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Improving meat quality and safety: innovative strategies

Maksim Rebezov, Mars Khayrullin, Bahytkul Assenova, Smolnikova Farida, Dmitry Baydan, Larisa Garipova, Raisa Savkina, Svetlana Rodionova

ABSTRACT

Ensuring meat products' quality and safety is paramount in today's food industry. This extended abstract delves into innovative strategies to enhance meat quality and safety throughout the production, processing, and distribution stages. The paper explores various cutting-edge approaches, technologies, and regulatory frameworks to mitigate risks and improve consumer confidence in meat products. The discussion begins with examining advancements in meat processing techniques, such as high-pressure processing (HPP), modified atmosphere packaging (MAP), and irradiation. These techniques are instrumental in reducing microbial contamination, extending shelf life, and preserving the nutritional integrity of meat products. Furthermore, the paper explores emerging technologies like nanotechnology and blockchain, which offer novel solutions for enhancing traceability, transparency, and accountability in the meat supply chain. Much of the paper discusses the role of quality control measures in ensuring meat safety and compliance with food safety regulations. From carcass inspection and microbiological testing to chemical residue analysis and packaging standards, rigorous quality control protocols are essential for identifying and mitigating potential hazards at every stage of meat production. Moreover, the paper highlights the importance of animal husbandry practices, feed management, and genetics in influencing meat quality attributes such as flavour, texture, and tenderness. Producers can enhance meat products' overall quality and palatability by implementing improved animal husbandry practices, optimizing feed formulations, and selectively breeding animals for desirable traits. In addition to technological advancements and quality control measures, the paper emphasizes the need for regulatory compliance and government oversight to uphold food safety standards. Ensuring adherence to regulations such as Hazard Analysis and Critical Control Points (HACCP) and implementing comprehensive food safety management systems are essential for safeguarding public health and consumer trust. In conclusion, this extended abstract provides a comprehensive overview of innovative strategies for improving meat quality and safety in the food industry. By embracing advancements in processing techniques, leveraging new technologies, implementing stringent quality control measures, and adhering to regulatory requirements, stakeholders can enhance the safety, integrity, and consumer perception of meat products in the marketplace.

Keywords: meat, quality, safety, meat processing, innovative strategies,

INTRODUCTION

Meat quality and safety are crucial to the global food supply chain, impacting human health, economic sustainability, and societal well-being. Achieving superior meat quality involves a complex interplay of factors, from genetic traits of livestock breeds to post-harvest processing techniques **[1]**.

Ensuring meat safety requires vigilance against microbial pathogens, chemical contaminants, and other hazards that could jeopardise food integrity. Innovative strategies play a pivotal role in enhancing meat quality and safety **[2]**. Advancements in technology, genetics, and production methodologies are harnessed to address challenges and optimise meat quality and safety. Research explores various aspects

such as meat processing, quality assessment methods, and food safety regulatory frameworks **[3]**. The relationship between animal husbandry practices, nutrition, genetics, and environmental conditions in shaping the final meat product is also scrutinised. Emerging trends like novel processing techniques and cellular agriculture are under examination for their potential impact on the meat industry. Scientific inquiry aims to foster a comprehensive understanding of these developments, considering their promises and complexities. By embracing a spirit of inquiry and commitment to excellence, researchers strive to propel the field towards unprecedented levels of quality and safety in meat production **[3]**, **[4]**.

Understanding Meat Quality

Meat quality is a complex concept encompassing various sensory characteristics, nutritional composition, and technological properties **[5]**. Recent research has shed light on myosin heavy chain isoforms, significantly impacting meat quality attributes like pH, drip loss, and sensory properties **[5]**. Furthermore, natural antioxidants derived from sources like blackcurrant and honeysuckle extracts have been found to effectively delay lipid oxidation in meat products, preserving their quality without adverse effects on colour or texture. In evaluating meat quality, electronic technologies such as electronic nose (E-nose), eye (E-eye), and tongue (E-tongue) offer efficient and cost-effective methods **[6]**, **[7]**, **[8]**.

These technologies can distinguish between different preservation methods, detect adulteration, monitor processing conditions, and even identify pathogenic microorganisms in meat products. Additionally, studies in fish quality have highlighted the importance of desensitisation methods, where electric shock intensities can affect various quality parameters in fish meat during refrigerated storage. Sensory evaluation is crucial in determining consumer acceptance of meat products **[9]**. For example, research on sausages with varying proportions of fish meat demonstrated that consumer preference decreased with higher fish content, particularly impacting factors like consistency, appearance, and tenderness **[10]**. Comprehending the multifaceted aspects of meat quality is essential for ensuring consumer satisfaction, optimising dietary value, and maintaining consistency across diverse product lines. Ongoing research efforts continue to explore various factors influencing meat quality, aiming to enhance our understanding and appreciation of this crucial component of human nutrition and culinary culture

Factors Affecting Meat Quality

Pre-Harvest Management Practices: Diet composition and management practices significantly impact meat quality attributes, influencing fat deposition, muscle development, and overall carcass composition **[11]**.

Minimising stress during pre-slaughter procedures is essential for preserving meat quality. Post-Harvest Handling and Processing: Humane slaughter methods are imperative for ensuring meat quality, while controlled ageing enhances tenderness and flavour development **[12]**. Proper packaging techniques help preserve meat quality by minimising oxidative reactions and spoilage, and innovative processing techniques offer opportunities to optimise meat quality attributes. Environmental Factors: Environmental conditions, such as temperature and humidity, influence factors like muscle glycogen depletion, microbial growth, and enzymatic activity, thereby affecting meat quality. Seasonal variations also impact animal growth rates, carcass composition, and meat quality attributes. Consumer Preferences and Market Demands: Consumer perceptions of meat quality are influenced by cultural factors, while market demands drive innovation in production practices to meet evolving preferences. Understanding the intricate interplay of genetic, management, environmental, and market-related factors is essential for optimising meat quality to meet consumer expectations in a dynamic marketplace **[12]**.

Importance of Meat Quality for Consumers

Consumers derive immense pleasure from the sensory attributes of high-quality meat. The rich, savoury flavours, often accompanied by subtle hints of sweetness, umami, and aromatic compounds, elevate culinary pleasure **[13]**. Moreover, attributes like tenderness, juiciness, and succulence profoundly impact eating experiences, contributing to consumer satisfaction. Visual cues such as colour, marbling, and surface texture further indicate freshness and quality, reassuring discerning consumers

[13]. Beyond sensory enjoyment, meat also holds substantial nutritional value and contributes to overall health. As a vital source of essential amino acids, vitamins (such as B vitamins), and minerals crucial for optimal nutrition, meat plays a significant role in maintaining health and well-being **[14]**. The fat content and composition of meat are particularly noteworthy, influencing flavour, juiciness, and mouthfeel while balancing flavour enhancement with health considerations. Ensuring the safety and integrity of meat products is another critical aspect that resonates with consumers **[12]**.

They prioritize meat products that adhere to stringent safety standards and are free from contaminants and hazards. Transparency in production practices, animal welfare, and ethical considerations are also highly valued by consumers, highlighting the importance of traceability in the supply chain **[15]**. Moreover, meat holds cultural significance and contributes to culinary satisfaction beyond its nutritional and sensory attributes. High-quality meat offers culinary versatility, allowing consumers to explore various cooking methods and unleash creativity. Additionally, meat plays a central role in cultural traditions and social gatherings across diverse societies, further accentuating its importance in the culinary landscape **[16]**. Understanding and meeting consumer preferences for high-quality meat products are paramount for stakeholders in the food supply chain. By prioritizing meat quality and addressing consumer expectations regarding sensory enjoyment, nutritional value, safety, and cultural significance, stakeholders can establish trust, loyalty, and satisfaction in an increasingly discerning market environment. Factors influencing meat purchasing decisions encompass various aspects, including quality control measures implemented by supermarkets and the accessibility of specific meat types across different locations **[17]**.

Consumers often rely on indicators such as colour and price to gauge meat quality, while freshness remains a critical consideration for consumers and meat handlers. Key indicators of meat safety include expiry dates, colour changes, and aroma, with consumer awareness influenced by educational status. Combining different types of meat or meat alternatives, hybrid meat products are increasingly evaluated by consumers based on ethical considerations, sustainability, taste, ingredients, healthiness, naturalness, innovation, and environmental impact **[18]**. Positive perceptions of hybrid products increase after consumers engage in co-creation activities. Ethical, moral, and social dimensions in farm production practices play a significant role in consumer perceptions of meat quality. For instance, Irish consumers exhibit varying perceptions of meat quality linked to farm-level practices such as organic farming and high animal welfare standards. These perceptions vary across consumer segments, influenced by gender, age, and motivations for meat purchase. Additionally, the choice of frying method can significantly impact the cooking yield, tenderness, and sensory properties of meat, such as chicken breast. Research indicates that air frying methods result in higher cooking yield and tenderness compared to traditional deep fat frying methods, highlighting the importance of cooking techniques in maintaining meat quality **[12]**.

Microbial Contamination in Meat: Risks, Sources, and Mitigation Strategies

The search results provide valuable insights into microbial contamination within the meat industry, highlighting various aspects and implications:

Reduction of Microbial Load in Meat Maturation Rooms: This study investigated the survival of pathogens such as Listeria monocytogenes, Escherichia coli, Salmonella spp., and Staphylococcus aureus on the inner surface of dry ageing chambers. It assessed the efficacy of alkaline electrolyzed water in reducing foodborne pathogens during meat storage, emphasizing the importance of implementing effective sanitation measures in meat processing facilities **[19]**. Microbial Contamination in Meat Industry: Research focused on assessing the prevalence of food infections and microbial contamination in meat products. The study evaluated microbial quality based on Iranian national standards by examining sausages, burgers, kebabs, and cutlets from factories, highlighting the need for stringent hygiene practices and quality control measures in meat production processes **[20]**. Post-slaughter Handling and Meat Quality: A study conducted in South Africa explored the perceptions and knowledge of consumers and meat handlers regarding meat quality and safety throughout the distribution chain. It identified factors influencing perceptions of meat quality, safety indicators, and consumer

preferences, emphasizing the importance of education and training in ensuring proper handling practices to minimize microbial contamination and maintain meat quality **[17]**.

Chemical Hazards in Meat: Sources, Risks, and Management Strategies

The search results provide valuable insights into chemical hazards in the food industry, particularly concerning meat products. Studies have examined various aspects related to food safety and quality:

Research conducted in the Eastern Cape Province, South Africa, investigated consumer and meat handlers' perceptions and knowledge regarding meat quality and safety throughout the distribution chain. The findings highlighted factors influencing perceptions of meat quality, safety indicators, and consumer preferences **[21]**. Similarly, a study in Saudi Arabia aimed to determine microbial contamination in imported fish and chicken products. The research analyzed parameters such as total plate count, Staphylococcus aureus, Vibrio parahaemolyticus, and Pseudomonas in samples, assessing their potential impact on food industry production workers. Moreover, research focused on determining the survival of pathogens like Listeria monocytogenes, Escherichia coli, Salmonella spp., and Staphylococcus aureus on the inner surface of dry ageing chambers **[22]**. In another study, researcher tested the efficacy of alkaline electrolyzed water for reducing foodborne pathogens during meat storage. These studies underscore the importance of addressing microbial and chemical hazards in the meat industry. Effective mitigation strategies are crucial to ensuring food safety, maintaining quality standards, and safeguarding consumer health **[19]**.

Ensuring Compliance with Food Safety Regulations in the Meat Industry

Regulatory compliance is the cornerstone of safety in the meat industry, safeguarding public health and maintaining consumer confidence. Stakeholders must understand and implement national and international standards, such as the Food Safety Modernization Act (FSMA) and the European Union's General Food Law, set by organizations like the Codex Alimentarius Commission. Regulatory authorities like the FDA and EFSA enforce standards, conduct inspections, and sanction non-compliance. Good Manufacturing Practices (GMPs) establish facility, equipment, and processes hygiene standards. Hazard Analysis and Critical Control Points (HACCP) principles identify and mitigate hazards **[23]**, **[24]**, **[25]**. The basic requirements for the HACCP system are based on the legal regulations in force in the country. They are applied in all branches of the food industry **[138]**, **[139]**, as well as the ISO 22000 standard and various private standards for food safety and quality recognized by the Global Food Safety Initiative such as IFS, BRC, PRIMUS GFS, RED MEAT, GLOBAL GAP, SQF, FSSC 22000 etc.

Traceability systems and recall procedures ensure swift responses to safety concerns. Mandatory labelling provides essential information to consumers. Implementation strategies include comprehensive education and training, thorough documentation, and continuous improvement of safety management systems. Collaboration among stakeholders fosters transparency and collective responsibility. Audits, both internal and external, assess compliance and identify areas for improvement. External inspections ensure accountability through enforcement measures. Maintaining compliance with food safety regulations demands commitment and collaboration from all stakeholders. By adhering to standards, implementing robust management systems, and embracing continuous improvement, the meat industry can ensure the safety and quality of its products, thus safeguarding public health and consumer trust **[26]**, **[27]**.

Innovative Technologies Transforming Meat Processing

The search results offer valuable insights into innovative technologies and food safety considerations within the meat industry. One study discusses the safety assessment of cell-cultured meat and seafood, highlighting the importance of a responsible, data-driven approach to ensure consumer acceptance and safe commercialization **[28]**. Another research explores the feasibility of pulsed light technology for surface decontamination of meat and meat contact materials, assessing its effects on microbial inactivation, lipid peroxidation, sensory quality, and colour of meat products. provide the most **[29]**, **[30]**. Additionally, a study investigates the efficacy of alkaline electrolyzed water for reducing foodborne

pathogens during meat storage in dry ageing chambers. These studies collectively underscore ongoing efforts to enhance efficiency, quality, and safety standards in the meat processing industry by leveraging innovative technologies and advanced food safety practices. Incorporating such approaches is crucial for improving food safety, meeting regulatory requirements, and fostering consumer confidence in meat products **[19]**.

High-Pressure Processing (HPP) in Meat Industry: Principles, Applications, and Benefits

High-pressure processing (HPP) is a non-thermal technique involving subjecting packaged food items to pressures between 100 and 600 megapascals within a hydraulic pressurization chamber. This process disrupts the cellular structures and enzymatic activities of microorganisms like pathogenic bacteria, viruses, and yeasts, rendering them inactive and ensuring food safety. Applications of HPP in meat processing are diverse **[31]**. It effectively reduces microbial contamination in raw and processed meat products, mitigating the risk of foodborne illnesses caused by pathogens such as Salmonella, E. coli, Listeria monocytogenes, and Campylobacter **[19]**. Additionally, HPP extends the shelf life of meat products by inhibiting spoilage microorganisms, enzymatic reactions, and oxidative degradation processes, thereby preventing quality deterioration, off-flavours, and discolouration. Furthermore, HPP enables clean label claims by eliminating the need for chemical preservatives or additives, meeting consumer demand for minimally processed natural foods **[32]**. The benefits of HPP adoption in meat processing are substantial. It significantly reduces pathogen levels without compromising product quality, ensuring consumer safety. Additionally, HPP preserves the nutritional quality of meat products by minimizing nutrient degradation and protein denaturation associated with thermal processing methods **[33]**. Moreover, HPP maintains meat products' natural colour, texture, and flavour, enhancing sensory attributes and consumer acceptance. It also extends the refrigerated shelf life of meat products, aiding inventory management and meeting market demand for fresh, high-quality products. However, equipment costs, operational complexity, and consumer education may hinder the widespread adoption of HPP in the meat industry. Continued innovation in HPP technology through advancements in equipment design, process optimization, and packaging solutions is expected to drive integration into meat processing facilities and expand applications. Regulatory agencies play a crucial role in establishing guidelines for HPP implementation to ensure compliance with food safety regulations and address consumer concerns regarding labelling and product claims **[34]**.

Irradiation Techniques in Meat Processing: Principles, Applications, and Considerations

Irradiation techniques are a valuable asset in the meat processing industry, providing effective solutions for bolstering food safety, prolonging shelf life, and diminishing microbial contamination in meat products. These techniques expose food items to ionizing radiation emitted by gamma rays, electron beams, or X-rays **[35]**. This radiation interacts with the molecular structure of microorganisms, rendering them incapable of reproduction or causing foodborne illnesses **[36]**. The irradiation applications in meat processing are diverse, encompassing pathogen reduction, shelf-life extension, and quarantine treatment for imported meat products **[37]**. Additionally, irradiation eradicates quarantine pests like insects and larvae while upholding product quality and safety standards **[38]**. Despite its benefits, irradiation comes with several considerations and challenges, including regulatory approval, consumer acceptance, proper packaging and handling, and cost considerations.

Nanotechnology Applications in Meat Processing: Innovations, Benefits, and Considerations

Nanotechnology presents various applications within the meat processing industry, offering innovative solutions to enhance food safety, quality, and sustainability. Through the integration of nanomaterials, significant advancements have been made in various areas:

Nanomaterials for Packaging: Active nanocomposites, comprising nanoparticles and nanofibers, are utilized to inhibit microbial growth, scavenge oxygen, and extend the shelf life of meat products.

Antimicrobial nanoparticles like silver and zinc oxide embedded in packaging materials prevent spoilage and reduce the risk of foodborne pathogens **[39]**. Additionally, barrier nanocoatings enhance packaging surfaces' properties, improving stability and freshness **[40]**. Nanosensors for Quality Monitoring: Nanobiosensors offer real-time detection of biochemical markers, pathogens, and spoilage indicators in meat products. Gas nanosensors rapidly assess product freshness and safety by detecting gases released during spoilage **[41]**. Nanoelectronic noses equipped with nanomaterial-based sensors aid in quality control by detecting volatile odour compounds emitted by meat products **[42]**.

Nanoparticle-Based Interventions: Antimicrobial nanoparticles such as silver, copper, and zinc oxide exhibit potent properties against foodborne pathogens and spoilage microorganisms. Nanoliposomes enhance the stability and efficacy of antimicrobial agents for targeted delivery in meat products **[43]**. Nanoscale emulsions improve the dispersion and functionality of bioactive compounds in meat formulations **[44]**. Nanostructured Additives for Quality Enhancement: Nanoencapsulated nutrients are incorporated into meat products to enhance nutritional value and sensory attributes **[45]**.

Nanofibrous scaffolds carry bioactive compounds, improving texture, juiciness, and shelf life. Nanocomposite coatings applied to meat surfaces create protective barriers, preventing moisture loss and enhancing texture and appearance **[45]**. Regulatory and Safety Considerations: The safety evaluation of nanomaterials is crucial for assessing their physicochemical properties, toxicity profiles, and potential impacts on human health and the environment. Regulatory compliance by agencies such as the FDA and EFSA ensures safety standards are met for nanotechnology-based food additives in meat processing. Addressing consumer perception through transparency, communication, and education is vital to mitigate concerns regarding the safety and benefits of nanotechnology applications in meat processing **[46]**.

Improving Meat Quality Through Animal Husbandry Practices

The search results provide insights into animal husbandry practices and meat quality. Studies conducted in regions like the north-western Himalayan region of India highlight issues such as open slaughtering, inadequate water provisions, and lack of light in lairage premises, impacting animal welfare and meat quality **[47]**. Research in Mongolia emphasizes the importance of hygienic practices in slaughter establishments to ensure the microbiological quality of meat products and prevent foodborne pathogens **[48]**. Additionally, nanotechnology offers potential benefits in meat processing, including improved bioavailability, antimicrobial effects, enhanced sensory acceptance, and targeted delivery of bioactive compounds **[49]**. However, challenges exist in ingredient production, stability of delivery systems, health risks, public acceptance, economics, and regulation. These findings underscore the significance of implementing proper animal welfare practices hygienic standards in slaughterhouses and exploring innovative technologies like nanotechnology to enhance meat quality and safety in the meat processing industry **[49]**.

Genetics and breeding for desirable meat traits

Various research findings reveal that Genetics and breeding play a crucial role in developing desirable meat traits in livestock. One study examined 26 different meat cuts, meat quality, and carcass traits in pigs, emphasizing the significant impact of genetic factors on the overall quality of meat produced **[50]**. Moreover, advancements in modern technologies such as advanced sequencing and genome editing are reshaping livestock genetic and breeding programs, specifically focusing on enhancing meat quality traits across different animal species **[51]**. Research into growth traits in meat pigeons has identified key mutations associated with muscle mass, offering valuable insights for selective breeding practices to improve the quality of meat produced **[52]**.

Similarly, studies on turkeys have explored genetic parameters for meat quality traits, including white striping, underscoring the importance of integrating considerations of meat quality into poultry breeding strategies to ensure the production of high-quality meat products **[53]**. Additionally, an investigation into Nellore cattle has assessed genomic prediction for carcass and meat quality traits using advanced algorithms, demonstrating promising results in terms of prediction accuracy **[54]**.

Integrating Animal Welfare Considerations into Meat Production Systems

The search results offer valuable insights into the integration of animal welfare considerations within meat production systems:

A study introduces a tool designed to benchmark animal welfare across countries, specifically on pigs and chickens. This tool evaluates parameters related to housing and management practices, aiming to facilitate the monitoring and comparison of animal welfare standards on an international scale **[55]**. In developed countries, animal welfare significantly influences beef production. Researchers explore various indicators for assessing animal welfare and its impact on meat quality. They also discuss potential strategies for improving beef production in developing countries by raising animal welfare standards. Farmers in New Jersey advocate for local food systems to address ethical concerns surrounding farm animal welfare **[56]**, **[57]**, **[58]**, **[59]**.

They emphasize the importance of maintaining happy animals in small-scale farming operations, highlighting local food systems as an organic solution to ensure the well-being of livestock. A review examines the role of reproductive hormones in cattle production and their effects on economically important traits, animal welfare, and human health. The review underscores the importance of considering animal welfare and consumer health when implementing hormone usage in beef and dairy cattle production **[60]**.

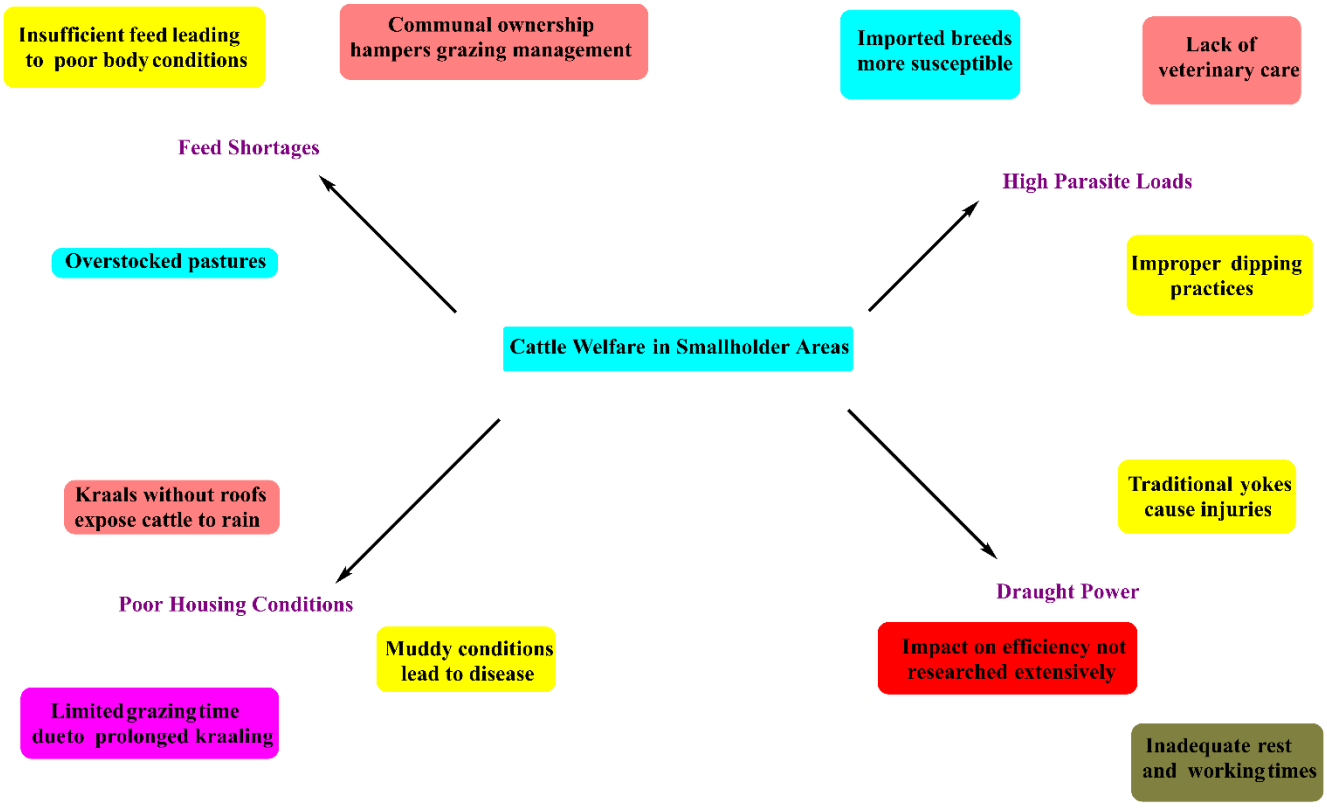

Figure 1. Factors Affecting Cattle Welfare in Smallholder Areas.

Furthermore, cell-cultured meat technology is explored from a bioethical standpoint, discussing its potential benefits for sustainable development, animal welfare improvement, and resource demand reduction. However, ethical risks related to food safety, technology misuse, and regulatory oversight are also addressed. Collectively, these studies emphasize the imperative of incorporating animal welfare considerations into meat production systems. By prioritizing ethical and sustainable practices, the meat industry can ensure the well-being of livestock and promote responsible production processes **[61]**. Figure 1 illustrates key challenges impacting cattle welfare in smallholder farming systems.

Quality Control and Assurance in Meat Production: Ensuring Safety, Consistency, and Compliance

The insights gleaned from various studies shed light on different dimensions of quality control and assurance in meat production:

One study explores the potential benefits of cell-cultured meat technology for the meat production industry, consumer groups, and sustainable development. It outlines how this technology could improve animal welfare, reduce resource demand, enhance nutritional function, and stimulate growth in other industries. However, the study also underscores ethical risks related to food safety, technology misuse, and the need for effective technical supervision **[62]**. Another discussion revolves around a tool designed to benchmark animal welfare across countries, specifically on pigs and chickens. This tool defines parameters related to housing and management to assess welfare levels, with careful consideration given to ethical concerns during the model-building process **[55]**. Researchers explore how animal welfare impacts meat quality and seek to enhance beef production in developing nations by prioritizing animal welfare considerations **[63]**. Factors influencing meat quality traits, such as intramuscular fat content, are discussed, along with the necessity for further research on adipogenesis to enhance meat quality **[64]**.

Furthermore, another study estimates genetic parameters for meat quality traits in turkeys, including white striping severity score. The study discusses heritability estimates for various characteristics and highlights unfavourable genetic correlations between body weight and meat quality. It stresses the importance of implementing selection strategies to improve meat quality **[53]**, **[65]**.

Quality Control Measures in Meat Processing

Quality control is paramount in meat processing to ensure compliance with safety, quality, and regulatory standards at each production stage. This involves rigorous measures throughout the process:

In the slaughtering and dressing phase, trained inspectors meticulously examine live animals for any indications of disease or abnormalities. Subsequently, veterinarians conduct thorough post-mortem inspections of carcasses to ensure meat quality and safety **[66]**.

During carcass fabrication and primal cutting, inspectors meticulously assess carcasses and cuts for cleanliness, contamination, and any defects that may compromise quality. Maintaining appropriate temperatures and following strict sanitation practices are essential for this stage. Further processing and value-added production necessitate strict control over ingredient sourcing and handling to prevent contamination **[67]**. Formulations are also closely monitored to ensure consistency in flavour and nutritional content. Packaging and labelling undergo stringent inspection to prevent contamination and ensure compliance with accuracy and regulatory standards. This includes thorough verification of labels to confirm regulatory compliance and accuracy **[68]**. Inspection of finished products encompasses a comprehensive evaluation, including visual examination, microbiological testing, and metal detection, to guarantee the highest quality and safety standards. During storage and distribution, temperature monitoring devices are utilized to maintain the integrity of the cold chain. Furthermore, periodic shelf-life testing is conducted to assess product stability, while robust traceability systems are implemented to track product movement effectively **[69]**, **[70]**, **[71]**.

Implementing HACCP (Hazard Analysis and Critical Control Points)

Implementing Hazard Analysis and Critical Control Points (HACCP) in meat processing is a systematic approach designed to ensure the production of safe meat and poultry products. This approach involves a thorough analysis of production processes, identification of potential hazards, determination of critical control points where these hazards can be controlled, establishment of critical limits, verification of the steps prescribed, and monitoring of the process control through the HACCP plan [24]. The effectiveness of HACCP systems in managing food safety risks has been demonstrated, provided they are correctly implemented. Many countries have adopted HACCP principles for meat processing at abattoirs, with regulatory bodies utilizing systems like the Hygiene Management System (HMS) and Hygiene Assessment System (HAS) to audit compliance **[72]**. The implementation of HACCP in the meat and poultry industry is crucial for enhancing consumer confidence in these products and reducing

barriers in international trade. Comprehensive flow diagrams of meat and poultry products applying HACCP principles ensure food safety **[73]**. However, challenges remain, such as in Uganda, where low food safety performance in the beef supply chain was attributed to poor sanitation, hygiene, and handling practices. This underscores the need for HACCP-based training and robust preventive, intervention, and monitoring systems **[74]**.

Moreover, implementing HACCP can impact costs and product offerings, with small and very small meat processors incurring higher compliance costs and potentially discontinuing a range of products due to the need for facility modification **[75]**. Continuous training and education on HACCP are essential for ensuring a stable system and maintaining hygiene during the production process **[76]**.

Critical Control Points (CCPs) are then determined, pinpointing specific points where control measures can prevent, eliminate, or reduce hazards. Factors such as temperature, time, pH, moisture levels, and sanitation are considered in this assessment. Critical limits define measurable criteria for acceptable control levels to ensure food safety **[77]**. These limits are based on scientific data, regulations, standards, and product specifications. Monitoring procedures are developed to verify CCP control and adherence to critical limits, specifying methods, frequency, responsible personnel, and documentation **[77]**. In the event of monitoring indicating loss of control or breaches in critical limits, corrective actions are implemented. These actions involve identifying the causes of deviations, taking corrective measures, and implementing preventive actions to avoid recurrence. Verification procedures are established to confirm the effectiveness of the HACCP plan in controlling hazards, including equipment calibration and internal audit **[78]**.

Emerging technologies for real-time quality monitoring

Blockchain technology is valuable for promoting traceability systems within agri-food supply chains. Its decentralized, immutable, and transparent nature enables real-time data monitoring and decision-making activities across food production and supply chains **[79]**. Implementing a Hazard Analysis and Critical Control Points (HACCP) program is crucial for small-scale cured ham production. This involves identifying potential hazards, determining critical control points (CCPs), and implementing control measures at key stages of production. These insights underscore the significance of advanced technologies, early warning systems, traceability solutions, and quality control measures in ensuring food safety, quality assurance, and operational efficiency in the meat processing industry **[80]**, **[81]**.

Enhancing Meat Flavour and Texture

Marination and flavour infusion methods

Postmortem ageing is vital for enhancing meat quality by leveraging endogenous proteolytic systems. The concept of "smart ageing" introduces a novel approach to optimize post-harvest ageing parameters, aiming to improve the quality and value of meat products. Metabolomics techniques play a crucial role in elucidating the biochemical mechanisms responsible for tenderness, flavour, colour, and oxidative stability during the ageing process **[82]**, **[83]**.

Combining different processing and preservation methods offers the potential for enhancing sensory attributes without compromising nutritional value. This underscores the importance of further research in exploring the synergies between different processing technologies. Enzymatic reactions, such as glycolysis, proteolysis, and lipolysis, are integral to converting muscle into meat and improving its quality. Exogenous enzymes find applications in tenderization, bioactive peptide production, and meat product restructuring **[84]**.

Enzymatic reactions are crucial in meat processing, influencing tenderness, aroma, and color. Exogenous enzymes such as papain, bromelain, and microbial enzymes are utilized for tenderization. Emerging technologies like ultrasound, pulsed electric fields (PEF), and high-pressure processing (HPP) intensify these reactions, enhancing meat quality. High-intensity ultrasound (HIUS) and high-pressure processing (HPP) are non-thermal methods employed for meat tenderization. Muscle composition affects the efficacy of HIUS, with certain muscle types being more resistant to tenderization. Optimal pressure levels and durations of HPP can enhance tenderization, though industrial implementation requires further optimization **[84]**, **[85]**.

Various processing techniques like dry ageing, HPP, sous-vide cooking, and 3D printing impact meat products' sensory and nutritional attributes. Combining different processing methods can improve sensory quality without compromising nutritional value, necessitating continued research in this field. The rise of plant-based meat alternatives has spurred the development of non-thermal technologies like HPP to modify plant proteins, mimicking traditional meat products' functionality and nutritional characteristics **[85]**. Protein modification is critical for achieving desired attributes such as solubility, gelling, emulsifying, and foaming properties in plant-based alternatives. High-power ultrasound (HPUS) is a non-thermal technology to modify food proteins, enhancing safety and quality by altering protein conformation and structure. In meat processing, HPUS can improve myofibrillar protein structure, enhancing functional properties and extending shelf life. These insights underscore the significance of enzymatic reactions, non-thermal technologies like HIUS and HPP, processing techniques' effects on meat quality, advancements in plant-based alternatives using emerging technologies, and the role of HPUS in modifying food proteins for improved functionality in meat processing **[85]**.

Carcass Inspection and Processing

Carcass inspection and processing represent critical stages in the meat production chain, where the quality and safety of meat products are meticulously upheld. Ante-mortem inspection involves assessing animals for signs of disease or other conditions that might affect meat quality **[86]**. In contrast, post-mortem inspection examines carcasses for abnormalities or defects immediately after slaughter. Following the inspection, carcasses undergo rapid chilling to inhibit bacterial growth and facilitate ageing, enhancing tenderness and flavour **[86]**.

Hygiene and Sanitation Practices

Temperature control and cold chain management are crucial aspects of ensuring the safety and quality of meat products within the industry. Following slaughter and processing, carcasses are promptly chilled to inhibit bacterial growth, with processing facilities maintaining strict temperature controls to prevent contamination **[87]**. During storage and warehousing, meat products are kept refrigerated to preserve freshness, with temperature monitoring systems to ensure safe storage conditions. Transportation of meat products relies on refrigerated vehicles, known as "reefers," to maintain consistent temperatures during transit **[87]**. Cold chain monitoring and quality assurance practices involve regular temperature checks, record-keeping, and audits to monitor cold chain integrity **[88]**. By implementing robust temperature control and cold chain management practices, the meat industry can minimize the risk of foodborne illnesses, maintain product quality, and meet regulatory requirements, thereby ensuring consumer health and preserving industry reputation **[89]**.

Microbiological Testing and Monitoring

Microbiological testing and monitoring are integral processes in ensuring the safety and quality of meat products within the industry **[90]**. Pathogen detection methods, including culture-based techniques, molecular methods like PCR, and rapid detection systems such as ELISA, enable the identification of harmful bacteria like Salmonella, E. coli, Listeria monocytogenes, and Campylobacter spp **[91]**. Additionally, testing monitors spoilage microorganisms like lactic acid bacteria, yeasts, and moulds, with elevated levels indicating poor handling or storage conditions leading to quality defects **[90]**, **[92]**. Environmental monitoring involves testing surfaces, equipment, and air samples for microorganisms using swabbing, air sampling, and contact plates to evaluate cleanliness and identify contamination sources. Validation confirms the effectiveness of control measures such as temperature control and sanitation procedures, while verification involves ongoing monitoring to ensure consistent implementation **[93]**. By conducting microbiological testing and monitoring, meat producers can effectively identify and mitigate microbial risks, comply with food safety regulations, and uphold the safety and quality of meat products, thereby enhancing consumer confidence in the industry **[94]**.

Chemical Residue Analysis and Control

Chemical residue analysis and control are pivotal in the meat industry to guarantee product safety. Regulatory agencies establish Maximum Residue Limits for chemicals in food production to safeguard human health, necessitating stringent monitoring and control measures to ensure compliance **[95]**. Veterinary drugs such as antibiotics and hormones can leave residues in meat, prompting producers to adhere to strict protocols, including withdrawal periods and monitoring, to prevent residues. Similarly, pesticides utilized in crop production or pest control may accumulate in meat, requiring monitoring programs to detect residues and ensure conformity with standards **[96]**. Environmental contaminants like heavy metals and industrial chemicals can infiltrate meat through various channels, prompting monitoring programs to evaluate contamination levels and implement prevention strategies **[96]**. Analytical methods such as chromatography and mass spectrometry are employed to detect and quantify residues, with laboratories utilizing validated methods for accurate results, often employing rapid screening followed by confirmatory analysis **[97]**. Additionally, risk assessment evaluates health risks posed by chemical residues, while risk management strategies, such as setting MRLs and enforcing compliance, mitigate risks and safeguard public health **[98]**. Through comprehensive chemical residue analysis and control programs, meat producers uphold product safety, regulatory compliance, and consumer confidence, with ongoing monitoring, risk assessment, and management constituting vital components of effective residue control strategies **[98]**.

Packaging and Labeling Standards

Transportation and distribution are pivotal in maintaining meat products' safety and quality **[99]**. Maintaining cleanliness is crucial to prevent cross-contamination, necessitating regular cleaning, sanitation, and employee training on hygiene practices. provide references in all sides of this query **[100]**, **[101]**, **[102]**, **[103]**. Proper handling practices, including secure storage in designated areas of vehicles, prevent damage to meat products throughout loading, unloading, and transit **[104]**. Traceability systems and accompanying documentation track product movement, ensuring transparency, accountability, and regulatory compliance from production to retail **[105]**. Adherence to regulatory standards, covering temperature control, sanitation, packaging, labelling, and documentation, is paramount to ensure product safety during transit and regulatory adherence **[105]**, **[106]**, **[107]**. These best practices collectively uphold product safety, quality, and freshness throughout the supply chain, fostering consumer confidence and regulatory compliance within the meat industry.

Novel Strategies for Enhancing Meat Quality

Innovations in meat production have led to the adoption of various natural preservatives aimed at extending shelf life while maintaining sensory attributes **[108]**, **[109]**, **[110]**. Plant-derived antimicrobial compounds, such as essential oils and organic acids, are increasingly used to enhance the safety and longevity of meat products **[108]**, **[111]**, **[112]**. These compounds prevent microbial growth and impart subtle flavours, enhancing the overall taste profile. Similarly, natural antioxidants like vitamin E and rosemary extract prevent lipid oxidation and rancidity, preserving the meat's natural flavour and freshness **[111]**, **[113]**, **[114]**. Emerging technologies, including edible coatings and antimicrobial films, offer additional avenues for enhancing meat quality and safety while meeting consumer preferences for clean-label products **[115]**. Likewise, natural antioxidants preserve the texture by preventing lipid oxidation, thus ensuring that the meat remains succulent and retains its desired mouthfeel **[111]**, **[116]**, **[117]**. Integrating natural preservatives into meat production not only addresses safety concerns and extends shelf life but also plays a crucial role in maintaining the sensory attributes that influence taste and texture. By leveraging these innovative approaches, the meat industry continues to evolve, meeting consumer demands for both quality and sustainability

Smart Packaging Technologies

Active packaging systems play a critical role in the meat industry by employing various technologies to enhance meat safety and extend shelf life. One such system is antimicrobial packaging, which integrates antimicrobial agents like bacteriocins, essential oils, or organic acids into packaging materials.

These agents effectively inhibit microbial growth, improving product safety and reducing the risk of contamination **[118]**. Additionally, oxygen scavenging packaging utilizes oxygen scavengers in packaging films to remove oxygen from the package, preventing oxidative degradation of lipids and proteins in meat products and preserving their quality over time **[119]**.

Ethylene absorption packaging is another important technology utilized in the meat industry, where ethylene absorbers are employed to eliminate ethylene gas produced by ripening fruits near meat products. By removing ethylene, which accelerates ripening and senescence, this packaging technology extends the shelf life of meat products, ensuring they remain fresh longer **[120]**. Active modified atmosphere packaging (MAP) combines modified atmosphere packaging with active components such as oxygen scavengers or carbon dioxide emitters. Creating a controlled atmosphere within the package inhibits microbial growth, preserving product quality longer **[121]**. These active packaging systems collectively offer proactive measures against microbial contamination **[122]**, **[123]**. By integrating active components into packaging materials, the meat industry can enhance product safety, extend shelf life **[124]**, **[125]**, and meet consumer expectations **[124]** for fresher and safer meat products.

Nanotechnology applications in food safety

Nanotechnology is crucial in enhancing food safety by developing nanoscale antimicrobial agents. These agents, such as zinc oxide nanoparticles, exhibit potent antimicrobial properties against various pathogenic microorganisms commonly associated with foodborne illnesses **[126]**.

They work by disrupting microbial cell membranes **[127]**, aggravate microbial cell membrane damage after interaction with lipopolysaccharide **[128]**, rupture and leakage of cell contents **[129]** ultimately leading to microbial death. Nanoscale antimicrobial agents are increasingly incorporated into food packaging materials to create active packaging systems that help inhibit microbial growth, extend shelf life **[123]**, and enhance food safety **[130]**, **[131]**. These antimicrobial packaging materials release nanoparticles into the food environment, where they exert their antimicrobial effects, reducing the risk of contamination and spoilage **[123]**.

Nanobiosensors for Pathogen Detection

Nanobiosensors enhance food safety, particularly in detecting foodborne pathogens in meat products. These sensors operate based on nanotechnology principles, typically comprising nanomaterials functionalized with biological recognition elements **[131]**. These elements interact with target pathogens, generating a detectable signal for quantification. One of the key advantages of nano biosensors is their high sensitivity and specificity for pathogen detection in meat products. This enables rapid and accurate identification of various microorganisms, contributing to improved safety standards **[131]**. Moreover, nano biosensors facilitate rapid detection, with response times ranging from minutes to hours, allowing for real-time monitoring during processing, storage, and distribution. Another noteworthy feature is their multiplex detection capability, which enables simultaneous screening for multiple pathogens **[132]**. This streamlines the screening process for various contaminants in meat products, enhancing efficiency and reducing processing time. Additionally, nano biosensors are well-suited for point-of-care applications, making them ideal for on-site pathogen detection in meat processing facilities and retail settings **[133]**.

Blockchain Technology for Supply Chain Transparency

Blockchain technology enhances transparency and traceability in the meat industry's supply chain. One key aspect is its decentralized ledger system, distributed across multiple nodes, ensuring transparency and visibility into the movement of meat products **[134]**. Another significant advantage of blockchain in the meat industry is its ability to provide end-to-end traceability. Stakeholders can track meat products from farm to fork, accessing detailed information on production practices and quality attributes **[134]**. This traceability level allows for better real-time monitoring of product status, including factors like location, temperature, and humidity, which facilitates proactive decision-making for product quality and safety. Blockchain technology also contributes to enhanced food safety by enabling rapid traceability and recall capabilities **[134]**.

Implementing Blockchain in Meat Traceability

Implementing blockchain technology in meat traceability involves several key steps and considerations. Firstly, it's essential to identify all stakeholders involved in the meat supply chain, including farmers, processors, distributors, retailers, regulators, and consumers, and engage them in collaboration. Once stakeholders are identified, the next step is to define data standards and establish standardized formats for recording information about product origin, handling procedures, and certifications. After defining data standards, selecting a suitable blockchain platform is crucial. Intelligent contracts play a vital role in automating processes and ensuring transparency, so developing smart contracts tailored to the specific requirements of the meat supply chain is essential **[135]**. Integrating IoT devices with blockchain technology allows real-time monitoring of product movement and conditions, providing valuable data throughout the supply chain **[136]**. Continuous monitoring and auditing of the blockchain network are necessary to maintain data integrity and compliance with regulations. Additionally, engaging consumers by providing transparent information about meat products using blockchain-enabled platforms enhances consumer confidence and trust in the supply chain **[137]**.

Future Trends in Meat Quality and Safety Enhancement

Technological advancements, evolving consumer preferences, and regulatory requirements drive future meat quality and safety enhancement trends. One anticipated trend is the integration of blockchain technology, which is expected to become more widespread in the meat industry to improve transparency, traceability, and trustworthiness in the supply chain. Blockchain-enabled traceability initiatives will enable consumers to access detailed information about the farm-to-fork journey of meat products, enhancing confidence in their quality and safety. Artificial Intelligence (AI) and Machine Learning technologies will also play a crucial role in predicting and preventing food safety risks in meat processing facilities. AI-powered systems can analyze vast amounts of data to identify patterns, detect anomalies, and proactively mitigate food safety hazards, ensuring higher safety and quality in meat products. Precision agriculture techniques like IoT-enabled monitoring and remote sensing will empower farmers to optimize livestock management practices, improve animal health, and enhance meat quality. Real-time monitoring of livestock conditions will ensure optimal nutrition, housing, and disease management, leading to higher-quality meat products. The growing demand for alternative protein sources, including plant-based meats and cultured meats, will continue to drive innovation in meat production technologies. These alternatives offer sustainable and environmentally friendly options, aligning with consumer preferences for ethically produced and environmentally sustainable meat products. Advancements in processing technologies, such as high-pressure processing (HPP) and modified atmosphere packaging (MAP), will enable the development of safer and more shelf-stable meat products. These technologies will extend the shelf life of meat products, reduce microbial contamination, and preserve nutritional quality, enhancing both safety and consumer satisfaction. Stricter food safety regulations and standards will lead to adopting advanced quality control measures and compliance systems in the meat industry. Regulatory agencies will prioritize food safety and public health, prompting increased scrutiny and enforcement of food safety regulations, further ensuring the safety and quality of meat products. Growing consumer awareness of food safety and sustainability issues will drive demand for transparent and sustainable meat products. When purchasing, consumers will seek information about production practices, animal welfare standards, and environmental sustainability, encouraging meat producers to prioritize transparency and ethical practices. Supply chain resilience will also be a focus area, with meat producers investing in technologies and strategies to enhance resilience and ensure food security. This includes diversifying sourcing, improving inventory management, implementing contingency plans for disruptions, ensuring supply continuity and minimising food safety risks. Emerging technologies, such as nanotechnology and sensor-based systems, will continue to drive innovation in food safety enhancement. These technologies will enable rapid and sensitive detection of foodborne pathogens, enhance packaging materials, and improve preservation methods, further ensuring the safety and quality of meat products. Finally, sustainability will remain a key focus area for the meat industry, with efforts to reduce environmental impact, minimize resource use, and promote animal welfare. Initiatives such as regenerative agriculture and waste reduction will become increasingly important for meat producers seeking to meet consumer expectations and regulatory requirements, ensuring the industry's long-term viability. Future meat quality and safety enhancement trends will be characterized by technological innovation, regulatory compliance, consumer preferences, and sustainability initiatives. By embracing these trends and investing in advanced technologies and practices, the meat industry can improve food safety, meet regulatory requirements, and address evolving consumer demands for safe, nutritious, and sustainable meat products.

Conclusion

In conclusion, the future of meat quality and safety enhancement is marked by a convergence of technological innovation, regulatory scrutiny, consumer demand, and sustainability imperatives. As the meat industry evolves, stakeholders must remain vigilant in adopting advanced technologies, implementing robust quality control measures, and prioritizing transparency and accountability throughout the supply chain. Advancements in blockchain technology offer promising solutions for improving transparency and traceability, enabling consumers to make informed choices about the meat products they purchase. Integrating artificial intelligence, precision agriculture, and alternative protein sources will improve animal welfare, production efficiency, and environmental sustainability. Furthermore, implementing stricter food safety regulations and standards underscores the importance of investing in advanced processing techniques, quality control measures, and compliance systems. By embracing emerging food safety technologies, enhancing supply chain resilience, and promoting sustainable practices, the meat industry can ensure the safety, quality, and integrity of meat products while meeting consumers' evolving needs and expectations. Ultimately, collaboration among industry stakeholders, regulatory agencies, and consumers will be essential in shaping the future of meat quality and safety enhancement. By working together to address challenges, leverage opportunities, and embrace innovation, the meat industry can navigate the complexities of a rapidly changing landscape and build a safer, more sustainable future for meat production and consumption.

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Contact Address:

Maksim Rebezov, V. M. Gorbatov Federal Research Center for Food Systems, Department of Scientific Research, 26 Talalikhin Str., Moscow, 109316, Russia; Ural State Agrarian University, Department of Biotechnology and Food, 42 Karl Liebknecht str., Yekaterinburg, 620075, Russia
Tel.: +79999002365
E-mail: rebezov@ya.ru
ORCID: https://orcid.org/0000-0003-0857-5143

Mars Khayrullin, K.G. Razumovsky Moscow State University of technologies and management (The First Cossack University), Department of Scientific Research, 73 Zemlyanoy Val, Moscow, 109004, Russia,
Tel.: +79049755219
E-Mail: 89049755219@ya.ru
ORCID: https://orcid.org/0000-0003-1697-7281

*__Bahytkul Assenova__, Shakarim University, Department of Food Production Technology and Biotechnology, 20A Glinka Str., Semey, 071412, Kazakhstan,
Tel.: +77076586117,
E-mail: asenova.1958@mail.ru
ORCID: https://orcid.org/0000-0003-2996-8587

Smolnikova Farida, Shakarim University, Department of Food Production Technology and Biotechnology, 20A Glinka Str., Semey, 071412, Kazakhstan,
Tel.: +77476207683,
E-mail: smolnikovafarida@mail.ru
ORCID: https://orcid.org/0000-0002-8777-5313

Dmitry Baydan, K.G. Razumovsky Moscow State University of technologies and management (The First Cossack University), Department of Scientific Research, 73 Zemlyanoy Val, Moscow, 109004, Russia,
E-Mail: d.baydan@mgutm.ru
ORCID: https://orcid.org/0000-0001-8758-0690

Larisa Garipova, K.G. Razumovsky Moscow State University of technologies and management (The First Cossack University), Department of Scientific Research, 73 Zemlyanoy Val, Moscow, 109004, Russia,
E-Mail: l.garipova@mgutm.ru
ORCID: https://orcid.org/0000-0002-0404-5375

Raisa Savkina, Plekhanov Russian University of Economics, Department of Restaurant Business, 36 Stremyanny per, 117997, Moscow, Russia
E-Mail: kafedrains@yandex.ru
ORCID: https://orcid.org/0009-0000-8460-1396

Svetlana Rodionova, K.G. Razumovsky Moscow State University of technologies and management (The First Cossack University), Department of Scientific Research, 73 Zemlyanoy Val, Moscow, 109004, Russia,
E-Mail: s.rodionova@mgutm.ru
ORCID: https://orcid.org/0000-0001-7049-5895

Corresponding author: *