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Review Article

AI driven approach and NIRS: A review on meat quality and safety

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Abstract

Consumers' increasing demand for high-quality and safe meat products has led the food industry to explore advanced analytical techniques, such as artificial intelligence and near-infrared reflectance spectroscopy to assess and monitor the quality and safety of meat. The quality and safety of meat products have become increasingly important considerations for consumers, driven by concerns over health implications and the need for transparency in the meat supply chain. The meat industry faces increasing demands from consumers for higher quality and safer products, driven by concerns over food-borne illnesses and the nutritional value of meat. Addressing these growing consumer expectations has become a priority, prompting researchers to actively investigate the potential of innovative non-destructive techniques, including near-infrared spectroscopy and others in combination with advanced data analysis methodologies to enable rapid, objective, and environmentally-friendly assessment of diverse meat quality and safety attributes. This review examines the current state of research on the application of these technologies in the meat industry. Additionally, it explores the integration of artificial intelligence algorithms with near-infrared spectroscopy data to enhance the accuracy and reliability of meat quality prediction and authentication.

Introduction

Meat serves as a significant source of protein in developing country like Bangladesh. Many people worldwide use it as their primary source of animal protein. The use of Artificial Intelligence in the evaluation and management of meat quality and safety has gained significant attention in recent years. Artificial Intelligence has emerged as a powerful tool in the food industry offering a wide range of applications in areas such as quality determination, control tools, classification, and prediction (Prieto et al., 2017). Artificial Intelligence techniques have also demonstrated their ability to effectively process and analyze large volumes of data, identify complex patterns and make accurate predictions making them a valuable tool in the food industry (Shi et al., 2021). AI can improve feeding strategies, breeding decisions, and health monitoring, while NIR provides real-time, non-invasive quality control to assess key attributes like fat content, tenderness, and nutritional value. These technologies help ensure that organic beef produced which is high quality, safe for consumption, and meets the growing demand for healthy, chemical-free meat in local and international markets (Hossain et al., 2016; Liza et al., 2024). Irradiation is acknowledged as a frequently used, efficient food processing method for meat preservation because it gets rid of harmful germs without sacrificing the product's nutritional value or sensory appeal (Haque et al., 2017). The food industry has witnessed a surge in the application of Artificial Intelligence to address various challenges including the evaluation and control of food quality and safety (Mavani et al., 2021). Near-Infrared Spectroscopy, on the other hand, has gained significant attention as a rapid, non-destructive, and efficient technique for evaluating various quality attributes of food products. The integration of Artificial Intelligence and Near-Infrared Spectroscopy has been a subject of growing interest in the food industry, particularly in the realm of meat quality and safety assessment (Kutsanedzie et al., 2019). Integrating AI-driven approaches with NIR technology offers innovative solutions to meet preservation by precisely monitoring and predicting microbial activity, ensuring extended shelf life, enhanced safety, and optimal quality (Rahman et al., 2023). Consumers' growing expectations for high-quality and safe food products have driven the need for innovative methods that can effectively assess and optimize these parameters throughout the food production and processing chain (Sahni et al., 2021). The capability of Artificial Intelligence systems in diverse tasks such as food quality determination, control tools, classification of food and prediction purposes has intensified their demand in the food industry. Furthermore, the integration of this system with other devices such as electronic nose, electronic tongue, computer vision system, and near infrared spectroscopy is also emphasized, all of which

will benefit both the industry players and consumers. Existing literature suggests that the integration of Artificial Intelligence and Non-Invasive Spectroscopic Techniques such as Near-Infrared Spectroscopy, holds immense potential for revolutionizing the way meat quality and safety are evaluated and managed in the food industry. This review paper aims to explore the potential of Artificial Intelligence-driven approaches with a particular emphasis on the integration of Near-Infrared Spectroscopy in enhancing the assessment and management of meat quality and safety.

AI Driven approach in Monitoring Meat Animal

The integration of AI-driven approaches and Near-Infrared Reflectance (NIR) Spectroscopy can significantly enhance the quality, safety, and overall management of livestock, particularly Black Bengal goats and cattle. These technologies play a crucial role in monitoring meat quality and key health indicators such as feed intake, growth performance, reproductive health, and parasitic infestations. AI algorithms can process data from NIR spectroscopy to assess the nutritional composition of livestock feed, ensuring optimal dietary formulations. By integrating real-time data from NIR sensors, AI can continuously monitor feed intake and the nutritional status of animals, allowing for early detection of potential health risks which can influence the carcass quality (Hossain et al., 2021; Hashem et al., 2020). For example, anomalies in feed consumption patterns detected by AI systems can flag deficiencies, parasitic infections, or other health concerns that might compromise growth rates and meat quality. Additionally, AI-driven systems help maintain livestock health by optimizing deworming schedules and nutrition programs, reducing parasite loads and minimizing the risk of parasitic transmission to humans. These results in safer meat production, improved animal welfare, and enhanced food safety standards. The synergy between AI and NIR spectroscopy enables a deeper understanding of livestock nutrition, growth trends, and disease prevention strategies (Moniruzzaman et al., 2002). These technologies optimize feeding strategies, predict health risks, and enhance meat quality, making them valuable tools in modern livestock farming. Smart farming innovations such as automated feeding systems and climate-controlled housing can further reduce feed wastage and enhance cattle fattening efficiency. AI-powered predictive models improve feed formulation, automate health monitoring, and maximize weight gain, leading to higher productivity and profitability. Near-Infrared Spectroscopy (NIRS) provides real-time analysis of feed quality, ensuring livestock receive a balanced diet for optimal growth (Hashem et al., 1999). The combination of AI-driven analytics and NIR spectroscopy represents a cutting-edge approach to livestock management, offering precise nutritional optimization and improving the overall quality and safety of meat production. This forward-thinking approach not only enhances economic outcomes for farmers but also contributes to a more sustainable and technologically advanced livestock industry. The AI-NIR synergy offers a forward-thinking approach to revolutionizing livestock management, especially in optimizing the nutritional input and output for goats and cattle, impacting the quality of the final meat product.

AI-Driven Approaches to Meat Quality Assessment

The incorporation of AI-based techniques with near-infrared spectroscopy has led to significant improvements in the accuracy and reliability of meat quality assessment. Specifically, artificial neural networks have demonstrated their exceptional ability to effectively classify and predict meat quality attributes by recognizing the complex nonlinear relationships present within the spectroscopic data, a task that would be extremely challenging for traditional statistical methods (Ahmed et al., 2021). Additionally, the application of fuzzy logic has allowed for the modeling of the inherent ambiguity and uncertainty associated with meat quality characteristics, resulting in more nuanced and precise evaluations of meat parameters (Peres et al., 2018). By seamlessly integrating AI-based approaches, such as expert systems, artificial neural networks, and fuzzy logic, with the powerful non-destructive capabilities of near-infrared spectroscopy, researchers have developed robust and versatile systems capable of comprehensively assessing a wide range of meat quality attributes, including chemical composition, authenticity, and safety (Kapovsky et al., 2017). The integration of cutting-edge AI technologies with the advanced analytical capabilities of near-infrared spectroscopy holds immense promise for revolutionizing the meat industry, driving significant improvements in efficiency, product quality, and consumer trust (Ali et al., 2022; Hossain et al., 2021; Roberts et al., 2017). Despite the significant progress made in the integration of artificial intelligence and near-infrared spectroscopy for meat quality and safety assessment, there are still several challenges and opportunities that need to be addressed to further enhance the effectiveness and widespread adoption of these technologies. Overcoming these challenges will require a multi-pronged approach, involving the continuous refinement and optimization of AI-driven techniques, the ongoing development and integration of near-infrared spectroscopy and other complementary technologies and the implementation of comprehensive strategies to facilitate the adoption and implementation of these transformative solutions across the meat industry. By addressing these key challenges and capitalizing on the synergies between artificial intelligence and near-infrared spectroscopy, the meat industry can unlock a new era of unprecedented quality, safety, and efficiency, ultimately benefiting both producers and consumers alike.

Artificial Intelligence in Meat Quality and Safety

Artificial Intelligence techniques have found widespread application in the assessment and optimization of meat quality and safety, leveraging their ability to process and analyze large amounts of data, identify complex patterns and make accurate predictions (Chidinma-Mary-Agbai, 2020). The detection and evaluation of food quality particularly meat, has been a long-standing challenge in the agri-food industry. Reliance on destructive techniques, such as those commonly used in the past for assessing meat quality, can be problematic as they are labor-intensive and lead to substantial postharvest losses (Ali et al., 2021). The rise of artificial intelligence has provided new avenues to address these challenges effectively (Shi et al., 2021). Artificial intelligence is a rapidly advancing field that has found numerous applications in the agri-food domain, including the assessment of meat quality and safety (Bandyopadhyay et al., 2021). In contrast to these destructive methods, non-invasive techniques like near-infrared spectroscopy have emerged as an innovative solution for efficiently evaluating meat quality and safety. Near-infrared spectroscopy is a powerful analytical technique that has garnered significant attention in the meat industry due to its ability to provide rapid, non-destructive, and comprehensive analysis of various meat quality parameters such as chemical composition, authenticity, and safety (Zheng et al., 2023). Integrating modern technologies like AI-driven approaches and NIR spectroscopy offers new, more efficient, and precise ways to monitor and enhance meat quality and safety. By enabling real-time monitoring, predictive modeling, and automated control systems, these technologies not only improve shelf life and food safety

but also ensure that meat quality is consistently maintained throughout the preservation process. The future of meat preservation lies in the synergy between AI and NIR, leading to smarter, more sustainable, and consumer-friendly solutions ((Rahman et al., 2023). Recent years have witnessed a growing body of research exploring the principles and applications of AI-based technologies in the realm of meat quality testing, grading and evaluation. These advancements have the potential to transform the industry by improving efficiency, reducing waste and enhancing consumer trust in the safety and quality of meat products.

Near-Infrared Spectroscopy for Meat Analysis

Near-infrared spectroscopy has emerged as a powerful non-destructive technique for the detection and evaluation of meat quality (Peng & Wang, 2015). This technology offers several advantages over traditional destructive methods including its ability to provide rapid, labor-free, and time-saving analysis of meat. Studies have demonstrated the versatility of near-infrared spectroscopy in assessing a wide range of meat quality parameters such as chemical composition, authenticity, and safety which are crucial for ensuring the overall quality and integrity of meat product. These non-invasive techniques have the potential to revolutionize the meat industry by improving efficiency, reducing waste, and enhancing consumer trust in the safety and quality of meat products. The integration of AI-based techniques with near-infrared spectroscopy has further enhanced the capabilities of these systems, enabling more accurate and reliable assessments of meat quality and safety (Jia et al., 2022). The rapid advancements in artificial intelligence and near-infrared spectroscopy have the potential to transform the meat industry by providing innovative solutions for assessing and monitoring meat quality and safety. While the promising integration of artificial intelligence and near-infrared spectroscopy holds great potential for improving meat quality and safety assessments, several challenges must be addressed to fully realize the benefits of these technologies. Continued research and development in this field, such as improving the accuracy and robustness of AI-driven models, enhancing the portability and user-friendliness of near-infrared spectroscopy systems and addressing regulatory and consumer acceptance barriers are essential to unlock the full potential of these innovative approaches in the meat industry.

Integrating AI and NIRs for Improved Meat Evaluation

Artificial intelligence and near-infrared spectroscopy have synergistically contributed to the advancement of meat quality assessment and safety monitoring. The incorporation of AI techniques, such as expert systems, artificial neural networks, and fuzzy logic, has significantly enhanced the capabilities of near-infrared spectroscopy in meat analysis. Expert systems integrate various quality indicators to provide informed assessments that mimic human decision-making (Wold & Løvland, 2020). By combining AI-driven approaches with NIR spectroscopy, the process of monitoring cell behavior and meat quality can be enhanced, leading to more efficient and predictable outcomes. This synergy holds great promise for improving quality control, ensuring safety, and maintaining the consistency of both conventional and cultured meat products (Hashem et al., 2006). Artificial neural networks excel at classifying and predicting meat quality attributes based on complex nonlinear relationships, while fuzzy logic addresses the ambiguity and uncertainty inherent in real-world assessments, enabling a more nuanced evaluation of meat quality (Kutsanedzie et al., 2019; Prieto et al., 2017). The integration of these AI techniques with near-infrared spectroscopic data has led to the development of robust, real-time monitoring systems, enhancing efficiency, reducing waste, and increasing consumer trust in meat safety and quality (Pérez et al., 2019). Additionally, heat stress negatively impacts meat quality by lowering dressing percentage, increasing drip loss, and altering protein content. Traditional assessment methods are slow and inefficient, but AI-powered systems can monitor temperature-humidity index (THI), body temperature, and feeding patterns, enabling automated cooling and predictive analysis of carcass traits. NIRS technology provides rapid, non-invasive evaluation of nutrient composition, water retention, and protein quality. By integrating AI and NIRS, farmers can detect heat stress early, optimize feeding strategies, and maintain superior meat quality, ensuring a more efficient and sustainable livestock industry (Rana et al., 2014; Murshed et al., 2014). Given the rapid advancements in these technologies, their integration holds immense potential for revolutionizing meat assessment and monitoring. AI-driven models can optimize irradiation doses while NIR spectroscopy enables real-time monitoring of meat composition, fat content, and oxidation levels. Together, these technologies contribute to safer, higher-quality meat with extended shelf life while meeting consumer preferences (Islam et al., 2019).

Machine Learning Models for Meat Quality Prediction

Machine learning algorithms, particularly artificial neural networks have demonstrated exceptional capabilities in effectively classifying and predicting meat quality attributes by leveraging the complex nonlinear relationships present within the data. Neural networks have the ability to learn from large datasets, identifying subtle patterns and relationships that may be difficult for human experts to discern and then applying this knowledge to make accurate predictions of meat quality parameters (Alves et al., 2018). In addition to neural networks, researchers have explored the use of other advanced machine learning techniques such as support vector machines, random forests and k-nearest neighbors to further enhance the accuracy and reliability of meat quality assessment (Taheri-Garavand et al., 2019). These machine learning models have been successfully applied to a wide range of meat quality characteristics including color, marbling, tenderness and chemical composition, all of which are crucial indicators of overall meat quality and safety. The combination of these sophisticated machine learning models with non-destructive analytical methods like near-infrared spectroscopy has been a particularly fruitful area of research, enabling the development of highly accurate and reliable systems for real-time monitoring and evaluation of meat quality and safety. By integrating near-infrared spectroscopic data with these powerful machine learning algorithms, researchers have developed robust and versatile systems capable of providing real-time, non-invasive and accurate evaluations of meat quality. The meat business has surely undergone a revolution as a result of the combination of these cutting-edge AI-driven methods with the sophisticated analytical powers of near-infrared spectroscopy which has changed how meat safety and quality are evaluated and tracked.

Computer Vision and Image Analysis in Meat Inspection

Computer vision and image analysis techniques have also been extensively explored for the assessment of meat quality and safety. These techniques leverage digital imaging technologies such as digital cameras and hyperspectral imaging to capture high-resolution visual information about meat samples, enabling the detailed evaluation of various quality attributes including

color, texture and marbling (Antequera et al., 2020). The primary advantage of these computer vision-based method is their ability to offer objective, quantitative and reproducible assessments of meat quality which can overcome the limitations of traditional manual inspection methods that are often subjective and inconsistent (Xiong et al., 2015). The applications of computer vision systems in the meat industry span a wide range, encompassing the classification of different meat cuts, the detection of defects or abnormalities and the prediction of key quality characteristics such as color, texture, and marbling. The adoption of computer vision-based approaches in the meat industry has the potential to revolutionize the way quality and safety assessments are conducted, enabling a more standardized, efficient and reliable process that can be seamlessly integrated into industrial workflows (Milovanović et al., 2019). By leveraging the synergies between artificial intelligence, near-infrared spectroscopy and computer vision, the meat industry can achieve a comprehensive and holistic approach to quality and safety monitoring, ensuring the delivery of high-quality and safe meat products to consumers while also enhancing operational efficiency and sustainability.

Sensor Fusion and Data Integration for Meat Monitoring

The individual applications of artificial intelligence, near-infrared spectroscopy and computer vision have demonstrated promising results in the assessment of meat quality and safety. However, the integration of these complementary technologies known as sensor fusion can further enhance the capabilities of meat monitoring systems. Sensor fusion involves the combination of data from multiple sensors such as near-infrared spectrometers, hyperspectral cameras, and other imaging modalities to provide a more comprehensive and accurate evaluation of meat quality and safety (Dixit et al., 2020). By integrating data from these diverse sources, researchers and practitioners can leverage the unique strengths of each technology to create a more robust and reliable monitoring system. For instance, near-infrared spectroscopy can provide valuable insights into the chemical composition and internal properties of meat such as protein content, fat marbling, and pH while computer vision techniques can offer detailed information about the physical appearance and surface characteristics of the meat including color, texture and the presence of defects or abnormalities (Arsalane et al., 2020). The combination of these data sources coupled with advanced machine learning algorithms can lead to the development of highly sophisticated meat monitoring systems capable of detecting a wide range of quality and safety issues from microbial contamination to fraudulent substitution of meat types.

AI-Driven Quality Control in Meat Packaging and Storage

The synergistic integration of artificial intelligence, near-infrared spectroscopy and computer vision technologies can revolutionize the meat industry by transforming the way quality and safety assessments are conducted (Khaled et al., 2021). By leveraging the complementary strengths of these technologies, researchers and practitioners can develop comprehensive monitoring systems capable of providing real-time, non-invasive, and highly accurate evaluations of meat quality and safety characteristics. Notably, this integrated approach offers several key advantages: it enables the rapid and reliable detection of quality and safety issues, allowing for immediate corrective actions; it provides a comprehensive assessment of meat characteristics from chemical composition to physical appearance, leading to more informed decision-making; it facilitates the implementation of predictive maintenance and proactive quality control strategies, enhancing the overall efficiency and sustainability of the meat supply chain (Geletu et al., 2021). As the demand for high-quality and safe meat products continues to grow, the adoption of these AI-driven, sensor-based technologies will become increasingly crucial, empowering the meat industry to meet the evolving needs and expectations of consumers while ensuring the long-term viability and competitiveness of the sector. Beyond the advancements in quality and safety assessment, the integration of artificial intelligence and advanced sensor technologies can also drive significant improvements in the traceability and supply chain management of meat products (Amani & Sarkodie, 2022). Furthermore, AI-powered traceability and supply chain management systems can enhance the transparency and accountability of the meat industry by providing detailed and verifiable information about the origin, processing, and distribution of meat products.

Challenges and Opportunities in AI-NIRs Integration

The successful integration of artificial intelligence and near-infrared spectroscopy for meat quality and safety monitoring faces several challenges that must be addressed to unlock the full potential of this synergistic approach. A critical challenge lies in the need to establish comprehensive and diverse datasets that accurately capture the wide range of meat products, processing conditions and quality characteristics encountered across the industry. Addressing this challenge requires a collaborative effort involving researchers, producers and regulatory authorities who must work together to develop robust and representative datasets that can serve as the foundation for training and validating AI-powered meat monitoring systems. Another key challenge is the development of interpretable and explainable AI models that can provide meaningful insights into the underlying relationships between the spectroscopic data, physical attributes and quality parameters of meat. By adopting advanced techniques such as feature engineering, which involves the selection and transformation of relevant data features and leveraging model interpretability methods such as visualization tools and explainable AI algorithms, researchers can ensure that the decision-making process of the AI systems is transparent and readily understood by industry stakeholders. Overcoming these challenges will be crucial for the widespread adoption and successful implementation of AI-driven, sensor-based meat quality and safety monitoring systems, as it will instill confidence among stakeholders and facilitate the seamless integration of these technologies into the meat industry, ultimately driving the transformation towards more efficient, sustainable, and consumer-centric meat production and distribution practices.

Future Trends and Innovations in Meat AI Technology

As the integration of artificial intelligence and near-infrared spectroscopy continues to evolve, several emerging trends and innovations are poised to shape the future of meat quality and safety monitoring. One particularly promising trend is the growing emphasis on the development of multimodal sensing platforms that combine various imaging and spectroscopic techniques such as hyperspectral imaging, ultrasound and X-ray to provide a more comprehensive and detailed assessment of meat characteristics. This multimodal approach, which leverages the unique strengths and capabilities of different sensing technologies, can enable the creation of highly sensitive and precise meat monitoring systems that are capable of identifying a broader range of quality and safety issues from microbial contamination to adulteration or fraudulent substitution of meat

products. Another key trend is the increasing focus on the incorporation of real-time, in-line monitoring capabilities within meat processing facilities enabling the continuous and automated assessment of meat quality and safety throughout the various stages of the production chain, from slaughter to packaging and storage. By integrating these AI-powered, sensor-based monitoring systems directly into the meat processing workflow, producers can enhance the overall efficiency, responsiveness and competitiveness of their operations that ensure the consistent delivery of high-quality and safe meat products that meet the evolving demands and expectations of consumers. As the field of artificial intelligence and near-infrared spectroscopy continues to progress, various emerging trends and innovations are poised to shape the future of meat quality and safety monitoring, transforming the way these critical aspects of the meat industry are assessed and managed.

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