		Breed and Origin Verification	Muroya et al. 2020
			Bassey et al. 2021
	Safety Biomarkers	Pathogen Detection	Sidira et al. 2024
		Contaminant Identification	Jagadeesh et al. 2017
			Pedrotty et al. 2021
	Processing and Storage Biomarkers	Heat Treatment Indicators	Hultman et al. 2020
		Oxidation Markers	Ramanathan et al. 2020
		Curing and Smoking Indicators	Hwang et al. 2023
			D'Alessandro et al 2013
	Nutritional Biomarkers	Nutrient Content	D'Alessandro et al 2013
Metagenomics	Safety Biomarkers	Pathogen Detection	Mullen 2006
		Antibiotic Resistance Genes	Gagaoua 2022
			Laville et al. 2009
	Quality Biomarkers	Spoilage Organisms	Jagadeesh et al. 2017
			Hwang et al. 2023
		Fermentation Microbes	Wang et al. 2023
			Hultman et al. 2020
	Authenticity Biomarkers	Species Identification	Gagaoua 2022
		Microbial Community Profiles	Laville et al. 2009
	Processing and Storage Biomarkers	Heat Treatment Indicators	Bassey et al. 2021
		Cold Storage Impact	Pedrotty et al. 2021
			Guo et al. 2022
	Microbial Safety and Hygiene Biomarkers	Hygiene Indicator Organisms	Zhang et al. 2021
		Biofilm-Forming Bacteria	Muroya et al. 2020

Genomics	Quality Biomarkers	Tenderness and Texture Marbling and Fat Content Juiciness and Water-Holding Capacity	Poirier et al. 2023 Abril et al. 2024 Wang et al. 2023
	Authenticity Biomarkers	Species Identification Breed and Origin Verification	Pedrotty et al. 2021 Guo et al. 2022
	Safety Biomarkers	Pathogen Detection Antibiotic Resistance Genes	Afzaal et al. 2022 Shulaev 2006
	Processing and Storage Biomarkers	Heat Stress Response Cold Storage and Freezing Impact	Zhang et al. 2021
	Production Efficiency Biomarkers	Growth Rate and Feed Efficiency Disease Resistance	Zhang et al. 2021 Muroya et al. 2020

Biomarkers in meat quality determination

Delivering high quality meat products with stable and acceptable sensory and safety properties has become the demand of the consumers to the food processing industry (Afzaal et al. 2022). To achieve the goal, it is important for the researchers to address the meat quality issues like acknowledging the biochemical pathways related to the conversion of muscle into meat after slaughter, effect of rigor mortis in the meat quality, how processing aids in the changes in the quality of meat (Bassey et al. 2021). To determine the meat quality biomarkers can be used as one of the most reliable tools. Biomarkers are tools that regulates the phenotypes of animals along with the meat quality and yields. Therefore, if the right biomarker can get identified related to the meat quality traits like tenderness, colour, texture then it will be easy to understand the mechanism behind these attributes and problems related to meat quality and spoilage can be addressed.

Use of biomarkers for the determination of post-mortem ageing of meat

Postmortem ageing of meat refers to the period after the animal has been slaughtered. This value-adding process has been used in meat industry from decades in which the desired sensory attributes of meat which contributes to enhancement of its qualities such as taste, tenderness, juiciness, texture, flavour etc. due to the biochemical and structural changes of meat (Muroya et al. 2020). Out of all these sensory attributes tenderness of meat is considered as the most important organoleptic characteristic and according to Mohammad Koohmaraie it is effected by variables such as animal age and sex, rate of glycolysis, amount and solubility of collagen, sarcomere length, ionic strength and degradation of myofibrilar proteins (Hultman et al. 2020). The post-mortem ageing of meat can be practiced in two different methods, wet ageing and dry ageing. Campbell et al states that wet or refrigerated ageing is the process of storing meat for a period of time in sealed or barrier packaging and dry ageing is the process of storing meat unpackaged at controlled temperature and relative humidity (Perrotta et al. 2017). It is reported that the dry aged meat has stronger nutty flavor whereas wet or vacuum aged meat has milder flavor. Both dry and wet aged meat shows similar tenderness due to the enzymatic breakdown of proteins and connective tissues. In appearance dry aged meat has rusty outlook and wet aged meat is bright and red in colour (Hwang et al. 2023).

As post-mortem ageing of meat has its effect on the meat quality, therefore specific molecules or chemicals can be identified which can act as indicators of specific traits of the meat quality which can further be identified as meat quality biomarkers primarily indicating tenderness, flavour, texture etc. The post-mortem ageing biomarkers can be classified into protein biomarker, enzymatic activity biomarker, lipid oxidation biomarker and metabolic biomarker.

Protein biomarkers of post-mortem meat ageing

In order to comprehend post-mortem meat aging that affects texture, flavour and tenderness, protein biomarkers identification is essential. Proteolysis is fueled by essential proteins like caspases and calpains, which break down muscle proteins to increase softness. Meat quality is preserved by antioxidant enzymes and heat shock proteins (HSPs), which guard against oxidative stress (Muñoz-Martinez et al. 2025). Colour stability is influenced by myoglobin and its derivatives, whereas texture is affected by the degradation of structural proteins including titin and desmin. In order to attain the appropriate level of meat quality, monitoring these indicators aids in optimizing aging circumstances, including temperature and time. Protein biomarkers can be used by manufacturers to guarantee consistent, premium aged beef products that satisfy consumer demands for flavour and softness. Protein biomarkers primarily involves degradation and structural and contractile protein by proteolytic enzymes (Abril et al. 2024). These proteins and enzymes can be identified using techniques like electrophoresis, western blotting, high performance liquid chromatography (HPLC) and mass spectrometry (MS) (Hultman. et al. 2020). Muscle fiber characteristics as biomarkers of beef tenderness across bovine muscles: An integrated approach). The key protein biomarker involves troponin-T, desmin, titin, nebulin, actin and myosin. The proteolytic enzymes involved in degradation of protein which leads to identification of protein biomarker fragments are Calpins (Calpain-1 (μ-calpain) and Calpain-2 (m-calpain)), cathepsin (Cathepsin B, D, and L).

Enzymatic activity biomarkers of post-mortem meat ageing

In post-mortem meat aging, enzymatic indicators play a crucial role in determining texture, flavour, and tenderness. Two important proteolytic enzymes that break down muscle proteins and increase tenderness are calapsins and caspases. Lysosomes include cathepsins, which aid in the degradation of proteins. Lactate dehydrogenase and other glycolytic enzymes control pH drop, which impacts colour and water-holding capacity (Banerjee et al. 2022). Superoxide dismutase and other antioxidant enzymes reduce oxidative stress and maintain the quality of meat. In order to attain the required meat qualities, ageing conditions, including temperature and time, can be optimized by keeping an eye on the enzymatic activity (Pedrotty et al. 2021). Producers can enhance the consistency and quality of aged meat and satisfy consumer demands for tasty and tender goods by comprehending and managing enzymatic indicators. Enzymatic activity biomarkers have very important role in post-mortem meat ageing of meat. These primarily involves proteolytic enzymes that help in degradation of muscle proteins leading to increase in meat tenderness (Wei et al. 2022). Regulating the activity of these enzymes may help in improvement of tenderness of meat. The key enzyme biomarkers of these type includes Calpins (Calpain-1 (μ-calpain) and Calpain-2 (m-calpain)), cathepsin (Cathepsin B, D, and L) and caspases (Caspase-3 and Caspase-9). SDS-PAGE, Western Blotting, Fluorometric and Colorimetric Assays and Zymography are the methods of detection of enzymatic activity biomarkers (Perrotta, et al. 2017).

Lipid oxidation biomarkers of post-mortem meat ageing

Lipid oxidation is one of the most important factor of post-mortem ageing of meat. It directly effects the meat quality by quality deterioration, producing off flavour, off odour, rancidity etc. The lipid oxidation biomarkers include malondialdehyde (MDA), 4-Hydroxynonenal (4-HNE), hexanal, conjugated dienes and peroxides and hydroperoxides (Banerjee et al. 2022). The methods of detection of lipid oxidation biomarkers are thiobarbituric Acid Reactive Substances (TBARS) Assay, Gas Chromatography-Mass Spectrometry (GC-MS), Liquid Chromatography-Mass Spectrometry (LC-MS), Headspace Gas Chromatography (HS-GC), Spectrophotometric Methods (Wei et al. 2022).

Metabolic biomarkers of post-mortem meat ageing

The metabolic processes that take place after slaughter result in changes in the concentration of several biochemical components, which are the metabolic biomarkers of post-mortem meat aging. The tricarboxylic acid cycle (TCA cycle), amino acid degradation, lipid metabolism, and metabolites from glycolysis are some of these indicators. Keeping an eye on these metabolic alterations can reveal details about the meat's maturing process and final quality. The ley metabolic biomarkers include lactic acid, Adenosine Triphosphate (ATP) and its Breakdown Products (IMP, Inosine, Hypoxanthine), Creatine and Creatinine, Glycogen and Glucose-6-Phosphate, Free Amino Acids (FAA), Biogenic Amines (e.g., Histamine, Tyramine, Cadaverine, Putrescine), Organic Acids (e.g., Succinic Acid, Acetic Acid). The methods of detection of metabolic biomarkers are High-Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), Capillary Electrophoresis (CE), Enzymatic Assays, Spectrophotometry. The Key post-mortem meat ageing biomarkers with their role and significance have been listed in the table 2.

Table 2: Key post-mortem meat ageing biomarkers with their role and significance

Key biomarkers	Role	Significance	Reference
Troponin-T	Involve in muscle contraction Forms specific protein fragments during post-mortem ageing	Meat tenderness is correlated with quantity of troponin-t fragments. Higher level indicates high tenderness	Hwang et al. 2023
Desmin	An intermediate filament protein. maintains the structural integrity of muscle cells by linking the myofibrils to the cell membrane	Degradation of desmin is considered as marker for degradation of muscle fibers and increase in tenderness	
Titin	A large protein that has its role in muscle elasticity and structure by anchoring thick filaments to the Z-line in sarcomeres.	Post-mortem degradation of titin leads to increase in muscle tenderness. It's change is indicator of muscle ageing	D'Alessandro, et al 2013
Nebulin	Regulates the length of thin filaments in skeletal muscle fibres by stabilizing them.	Post-mortem degradation of nebulin leads to structural disassembly of muscle fibres and increase tenderness of meat	

Actin and myosin	Primery contractile proteins responsible for muscle contraction	Resistant to proteolysis. Partial degradation of them leads to meat tenderiztion	Hocquette et al. 2006
Calpins Calpain-1 and Calpain-2)	Initiation of proteolytic breakdown of myofibriller and cytoskeletal protein	initial weakening of muscle fibers, leading to tenderness. Calpin activity regulated by calcium levels	Magalhães et al. 2019 Banerjee et al. 2022
Cathepsin (Cathepsin B, D, and L)	Lysosomal proteases Become more active in acidic environment in muscle	Helps in protein degradation at low pH conditions Enhance meat tenderness by degrading remaining structural proteins	
Caspases (Caspase-3 and Caspase-9)	Involves in apoptosis Helps in muscle proteases	Helps in degradation of cytoskeletal and regulatory proteins, facilitating structural changes in muscle fibers leading to meat tenderization	Sidira et al. 2024
Malondialdehyde (MDA)	Breaking of polyunsaturated fatty acis leads to the formation of MDA which is one of the most common aldehyde	Its concentration is a marker for meat quality. Higer level of MDA indicates rancid meat with off flavours.	Capozzi et al. 2017
4-Hydroxynonenal (4-HNE)	Peroxidation of n-6 polyunsaturated fatty acids leads to the formation of 4-HNE which is an aldehyde	4-HNE is a toxic aldehyde which can modify DNA and proteins. Its level is a marker for oxidative stress and lipid degradation of muscle	Bassey et al. 2021
Hexanal	Hexanal forms from the oxidation of lenleic acid and is a volatile compound.	Its presence is indicated by off flavours in oxidized meat as a result of lipid oxidation	Pedrotty et al. 2021
Conjugated Dienes	Forms at the initial stages of lipid oxidation	Its presence indicates early lipid oxidation and onset of rancidity	Jagadeesh et al. 2017
Peroxides and Hydroperoxides	Forms at the initial stages of lipid oxidation	Its level indicates extant od lipid oxidation before aldehydes are formed	Mullen 2006
Lactic acid	Lactic acid forms by anaerobic glycolysis from pyruvate after slaughter of animal	Its accumulation indicates low pH which enhances tenderness, water holding capacity of meat and colour	Jagadeesh et al. 2017
ATP and its breakdown products	ATP breaks down into inosine monophosphate (IMP), inosine, and hypoxanthine	ATP degradation is associated with development of meat flavour followed by ageing	D'Alessandro et al 2013 Goll Thompson et al. 2003
Creatine and Creatinine	Creatine is converted to creatinine post-mortem.	The creatine/creatinine ratio can be an indicator of muscle metabolism and energy state.	Allan 2014
Glycogen and Glucose-6-Phosphate	Glycogen is broken down to glucose-6-phosphate during glycolysis.	The rate of glycogen depletion and glucose-6-phosphate formation impacts the extent of glycolysis and pH decline	Bassey et al. 2021
Free Amino Acids (FAA)	Amino acids are released during protein breakdown	The composition and concentration of FAAs affect flavor and taste development.	Hultman et al. 2020
Biogenic Amines	Formed from amino acid decarboxylation	High levels of biogenic amines is a marker for meat spoilage and affect safety and quality.	Hwang et al. 2023
Organic Acids	Produced during carbohydrate metabolism and fermentation	Changes in organic acid levels can influence meat flavor and shelf-life	Munekata et al. 2021

CONCLUSION

Meat science biomarker discovery has been transformed by omics technologies, which provide profound insights into the production, safety and quality of meat. By identifying protein biomarkers associated with spoilage, colour stability and tenderness, proteomics allows for efficient processing. By identifying metabolic pathways that impact flavour, texture, shelf life of meat, metabolomics improves nutritional and sensory attributes. By revealing the functions of microbes in fermentation and safety, metagenomics helps to verify authenticity and manage microbial spoilage of meat and meat products. In order to support trait selection, transcriptomics investigates gene expression during stress and muscle development. Multiomics combines various levels to provide a comprehensive understanding of meat systems, whereas lipidomics examines lipid patterns that impact marbling, flavour, and nutrition. By facilitating precision breeding, enhancing animal welfare, ensuring food safety and confirming product authenticity, these methods have revolutionized the field of meat science. They tackle global issues like as sustainability, food security, and consumer expectations for premium, ethically produced meat. But there are still issues like high prices, data integration, and validation. Future research should use artificial intelligence to analyze data, create affordable tools and turn results into useful applications. To conclude, omics technologies have greatly improved the field of meat science and opened the door for creative ways to satisfy business demands. By developing and integrating these technologies, researchers and producers may provide safe, nutritious, and high-quality meat products.

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