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Review Article

Advancing the meat industry with machine learning: A study of progress, challenges, and potential

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Abstract

The integration of machine learning (ML) in the meat industry is reshaping traditional practices by introducing data-driven approaches to improve product quality, operational efficiency, safety, and sustainability. This comprehensive overview explores the application of key ML techniques including supervised learning, unsupervised learning, reinforcement learning, and deep learning in various domains such as meat quality assessment, supply chain optimization, adulteration detection, automated processing, and consumer behavior analysis. As ML algorithms become increasingly sophisticated and accessible, their ability to process large datasets from imaging systems, sensors, and chemical analyses enables the detection of complex patterns and the automation of critical decisions. While the benefits of ML in the meat industry are substantial, the adoption of these technologies is not without challenges. Issues such as data availability, high computational requirements, integration with legacy systems, and the need for standardized regulations pose significant barriers. Nonetheless, ongoing technological advancements particularly in the realms of IoT, big data, and predictive analytics are paving the way for more efficient disease prevention strategies, enhanced food safety, and reduced environmental impact. This paper highlights the current state, challenges, and future trends of machine learning applications in the meat industry. It emphasizes the potential of ML to build a more intelligent, transparent, and sustainable meat production ecosystem, ultimately aligning industry practices with modern consumer expectations and global food safety standards.

Introduction

The meat industry plays a crucial role in global nutrition and economy, supplying a significant portion of the world's protein needs and supporting millions of livelihoods (Rijsberman, 2017). However, this industry is confronted with numerous challenges including the demand for higher product quality, food safety, sustainability, cost-efficiency, and transparency. Traditional methods for ensuring meat quality and safety often rely on manual inspections, subjective assessments, and resource-intensive processes, which can be slow, inconsistent, and prone to error. In recent years, the rapid advancement of machine learning (ML) technologies has opened new avenues for addressing these challenges, revolutionizing how meat is produced, processed, and delivered to consumers.

Machine learning, a subset of artificial intelligence, involves training algorithms to learn from data and make decisions or predictions without explicit programming (Ghahramani et al., 2015). By harnessing vast amounts of data collected through sensors, imaging devices, chemical analyses, and consumer databases, ML models can uncover complex patterns, automate decision-making, and optimize processes throughout the meat supply chain. Techniques such as supervised learning help predict key quality attributes like tenderness and fat content, while unsupervised learning can identify hidden clusters and detect anomalies indicative of spoilage or adulteration. Reinforcement learning enables the optimization of production lines by learning the most efficient operational strategies, and deep learning models, especially convolutional neural networks (CNNs), excel in image recognition tasks crucial for non-destructive meat inspection.

Recent studies have demonstrated how ML-based classification can benefit from reliable indicators such as water-holding capacity, drip loss, and pH—particularly in poultry meat—where filter paper wetness and standard bag methods showed strong predictive power for classifying broiler meat quality into PSE, normal, and DFD categories (Sarker et al., 2024). Additionally, the structural and genetic features of muscle tissue, such as muscle fiber histomorphology and expression of genes like calpain and calpastatin, have been identified as significant predictors of tenderness, suggesting potential integration of molecular data into predictive ML models for beef grading (Sarker et al., 2024b).

Beyond quality assessment, ML enhances supply chain efficiency by forecasting demand, optimizing inventory, and streamlining logistics, thereby reducing waste and ensuring timely delivery (Pasupuleti et al., 2024). It also plays a pivotal role in combating food fraud by detecting adulteration through chemical and visual data analysis. The integration of ML-powered automation further boosts productivity and consistency while addressing labor shortages and minimizing human error. Additionally, analyzing consumer behavior through machine learning enables producers to adapt products to evolving market trends and preferences, ensuring better alignment with consumer expectations.

Value-added product development using natural functional ingredients like ginger and tulsi extract has also shown promise for improving sensory and oxidative quality, offering new features for ML-based predictive models in processed meat optimization (Hossain et al., 2021; Siddiqua et al., 2018). Recent advances in nondestructive quality assessment—such as near-infrared spectroscopy combined with AI—offer fast, accurate tools for evaluating meat freshness, tenderness, and safety in real time. Integration of NIRS with AI has proven particularly effective in quality authentication of meat products, supporting rapid, environmentally friendly, and objective evaluations in the meat supply chain (Sarker et al., 2024a).

Postmortem meat processing improvements, like rigor-aging of broiler meat, have also shown to enhance sensory and physicochemical quality, indicating promising directions for data-driven optimization of meat texture and acceptability (Khatun et al., 2025). Furthermore, new preservation methods like gamma irradiation have demonstrated effective microbial load reduction and shelf-life extension for beef, with the 6 kGy dose being optimal for maintaining nutritional and sensory qualities (Haquea et al., 2017).

Despite the clear benefits, the meat industry's adoption of machine learning faces significant hurdles. Challenges such as limited data availability and quality, technical integration with legacy systems, high computational costs, ethical concerns, and the absence of standardized regulatory frameworks need to be addressed to fully realize ML's potential. However, ongoing advances in algorithm development, the proliferation of Internet of Things (IoT) devices generating big data, and increased emphasis on sustainability and safety present exciting future prospects (Zikria et al., 2021). Predictive analytics for disease prevention, waste reduction strategies, and improved environmental management underscore the transformative power of machine learning to create a smarter, safer, and more sustainable meat industry.

Meanwhile, predictive features such as growth performance, sex, season, and litter size—explored in studies of Jamuna Basin lamb—present opportunities for precision livestock models using structured performance datasets (Hashem et al., 2020). Recent research has significantly contributed to the understanding of various aspects of animal production and meat quality, including the use of probiotics (Mia et al., 2024a), freezing impacts on organ meat (Sharker et al., 2024), and meat adulteration detection using NIRS and chemometric analysis (Hashem et al., 2024a). Furthermore, studies have explored innovative technologies like machine learning and AI for improving livestock management and meat safety evaluation (Mia et al., 2025; Sarker et al., 2024a), while functional ingredients such as 2% ginger extract and 0.3% tulsi leaf extract have proven effective in enhancing sensory qualities and antioxidant capacity in value-added products like sausages and meatballs (Hossain et al., 2021; Siddiqua et al., 2018).

In broiler meat, reliable classification of quality types such as PSE, normal, and DFD has been achieved using drip loss and water-holding capacity metrics, with strong predictive relationships validated through statistical modeling (Sarker et al., 2024). Variation in lamb growth performance due to factors such as sex, litter size, and season has also been studied, providing potential features for predictive models to improve flock management and meat yield (Hashem et al., 2020). Moreover, gene expression and muscle fiber histomorphology have been identified as influential factors for meat tenderness, suggesting deeper integration of molecular data into ML models (Sarker et al., 2024b). These collective efforts underscore the growing reliance on interdisciplinary approaches for enhancing meat quality, food safety, and animal productivity using machine learning techniques.

This comprehensive overview explores the fundamental machine learning techniques applied in the meat sector, their diverse applications, the challenges faced, and emerging trends shaping the future of the industry. By embracing these technological innovations, the meat industry stands poised for a paradigm shift that promises enhanced efficiency, higher quality products, improved consumer trust, and a reduced environmental footprint, ultimately advancing towards a modern, intelligent food production ecosystem.

Machine Learning Techniques Used in the Meat Industry

Supervised Learning

Supervised learning is a fundamental approach in machine learning where models are trained using labeled datasets, meaning each input is paired with a known output (Ren et al., 2023). This method includes two main types: classification, which is used to predict categorical outcomes (such as determining the type of meat), and regression, which is used to predict continuous variables (such as fat content or tenderness scores). In the context of meat science, supervised learning models are developed by feeding the algorithm data from previous experiments or measurements such as spectral information, chemical composition, or sensory attributes along with the corresponding known outputs (Lin et al., 2023). Once trained, these models can predict quality parameters or detect patterns in new, unseen data with high accuracy.

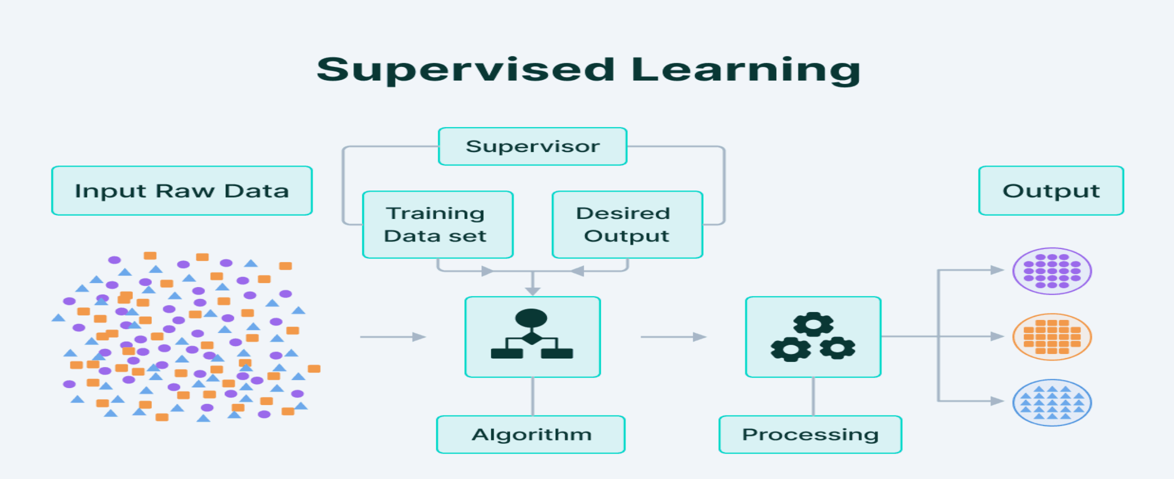

Figure 1: Supervised Learning Model.

In the meat industry, supervised learning has shown great potential for improving product quality and ensuring food safety (Chhetri et al., 2024). For instance, regression models are widely used to predict key quality traits like tenderness, juiciness, moisture, and fat content using inputs from NIR spectroscopy or GC-MS data. Similarly, classification algorithms help in identifying meat species or detecting adulteration, such as distinguishing between beef and pork (Siddiqui et al., 2021). These techniques are also used to estimate shelf life, predict spoilage, and evaluate consumer preferences based on sensory data. Overall, supervised learning enhances decision-making and automation in meat processing by enabling rapid, non-destructive, and accurate assessments of meat quality.

Unsupervised Learning

Unsupervised learning is a machine learning approach where algorithms are applied to datasets without predefined labels or target outputs (Tyagi et al., 2022). The goal is to uncover hidden patterns, structures, or groupings within the data. Common techniques include clustering, which groups similar data points together, and anomaly detection, which identifies data points that deviate significantly from the norm. In the meat industry, unsupervised learning is particularly useful when there is no prior labeling of data, such as during initial quality assessment or when exploring new datasets from sensors or chemical analyses like NIR or GC-MS.

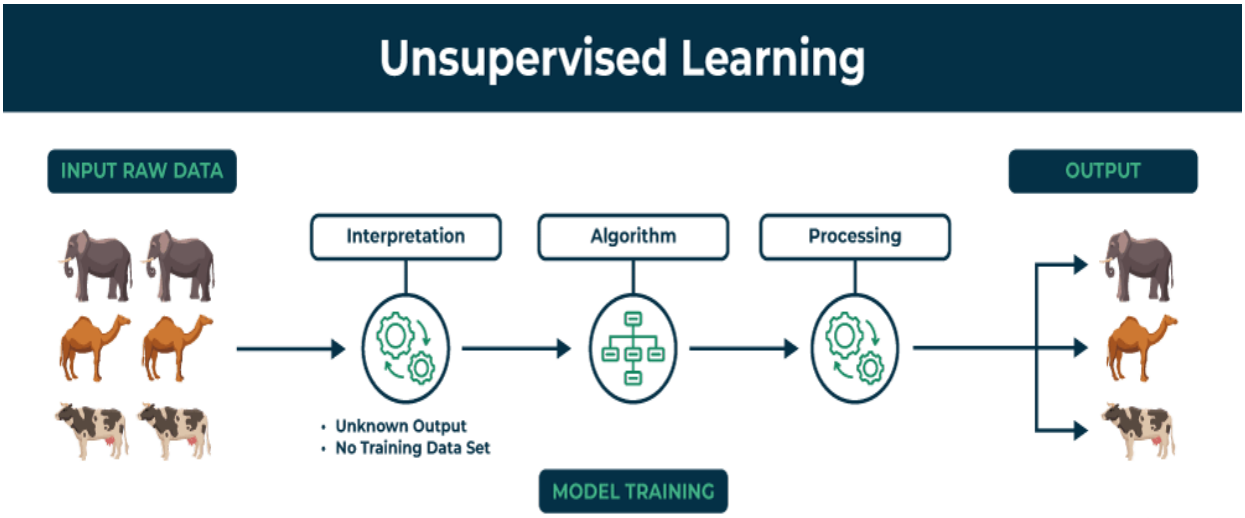

Figure 2: Unsupervised Learning Model.

These techniques have practical applications in identifying variations in meat quality and detecting abnormalities. For example, clustering can be used to group meat samples based on intrinsic characteristics such as texture, moisture, or fat levels, helping to classify them into different quality grades (Ahmed et al., 2021). Anomaly detection is valuable for identifying outlier samples that may indicate spoilage, contamination, or adulteration. Unsupervised learning also assists in exploratory data analysis, allowing researchers and industry professionals to understand the underlying structure of meat-related data without needing predefined categories. This helps improve quality control, product consistency, and safety in meat processing operations.

Reinforcement Learning

Reinforcement learning (RL) is a type of machine learning where an agent learns to make decisions by interacting with an environment (Fayaz et al., 2022). Unlike supervised learning, which relies on labeled data, reinforcement learning works on a system of rewards and penalties. The algorithm continuously improves its performance through trial and error, aiming to maximize cumulative rewards over time. In this process, the model receives feedback based on its actions and uses this information to adjust future decisions. This dynamic learning approach is well-suited for environments where decisions must be made sequentially and adaptively.

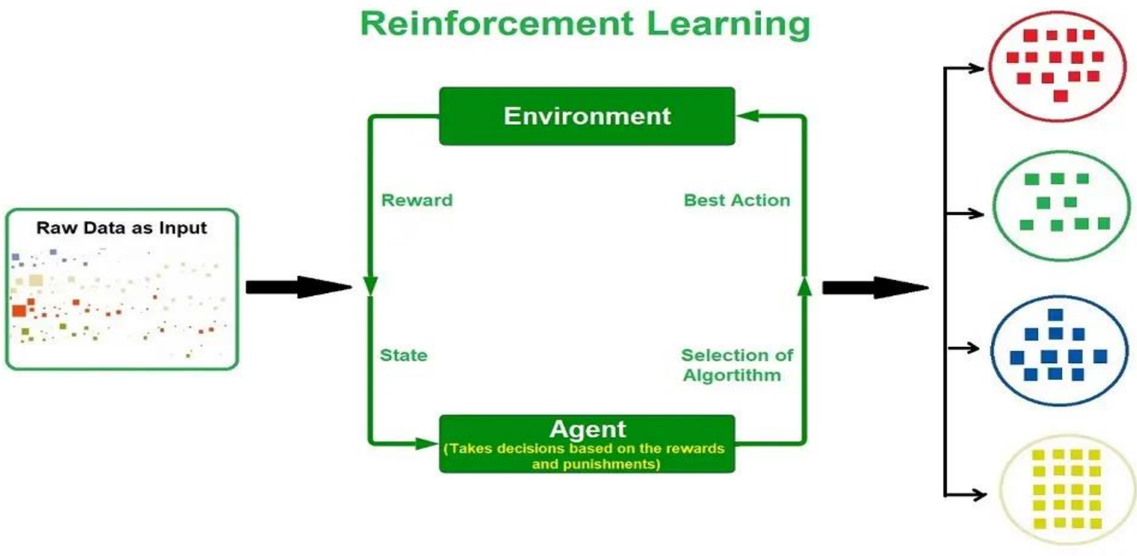

Figure 3: Reinforcement learning Model.

In the meat industry, reinforcement learning is emerging as a powerful tool for process optimization (Rakholia et al., 2025). It can be applied to automate and fine-tune various stages of meat production, such as controlling conveyor belt speed, optimizing cutting techniques, or managing chilling and packaging operations. By simulating different scenarios and learning from outcomes, RL algorithms can identify the most efficient strategies to reduce waste, improve yield, and maintain consistent product quality. Moreover, in smart meat processing facilities, reinforcement learning can integrate with sensors and IoT devices to make real-time adjustments, enhancing both productivity and sustainability (Dayoub et al., 2024).

Deep Learning

Deep learning is a subset of machine learning that involves artificial neural networks with multiple layers capable of learning complex patterns from large datasets (Sarker, 2021). One of the most widely used deep learning architectures is the Convolutional Neural Network (CNN), which excels in processing image and spatial data (Goel et al., 2023). These networks automatically extract features from raw input images, eliminating the need for manual feature selection. By learning hierarchical representations, deep learning models can perform highly accurate classification, detection, and segmentation tasks, making them ideal for visual inspection systems.

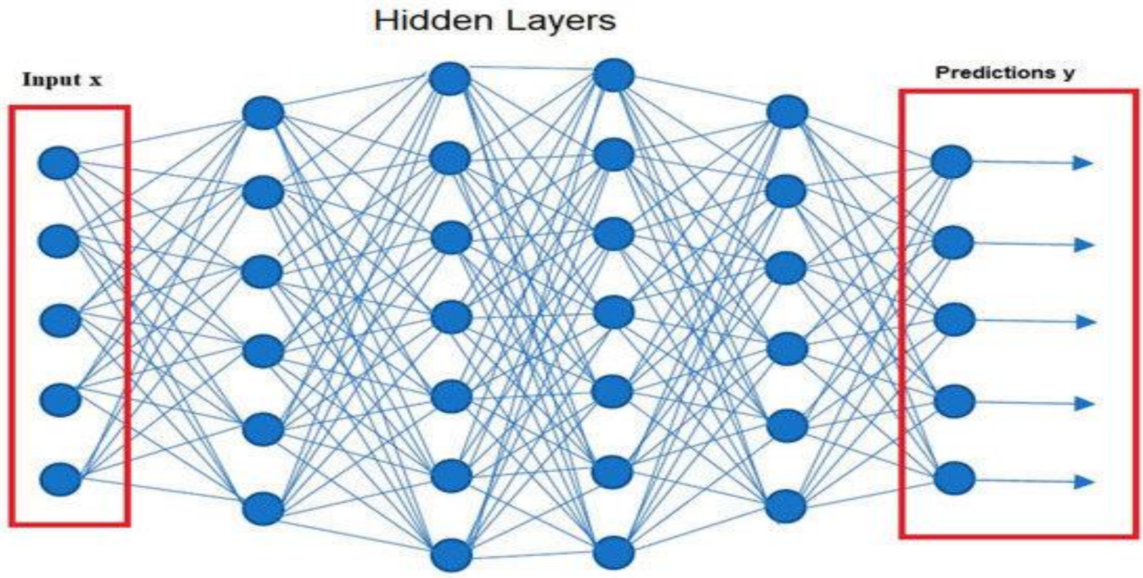

Figure 4: Deep Learning Model.

In the meat industry, deep learning has transformed traditional inspection methods by enabling automated, non-invasive quality assessment (Li et al., 2023). CNNs are used to analyze images of meat cuts to detect defects, classify meat types, assess marbling, and grade overall quality. These models can also identify signs of contamination or spoilage that may not be visible to the human eye. Additionally, deep learning supports robotic vision systems in processing lines, ensuring consistency and speed in sorting and packaging. With continuous advancements in imaging and computing power, deep learning is becoming an essential tool for enhancing efficiency, accuracy, and safety in meat production and inspection processes.

Applications of Machine Learning in the Meat Industry

Figure 5: Application of Machine learning in Meat Industry.

Meat Quality Assessment

Machine learning plays a vital role in predicting and assessing meat quality parameters such as tenderness, flavor, juiciness, texture, color, and water-holding capacity (Kucha & Olaniyi, 2024). These attributes are essential indicators of consumer satisfaction and product value. Traditional quality assessment methods often rely on destructive testing or subjective evaluation by trained panels, which can be time-consuming and inconsistent. Machine learning models, particularly regression and classification algorithms, provide a more objective, rapid, and non-destructive alternative. By analyzing data from NIR spectroscopy, GC-MS, imaging systems, or sensor readings, ML models can accurately estimate the quality characteristics of meat products. This allows meat processors to maintain high and consistent product standards, reduce waste, and meet both regulatory and consumer expectations more effectively.

Supply Chain Optimization

Machine learning is also transforming supply chain management within the meat industry (Amani et al., 2022). ML algorithms are used to predict demand patterns, optimize inventory levels, and manage transportation logistics in real time. For example, predictive models can analyze historical sales data, weather patterns, seasonal demand fluctuations, and market behavior to forecast future demand for different types of meat products. This enables producers and retailers to avoid overproduction, reduce storage costs, and minimize spoilage. Additionally, route optimization algorithms help streamline delivery logistics, ensuring that meat products reach consumers and retailers in optimal condition. As a result, machine learning contributes to making the meat supply chain more efficient, sustainable, and responsive to market dynamics.

Detection of Adulteration and Fraud

Food fraud, particularly meat adulteration, is a significant concern in the global meat industry (Gbashi et al., 2024). Machine learning is a powerful tool for detecting such fraudulent practices by analyzing chemical profiles, spectral signatures, microscopic images, or other physical and biological data. By training classification algorithms on known samples, ML models can accurately distinguish between authentic and adulterated meat, detect the presence of unauthorized species, or identify the addition of non-meat fillers. For example, support vector machines, random forests, and neural networks have been effectively applied to data from GC-MS, DNA sequencing, or hyperspectral imaging to detect subtle differences that are not visible to the human eye. This ensures food safety, traceability, and regulatory compliance, thereby protecting both consumers and producers from health risks and economic losses.

Automation in Processing

Machine learning enhances automation in meat processing, contributing to increased productivity, reduced labor dependency, and greater product consistency (Canatan et al., 2024). Intelligent systems powered by ML are integrated into processing lines to perform tasks such as cutting, deboning, sorting, grading, and packaging with high precision. These systems use data from visual cameras, pressure sensors, and weight scales to make real-time decisions, ensuring that each product meets specific standards. Deep learning models, particularly convolutional neural networks (CNNs), are used for visual inspection, allowing robotic arms to recognize meat types, detect defects, and execute operations without human intervention (Xu et al., 2023). Automation not only improves efficiency and hygiene in meat processing but also addresses labor shortages and reduces the likelihood of human error.

Consumer Behavior and Market Trends

Understanding consumer preferences is essential for staying competitive in the meat industry, and machine learning provides powerful tools to analyze such data (Silveira et al., 2023). ML algorithms process large volumes of consumer information, including purchase history, social media activity, feedback, and demographic data, to identify buying patterns, taste preferences, and emerging market trends. This helps meat producers tailor their product offerings, develop new products, and implement targeted marketing strategies. For instance, clustering algorithms can segment consumers into different groups based on behavior, while predictive models can forecast how trends such as plant-based alternatives, organic meat, or health-conscious diets will evolve. By aligning production and marketing strategies with real-time consumer insights, the meat industry can enhance customer satisfaction and profitability.

Challenges and Limitations of Machine Learning in the Meat Industry

While machine learning (ML) offers transformative potential for the meat industry, its implementation is not without challenges (Paleyes et al., 2022). One of the most fundamental issues is the availability and quality of data. ML models require large amounts of high-quality, well-labeled data to function effectively. However, in many meat production environments, data collection is either insufficient, inconsistent, or lacks proper labeling. Factors such as variations in meat types, breeds, environmental conditions, and measurement instruments can introduce noise and reduce the reliability of the data. Furthermore, historical data may not be digitized or standardized, making it difficult to apply modern ML algorithms without extensive preprocessing and validation. Another significant challenge lies in the integration of ML solutions with existing production systems. Many meat processing facilities rely on traditional equipment and manual labor, which are not always compatible with modern AI or ML-based tools. Integrating ML models into these workflows often requires substantial investment in hardware, software, and employee training. The lack of infrastructure and technical expertise in many regions can further delay adoption. Additionally, ensuring real-time performance of ML systems in a fast-paced processing line, where decisions must be made in milliseconds, presents a considerable engineering and operational challenge.

Ethical concerns and consumer acceptance also present barriers to the widespread use of ML in the meat industry. Some consumers may be wary of automation in food processing, fearing a loss of transparency or the depersonalization of food production. Concerns about data privacy, especially when analyzing consumer behavior or preferences, must be addressed with clear data protection policies. Moreover, ethical issues surrounding the use of animal-based datasets or the potential misuse of AI for deceptive marketing must be handled with regulatory oversight and public engagement to build trust. From a technical standpoint, high computational costs and resource demands can limit the scalability of ML applications. Training complex models, especially deep learning networks, requires powerful computing infrastructure, which may not be accessible to all meat producers—particularly small and medium-sized enterprises. In addition, maintaining and updating these systems over time can be expensive and require continuous technical support, making long-term sustainability a concern for some businesses.

Lastly, the lack of regulation and standardization in the use of ML in the meat industry poses a risk to consistency and safety (Chhetri, 2024). Without clearly defined standards for model accuracy, validation protocols, and performance benchmarks, it becomes difficult to compare results or ensure the reliability of AI-driven decisions. Regulatory frameworks must be developed to ensure that ML applications meet food safety, traceability, and ethical requirements. Cross-industry collaboration will be essential to establish standardized practices, guidelines, and certifications that can support the responsible use of ML technologies in the meat sector (Prasanna et al., 2024).

Future Prospects and Trends

The future of machine learning (ML) in the meat industry is exceptionally promising, with emerging technologies poised to revolutionize the way meat is produced, processed, and consumed (Bidyalakshmi et al., 2024). As computational power increases and algorithms become more sophisticated, machine learning models are expected to achieve greater accuracy, adaptability, and real-time decision-making capabilities. The integration of advanced ML techniques, such as deep learning, transfer learning, and reinforcement learning, will enable more nuanced analysis of complex datasets, allowing for enhanced prediction, classification, and automation across all stages of the meat production chain. These developments will pave the way for more intelligent systems that continuously improve through self-learning and adaptive feedback.

One of the most significant drivers of future ML success in the meat sector will be the synergy between Big Data and the Internet of Things (IoT) (Purnama & Sejati, 2023). Smart sensors, wearable devices on livestock, automated monitoring systems, and cloud-based platforms will generate vast amounts of real-time data, covering everything from animal health and feed intake to environmental conditions and equipment performance. Machine learning models can harness this continuous data stream to monitor operations more closely, detect issues before they escalate, and offer actionable insights (Nyoni, 2025). For example, ML can use sensor data to predict equipment maintenance needs or identify deviations in meat quality early in the production process, leading to proactive and efficient management practices. Sustainability and waste reduction are becoming increasingly important in global food systems, and machine learning offers powerful tools to support these goals in the meat industry. Predictive models can help optimize resource use, such as water, feed, and energy, by analyzing consumption patterns and identifying inefficiencies. Additionally, ML can assist in minimizing product waste through better demand forecasting, inventory management, and dynamic pricing strategies. In meat processing, intelligent systems can reduce trimming waste and ensure more accurate portioning, thereby maximizing product yield and reducing unnecessary loss. These innovations contribute not only to economic efficiency but also to environmental conservation and corporate responsibility.

Another emerging application of machine learning lies in predictive analytics for disease prevention and meat safety (Wang et al., 2022). ML models can be trained to recognize early warning signs of diseases in livestock based on behavior, physiological data, or environmental factors, enabling timely interventions and reducing the risk of outbreaks. Similarly, ML can enhance food safety by detecting contamination, spoilage, or adulteration risks before products reach consumers (Chhetri, 2024). With the increasing integration of genomic, proteomic, and metabolomic data, machine learning will also play a role in precision breeding and health monitoring, leading to healthier animals and safer meat products. These capabilities are expected to revolutionize biosecurity and traceability, ensuring a more resilient and transparent meat supply chain. Finally, the integration of cutting-edge machine learning technologies with smart farming, sustainable processing, and predictive health analytics marks the dawn of a data-driven meat industry. As these trends evolve, ML will not only boost efficiency and profitability but also help address key global challenges related to food security, environmental impact, and consumer trust.

Conclusion

Machine learning is rapidly emerging as a transformative force in the meat industry, offering innovative solutions across the entire value chain—from farm to fork. By enabling data-driven decision-making, ML technologies are improving the efficiency, accuracy, and consistency of meat production, processing, and distribution. Applications such as meat quality assessment, supply chain optimization, fraud detection, and automation in processing are already demonstrating the tangible benefits of integrating intelligent systems into traditional meat industry practices. Furthermore, ML empowers producers to meet the evolving expectations of consumers for safer, high-quality, and ethically produced meat products. As machine learning algorithms become more advanced and computational power more accessible, the scope for innovation in the meat industry continues to expand. The integration of IoT devices, big data platforms, and real-time analytics is setting the stage for a smarter, more responsive, and sustainable industry. Predictive tools for animal health monitoring, resource optimization, and environmental management are helping reduce waste and improve food safety, contributing to broader global goals such as food security and climate resilience. Finally, the future of the meat industry lies in the successful adoption and scaling of machine learning technologies. While challenges such as data quality, infrastructure limitations, and regulatory concerns remain, the potential for long-term impact is immense. With strategic investment, cross-sector collaboration, and responsible implementation, machine learning will play a pivotal role in shaping a modern, efficient, and sustainable meat industry for the years to come.

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