

Applications of Artificial Intelligence in the Dairy Industry: From Farm to Product Development

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Abstract

The dairy industry faces increasing demand for enhanced productivity, sustainability, and innovation. Artificial Intelligence (AI) has emerged as a transformative tool capable of addressing these challenges by enabling data-driven decision-making across the dairy supply chain. AI integrates machine learning (ML), big data analytics (DA), and predictive algorithms (PA) to optimize processes, improve efficiency, and foster innovation. This review examines the diverse applications of AI in the dairy industry, including dairy farming, processing, and product development. In this context, an overview of AI, including ML, DA, and various algorithms used in these processes, is discussed. A major discussion has been provided on AI for animal performance (e.g., disease detection, reproductive management, milk yield enhancement, nutrition) and sustainable practices (e.g., emission control, precision farming). Furthermore, AI in dairy processing (quality control and process optimization) and product development (flavor and texture prediction, and customized products) has been developed. Finally, the challenges of AI integration, including data privacy, ethical considerations, and technical barriers, are reported. The findings indicate that AI revolutionizes traditional practices by enabling precise farming, energy-efficient processing, and the creation of customized, high-quality products. Despite its transformative potential, challenges, such as ethical concerns and technological limitations, must be addressed.

Keywords: Artificial intelligence, Dairy, Industry, Precision farming, Process, Sustainability

1. Introduction

The integration of AI into the dairy industry is rapidly transforming traditional practices across the entire value chain, from farm management to product development. Milk is one of the most nutrient-dense food sources and plays a critical role in global nutrition. Global milk production has exceeded 936 billion kg (approximately 900 billion liters), playing a crucial role in providing essential nutrients while supporting nearly 250,000 jobs, representing 7% of the global workforce (Hill, 2024). The market is expected to surpass \$860 billion by 2024, with projections indicating growth to over \$1 trillion by 2028 (Dairy Food Global Market Report (2024)). The dairy food market is poised for growth due to several interrelated factors. These factors underscore a promising trajectory for the dairy market driven by health awareness, technological innovation, and evolving consumer preferences. Considering the growing consumer demand for high-quality dairy products, the industry is facing pressing challenges related to productivity, sustainability, and animal welfare. Hence, the adoption of AI and Internet of Things (IoT) (refers to a network of interconnected physical devices embedded with sensors, software, and other technologies that enable them to collect and exchange data over the internet) technology could improve tracking and handling of dairy products, thereby ensuring compliance with safety standards.

AI technologies, including ML, deep learning (DL), and data analytics (DA), offer unprecedented opportunities for enhancing operational efficiency and fostering innovative practices. These advancements have enabled real-time data collection and analysis, facilitating improved herd management through health monitoring (Aravamuthan et al., 2024) and reproductive performance assessments (Cho and Kim, 2023). Moreover, AI applications extend beyond farms to encompass dairy processing and product development (Freire et al., 2024). From quality control and defect detection to optimizing processing techniques and predicting flavor

profiles (Li et al., 2024; Yi et al., 2024), AI's capabilities are reshaping the landscape of dairy manufacturing. Key components of AI, such as ML, DL, natural language processing, and computer vision, are being applied specifically to daily operations. Big data refers to vast and diverse data generated from various sources, characterized by high speed, density, and dimensionality. This necessitates specialized technologies for storage, processing, and analysis tailored to dairy production. In the dairy sector, big data analytics enhances market demand predictions (Seyedan and Mafakheri, 2020), optimizes supply chains (Trollman, 2024), and improves both food safety and product quality, offering significant competitive advantages. Moreover, big data analytics enables dairy companies to extract valuable insights into market trends and consumer preferences (Nozari et al., 2021), allowing for optimized operations (Malik et al., 2022) and reduced waste (Hassoun et al., 2024).

However, the current literature has been scattered across various aspects of AI in the dairy industry, while some review article focuses on specific concepts as mentioned above. The current article identifies this gap and provides a comprehensive review of AI applications in the dairy industry, covering its role in farming, processing, and product development. It integrates insights from ML, big DA, and PA to illustrate how AI enhances efficiency, optimizes processes, and drives innovation. Unlike existing literature, this review consolidates diverse AI applications across multiple domains, offering a structured analysis of AI's impact on dairy production. Key areas of focus include AI-driven animal performance optimization (e.g., disease detection, reproductive management, and milk yield prediction), sustainable practices such as emission control and precision farming, and AI applications in dairy processing for quality control and efficiency improvements. While the manuscript does not introduce entirely new frameworks, its contribution lies in synthesizing current applications, identifying sector-specific challenges, and

outlining future research directions. Also, challenges, technical barriers, and limitations in AI implementation in the dairy industry have been highlighted.

2. Method of search

A structured literature search was performed using electronic databases, including Google Scholar and PubMed, to identify relevant studies, reviews, and publicly available sources. A broad range of search terms was employed, including but not limited to "Artificial Intelligence in dairy farming," "machine learning in dairy industry," "big data in dairy production," "AI for milk yield optimization," "AI in dairy product development," "precision farming and AI," etc were used. The searches yielded approximately 200 scholarly sources, out of which 150 were shortlisted based on relevance, date published, and language. After a thorough screening process, 110 sources were utilized in the preparation of this manuscript. Inclusion criteria emphasized studies with clear AI applications in dairy production, innovation, or sustainability, while excluding those with limited relevance or lacking empirical basis. The selected literature was critically analyzed to identify key trends, advancements, and challenges associated with AI implementation in the dairy industry. A broad discussion on AI's role in dairy farming, sustainability, quality assurance, and product development has been documented.

3. Overview of AI and AI algorithms in Dairy

AI refers to the capability of machines and computers to mimic human abilities, such as learning, understanding, problem-solving, decision-making, creativity, and autonomy. AI can be broadly classified into three categories: narrow AI (ANI), general AI (AGI), and super AI (ASI). In addition, AI algorithms can be categorized into supervised learning, unsupervised learning, and

reinforcement learning (**Figure 1**). In the dairy sector, AI algorithms are particularly important for boosting productivity, enhancing quality control, and managing resources effectively (Balhara et al., 2021). By utilizing ML, DA, and other AI technologies, dairy farms and companies can better manage livestock, predict yields, maintain product quality, and minimize waste. The dairy industry faces numerous challenges, including fluctuating milk prices, disease outbreaks, and demand for sustainable farming practices. AI technologies provide solutions through real-time data analysis, predictive insights, and automated processes (Sharma et al., 2021). For example, ML algorithms can identify patterns in milk production and detect anomalies that may indicate health issues in cows (Wagner et al., 2020). Furthermore, AI can automate milking processes, reduce labor costs, and increase operational efficiency (Kumar et al., 2024). By integrating AI, the dairy sector can enhance productivity, improve animal welfare, and achieve improved economic outcomes. ML algorithms analyze large datasets collected from sensors and IoT devices on farms to predict optimal feeding times, detect disease outbreaks, and forecast milk yields based on historical data (Neethirajan, 2020). DL, a subset of ML, is used to understand complex patterns, such as animal behavior or environmental changes that impact milk production (García et al., 2020). Computer vision algorithms are employed for tasks such as automated monitoring of cows' body condition and gait analysis, enabling the early detection of lameness or other health issues (Silva et al., 2021). In addition, natural language processing (NLP) algorithms assist in managing farm operations by automating documentation and interpreting spoken instructions and notes (Nayak and Sowmya, 2021). Collectively, these technologies enable a data-driven approach to dairy farming, thereby enhancing precision and efficiency. Automated milking systems use AI to schedule and control milking sessions based on individual cows' production cycles and health status, which maximizes milk yield and enhances cow comfort (Zhang et al., 2023a). Precision feeding systems, guided by

AI, optimize feed composition and delivery based on real-time data about each cow's nutritional needs and milk production levels (Bhardwaj et al., 2023). Additionally, quality control can be improved through AI systems that monitor milk quality throughout the production process, ensuring compliance with health and safety standards (Neethirajan, 2020). As these technologies continue to evolve, the dairy industry is poised to become more sustainable, efficient, and responsive to consumer demand.

4. AI in Dairy Farming

4.1 AI for Animal Performance

AI assessed the dairy animal performance such as milk yield and quality, feed intake, estrous detection, pregnancy detection, disease prevention, diagnosis, and treatment (Slob et al., 2021). The use of AI in the management of animal health, nutrition, and production during intensive farming may lead to a reduction in human interference in different operations, thus reducing the cost of production, ease, and accuracy of operations, and minimizing the chances of the spread of zoonotic diseases.

4.1.1. Animal health

Timely detection, prevention, and treatment of prevalent diseases are of the utmost importance to safeguard the health of animals, farm workers, and nearby populations. The prevalence of diseases in dairy farms and production activities is inversely proportional. AI might be a very important tool for the prediction of disease outbreaks, diagnosis (Fuentes et al., 2022; Kour et al., 2022), patient monitoring, medical device automation, and record keeping (Bohr and Memarzadeh, 2020). AI can analyze a large set of epidemiological data and recognize specific patterns, thus helping to

predict disease in animal farms (Ezanno et al., 2020). The AI can empower and complement animal healthcare workers in animal disease prevention, diagnosis, and treatment (Pillai et al., 2022). Automation in the medical field and high-end equipment, such as X-rays, CT scans, and magnetic resonance imaging (MRIs), have been used to create AI-powered algorithms that accurately analyze medical images. This technology helps veterinarians/health workers efficiently predict, diagnose, and treat various diseases (Yoo et al., 2022). The use of AI and radionics in diagnosing animal disease through images is emerging for early diagnosis (Bouhali et al., 2022). AI-based tools like Natural Language Processing (NLP) are used for analyzing a large set of data or text related to clinical cases, which helps in the interpretation of data and gives suitable therapeutic decisions. Xiao et al. (2025) stated that NLP technology is advantageous in veterinary medicine, especially in rural and underdeveloped areas. Xiong et al. (2025) developed an AI-based model named SheepDoctor for disease diagnosis, which is based on a pre-set question-answer dataset. This model was coupled with LLaMA2–13B-Chinese model (a large language model) and a knowledge graph to enhance the efficacy of disease diagnosis in sheep.

Digital twin (DT) technology creates the virtual shadow of the cows (Purcell and Neubauer, 2023). This technology helps in the management of the cow herd through predicting the possible occurrence of disease, health, and feeding monitoring (Tao et al., 2022). Zhang et al. (2023b) developed a DT model for the prediction of cow behavior using an intelligent collar to receive data. This data was analyzed using different AI tools such as Long Short-Term Memory (LSTM) models and K-Nearest Neighbor (KNN). Also, MLA can be employed to generate real-time 3D faces of animals as a virtual DT (Neethirajan and Kemp, 2021). Using this virtual data, farmers can analyze the animal behavior, stress, and early signs of pain or disease. Han et al. (2022) utilized the sensor data from a cattle farm IoT system and developed a DT model using DL. The model not

only enables monitoring the physiological cycle of cattle, but also predicts the next state of the physiological cycle. The developed DT model has high accuracy with a loss of error of 0.580 (Han et al., 2022). Digital health interventions (DHI) are another AI-based tool that enables an expert to handle a large number of clinical cases in animals (Funk et al., 2020). Benis et al. (2023) applied the model of One Digital Health Intervention (ODHI) for monitoring animal and human health and well-being in small cities. The various AI-based technologies utilized for disease prediction, diagnosis, treatment, vaccine delivery, gene editing for disease prevention, and control of parasitic infestations are presented in **Table 1**.

Farm animals produce different types of sounds to show their behavior and feelings. Recording and processing of these sounds using machine learning is useful for the welfare and health monitoring of animals (Caiger et al., 2020). Researchers from the Department of Biology, University of Copenhagen, used a machine learning algorithm (eXtreme Gradient Boosting [XGBoost]) to differentiate between the pleasant and unpleasant sounds produced by different farm animal species with an accuracy of 89.49% (Lefèvre et al., 2025). The audio processing technology (APT) can also predict the grazing behavior of animals by analyzing the grasping, cutting, chewing, and rumination sounds during pasture feeding. Martinez-Rau et al. (2025) demonstrated the Noise-Robust Foraging Activity Recognizer (NRFAR) based on the events of jaw movements during grazing and rumination in cattle with an accuracy of 86.4% in predicting the grazing behavior. Hegde et al. (2024) also analyzed the cough sounds produced by the animals for the diagnosis of respiratory disorders. Moreover, ear tags with electronic identification, collars with GPS (global positioning system) integrated with DT could be used to assess animals' movement, habitat selection, health, and welfare (Herlin et al., 2021). Additionally, DT-based

virtual fencing has potential for precise animal grazing using an audio signal coupled with a weak electric shock (Herlin et al., 2021).

4.1.2. Reproduction

AI and other automation techniques such as ML (biosensors, activity meters, video cameras, microphones, etc.), have been reported in the field of animal reproduction, especially for the detection of estrus, evaluation of semen quality, use of sexed semen for artificial insemination, and early prediction of fertility in female animals (Reis et al., 2024). Wang et al. (2024) investigated the backpropagation neural network (BPNN) algorithm integrated with the number of hidden layer neurons and learning rate to detect estrus onset in dairy cows based on acceleration and location data acquired by a neck-tag. Seven behavioral matrices, including duration of standing, lying, walking, steps, displacement, switching time between standing and walking, and number of standing mounts, were used to differentiate the activities before and after estrus (wang et al., 2024). The developed BPNN algorithm showed 95.46% of accuracy, 72.80% of precision, 98.29% of sensitivity, 95.08% of specificity, and 83.65% of F1 score, respectively (wang et al., 2024). Recently, Lei et al. (2025) developed a 3D convolutional neural network (3D-CNN) based on video data from the sow estrus cycle and analyzed four physiological behaviors including; fence-biting during the estrus cycle (SOB), head stillness and ear erect posture during estrus (SOS), sniffing boar pheromones during estrus (SOC), and significant head swinging during estrus (SOW). The results indicated a high level of accuracy, recall, and F1 score for all four behaviors based on the 3D-CNN model (Lei et al., 2025). These findings provide a practical solution for rapid video-based behavior detection and welfare monitoring. Besides this, body and vulvar temperature, posture recognition, and activity measurements provide higher precision information

related to estrus detection (Sharifuzzaman et al. 2024). However, future work should focus on minimizing the misclassification rate to improve the detection system. Various AI techniques utilized to improve dairy reproduction are presented in **Table 1**.

4.1.3. Milk production and quality analysis

The profitability of dairy farms depends primarily on the production of high-quality milk. Predicting future milk production is important to estimate the revenues from the sale of milk and any possible outbreak of disease (Liseune et al., 2021). Large dairy farms are adopting AI technologies for the prediction of the milk production potential of the herd (Slob et al., 2021), daily recording of milk production (Denholm et al., 2020), lactation days, dry period, milking of animals, circulation of milk to the storage tanks, analysis of the quality of milk produced (proximate composition, somatic cell count, adulteration, etc.) (De Vries et al., 2023), and monitoring the storage conditions of milk. Fully automated dairy farms have robots to guide the animals to milking pens, proper teat placement in the milking machine using lasers, and the use of self-driving cars for the transfer of milk and fodder inside the farms (De Vries et al., 2023).

4.1.4. Nutrition

Modern dairy farms use AI and DA for the smart feeding or precision feeding of individual animals as well as herds. Common AI used in animal nutrition include animal activity sensors for detecting the health status of animals, evaluating the proximate composition of feed in real time, optimizing feed formulations for individual animals as well as for herds, calculation of fodder required to date, monitoring feeding behavior of animals, ensuring proper feed intake (Lee and Seo, 2021), programming for concentrate and roughage feeding (Fuentes et al., 2020), analysis of excreta, and

analysis of milk production and composition to reveal any nutritional deficiency and excess (Curti et al., 2023).

4.1.5. Animal waste disposal

Artificial intelligence techniques can also be effectively utilized for dairy farm cleaning through manure collection, processing, and disposal of animal waste. An automated waste collection system involves vacuum collection systems, robotic systems, automated scrapers, and flush systems. Automated vacuum collection systems involve a pipeline below the floor and vacuum systems to collect the waste generated from the farm and its transportation to the processing area (Farré et al., 2023). Robotic systems are also used to carry out various dairy farm cleaning operations that include automatic manure collection (Sun et al., 2024), mechanical scrapers (Nielsen et al., 2023), spraying of decontaminants and sanitizing agents (Feng et al., 2021), and real-time monitoring of cow dung composting (Ren et al., 2023). Utilization of AI-based technologies for the animal farm cleaning and sanitation causes minimal human-animal interaction, time saving, and increased efficiency of operations.

4.2. AI for Sustainable Innovations

Milk is responsible for 2–3% of anthropogenic emissions, approximately 10% of food emissions, and 20% of livestock emissions (Hill, 2024). Consequently, significant research has been directed toward reducing methane emissions from livestock, including the reduction of enteric methane. AI can be an enabler of many sustainable innovations.

4.2.1. Dairy Methane Emissions

AI has been employed to detect, estimate, and predict dairy methane emissions. Enteric fermentation is the most significant contributor to methane emissions from dairy cows. AI techniques for predicting methane emissions based on various inputs include multiple linear regression, support vector regression, random forest regression, and Artificial Neural Networks (ANNs) (Ghassemi Nejad et al., 2024). The three main data collection methods based on AI models at the farm and region levels are aerial imagery processing, deep learning image segmentation, and dairy facility area estimation (Jeong et al., 2022). AI prediction of herd size from aerial imagery has been used to provide a low-cost alternative to human visual inspection, which can then be used to estimate enteric and manure methane emissions (Jeong et al., 2022). At the farm level, AI has been used to predict methane emissions based on surface and animal feed characteristics (Wang, 2023). Methane emissions can also be predicted from animal information such as diet, genetic factors, and lactation stage. **Figure 2** illustrates the steps for developing an AI model for measuring methane emissions from dairy cows. Feature selection or extraction may be required to reduce dimensionality (Trollman, 2024). ML in vitro rumen models have proven valuable for quantifying rumen fermentation parameters (Wang et al., 2024). A stacking ensemble learning method has been used to successfully simulate the transition of rumen fermentation type and the change in methane content under different concentrate-to-forage ratios of total mixed rations (Wang et al., 2023).

However, AI-based methane emission reduction in the dairy industry faces several challenges, including data gaps, computational constraints, limited model generalization, economic feasibility, and regulatory barriers. AI models require large, high-quality datasets, but methane emission data are often incomplete or inconsistent, affecting model reliability (Ross et al.

2024). Ross et al. (2024) proposed a simulation system that replicated dairy cattle methane emission experiments to address the problem of insufficient datasets for predictive AI models. DL models also demand significant computational power, which can be a barrier for smaller farms. Additionally, AI models trained on specific datasets may not adapt well to varying farm conditions, limiting their scalability. High implementation costs could further hinder adoption, while the absence of standardized regulatory frameworks complicates AI integration. To address these challenges, several implementation strategies can enhance AI adoption in methane management. While cloud and edge computing reduce computational burdens, making AI accessible to smaller farms, collaborative data-sharing platforms can enhance dataset quality and model robustness. Developing scalable, cost-effective AI solutions tailored to different farm sizes can increase adoption, and policy support through financial incentives and regulatory frameworks can drive implementation. AI offers powerful predictive capabilities for methane emissions using diverse data sources and modeling techniques. While promising in reducing environmental impact, challenges such as data scarcity, computational demands, and lack of scalability remain. Addressing these with collaborative, cost-effective, and policy-supported strategies will be key to advancing AI-led emission management in the dairy sector.

4.2.2. Emission Management and Energy Efficiency

Net-zero farming relies on the transformative potential of AI and big DA to enhance the environmental sustainability of dairy farms (Neethirajan, 2024). When complete data from individual animals is not available, state-of-the-art techniques for imputation and advanced ML algorithms can be used for predictive modeling (Negussie et al., 2022). ML can provide emission management solutions that include carbon emissions for better planning on smart farms (Silva et

al.). Macro-level dairy energy statistics can be obtained from artificial neural network models to calculate the effectiveness of government policy changes that affect grass-based milk producers (Shine et al., 2022).

4.2.3. Precision Farming

Precision farming relies on digital technologies to advance animal farming automation towards economic and environmental sustainability (Yaseer and Chen, 2021). In addition to reducing methane emissions, product quality and animal welfare should be improved. Continuous and reliable data are required to obtain optimal results. In the case of grazing over long distances, data collection, as well as the identification of low-cost, highly accurate cow behavior estimation devices with long battery life, becomes problematic. The proposed solution is TinyCowNet, a cow behavior distribution regression with Recurrent Neural Networks (RNNs) for estimating mixed-label sample spaces (Bartels et al., 2022). Behavior monitoring in stalls facilitates improved monitoring of animal health. A time-driven embedded sensor attached to the back of a dairy cow containing a machine learning model has been proposed with promising classification rates and energy consumption (Achour et al., 2022). A computer vision AI model has been trained to detect digital dermatitis in dairy cows on an edge device, demonstrating high performance and speed in support of real-time detection of health outcomes in precision farming (Aravamuthan et al., 2024).

Incorporation of AI in dairy farming has brought about revolutionary progress in key areas like animal health, reproduction, milk yield, diet, and sustainability. AI-driven solutions enable timely disease detection, enhance reproductive performance, maximize milk volume and quality, and enable precision feeding approaches, all in the service of greater productivity and animal welfare. In addition, AI is critically positioned to address environmental challenges by ensuring

proper predictions and regulation of methane emissions, energy usage, and precision farming methods. Irrespective of concerns over the quality of data, the high computationally demanding nature, and scalability issues, AI presents an effective model for driving innovation and sustainability in dairy farming. The integration of AI in processing represents the next critical phase in the dairy value chain, where intelligent systems are reshaping traditional practices.

5. AI in Dairy Processing

AI technologies are becoming integral to modern dairy production, providing real-time insights, automating processes, and reducing operational costs (Alwadi et al., 2024; Hassoun, Garcia-garcia, et al., 2023; Hassoun, Jagtap, et al., 2023).

5.1. Quality control and inspection

AI, such as computer vision and sensor-based monitoring systems, plays a crucial role within the broader framework of Industry 4.0. These technologies significantly enhance the quality control in dairy processing by enabling real-time monitoring and precision analysis. As a result, they not only improve product quality but also reduce waste and transform by-products into valuable resources (Hassoun et al., 2024; Oztuna Taner and Çolak, 2024).

5.1.1. Computer vision for defect detection in dairy products: AI systems analyze dairy products for defects such as irregularities in texture, color, or shape, which may compromise the quality of dairy products. These systems offer high-speed, accurate detection capabilities that far exceed those of traditional manual inspections, ensuring that only products meeting strict quality and authenticity standards are delivered to consumers (Konstantinidis et al., 2023). For example, in a

recent study, it was shown that computer vision can be used for defect detection in the high-efficiency defect inspection prototype for dairy plastic cutlery by leveraging advanced image recognition algorithms to identify inconsistencies or flaws in products (Yang et al., 2024). By integrating deep learning models, such as You Only Look Once (YOLO), computer vision systems can detect even small defects in real time, such as irregular shapes, discolorations, or contamination, during the production process. This automated system not only improves inspection accuracy but also significantly reduces labor costs and enhances production efficiency.

5.1.2. Sensor-based monitoring systems of dairy products: AI integrated with sensor technology allows the continuous monitoring of critical parameters, such as temperature, humidity, and pH, during the production and storage of dairy products. This ensures that every stage of the process meets predefined standards and safety criteria, reducing waste and minimizing the risk of contamination or spoilage (Dragone et al., 2024; Fernández González et al., 2024).

Computer vision and sensor-based technology are transforming dairy processing quality control with AI technologies. These systems provide real-time monitoring and high-precision detection of product defects, improving safety, consistency, and reducing waste. They also help regulate environmental and product parameters throughout manufacturing and storage, ensuring compliance with hygiene and quality standards.

5.2. Optimization of processing techniques

AI is also transforming the operational aspects of dairy processing by optimizing production techniques and equipment maintenance.

5.2.1. Process control: By analyzing vast amounts of real-time data, AI can adjust processing parameters, such as temperature, pressure, and timing, to optimize yield, energy usage, and dairy product quality. This dynamic process control ensures efficiency, consistency, and authenticity while also reducing resource consumption in the dairy sector (Oztuna Taner & Çolak, 2024). For example, it was found that AI applied to the enzymatic hydrolysis of lactose can improve the control of industrial processes by indirectly estimating lactose concentration using an algorithm that associates cryoscopy and glucose concentration (dos Santos et al., 2022).

5.2.2. Predictive maintenance in dairy equipment: Predictive maintenance powered by AI uses ML algorithms to analyze data from equipment sensors. It predicts when machinery is likely to fail or require maintenance, provides an automated food safety early warning system, and enables proactive repairs that reduce downtime and extend the life of dairy processing equipment (Lee et al., 2022; Neethirajan, 2024).

6. AI in Product Development and Innovation

6.1. Flavor and Texture Prediction

AI can assist in analyzing sensory characteristics, such as taste, aroma, and texture, in a variety of food and beverage products. By utilizing extensive datasets of sensory evaluations, ML can be trained to recognize patterns and relationships among different sensory features. Furthermore, AI has the potential to be used to investigate the molecular structure of ingredients and their influence on flavor, focusing on the presence and concentration of specific compounds that affect taste and smell. Additionally, AI can enhance the analysis of intricate chemical data by integrating techniques, such as spectroscopy and chromatography.

6.1.1. Machine Learning for Taste Profiling

Food flavor includes the total experience of tasting food, which is primarily driven by smell and taste. It plays an important role in identifying factors, such as type, geographic origin, ripeness, spoilage, and overall sensory quality, which ultimately shape consumer preferences during food consumption. It also serves as an important metric for food production. Thus, the effective prediction and management of flavors are essential for quality enhancement. To meet consumer demand for safe and high-quality food products, the industry must establish robust standards and procedures for quality control. However, challenges arise from the nonlinear nature of the variables, such as inconsistent raw materials and processes. Therefore, developing AI tools for food supply chains is essential to enhance the monitoring of both processes and products. Advances in computational techniques and growing data in this area have made ML models valuable for accurately predicting and regulating food flavors (Bouysset et al., 2020). Utilizing ML to predict and regulate food flavors can enhance flavor promotion and boost consumer acceptance of new products. Additionally, this approach can help prevent food adulteration and ensure quality, thereby drawing significant interest in the overall advancement of the food industry. While recent research has focused on ML applications in areas like food origin, type, quality, storage duration, and authenticity, there is still a lack of studies specifically addressing ML's role in flavor prediction and regulation (Jiménez-Carvelo et al., 2019).

Predicting and understanding food perception and appreciation are significant challenges in food science. Qiu et al. (2024) developed logistic regression classification models to predict yogurt aroma types based on aroma-active compound concentrations, achieving a high classification accuracy. The key indicator compounds identified from the feature importance

analysis enabled the formulation of the classification criteria for yogurt aromas. These findings establish an automated pipeline for monitoring the sensory properties of yogurts. Another study by Chen et al. (2018) investigated the link between untargeted SPME-GC/MS data and the sensory fishiness of dairy powders fortified with long-chain polyunsaturated fatty acids and iron. Using a machine learning approach with a Random Forest model, sensory predictions were made directly from the GC/MS data without prior peak identification. Accurate predictions were achieved with key peaks linked to fishiness identified as alcohols, ketones, aldehydes, and furans. Bi et al. (2022) proposed a study that developed an intelligent optimization framework utilizing a previously proposed deep convolutional autoencoder (DCAE) model to design a yogurt product based on sensory evaluation attributes. The DCAE, which combines a convolutional neural network and an autoencoder, identifies key features from sensory heat maps, whereas a support vector machine (SVM) model regresses the liking attributes from these features. The optimization employs a hybrid genetic algorithm and particle swarm optimization to determine the global optimal liking attributes, which are then converted into sensory attributes through the DCAE decoder, demonstrating the effectiveness of the approach with yogurt samples under various storage conditions.

6.1.2. Texture Analysis and Modeling

Texture is a key image feature that has been extensively applied in the food industry to evaluate quality and conduct inspections. The complex structure of food makes it difficult to incorporate into mathematical models that predict its characteristics and variations (Mengucci et al., 2022). Texture is a key factor in yogurt acceptance and quality control, but measuring it often requires expensive equipment. To address this, artificial neural networks (ANNs) have been developed to

predict yogurt texture properties based on the formulation and processing conditions. The models demonstrated high accuracy ($R^2 > 0.95$) and low error rates, highlighting their potential for effectively evaluating yogurt properties in a study by Batista et al. (2021). In another study, thirty-six samples of low-fat mozzarella cheese were produced under varying thermomechanical properties and storage conditions, and their textures were analyzed using texture profile analysis (TPA) and hyperspectral imaging. The results showed that increased stretching time improved hardness, springiness, gumminess, and cohesiveness, while reducing adhesiveness. Various calibration models indicated that the majority vote algorithm performed best in predicting hardness, while random forests excelled in adhesiveness prediction, confirming the effectiveness of hyperspectral imaging using machine learning methods for assessing mozzarella's textural properties (Jahani et al., 2024). ML can learn from data without using explicit programming. In recent decades, advancements in machine learning have enabled rapid hyperspectral image analysis, allowing for the creation of spectral libraries and the real-time application of hyperspectral imaging systems (Khojastehnazhand et al., 2014). With advancements in computational power, AI has been used to address a wide range of engineering problems, including ML and DL. Understanding the distinction between ML and DL is crucial, as they are often mistakenly used interchangeably despite being different subsets of AI. Both methods are effective in modeling the flow and textural properties of liquids and semi-solids, particularly for foods with complex viscoelastic behaviors (Ahmad and Benjamin, 2023). A study compared the predictive capabilities of multiple linear regression (MLR) and artificial neural networks (ANN) for assessing the quality of spreadable Gouda cheese stored at 8, 20, and 30 °C. Both models showed high determination coefficients (R^2 ranging from 0.87 to 0.99), with the ANN model outperforming MLR in accuracy, particularly for cheese stored at 8 °C. These findings suggest that the ANN

model is more effective for predicting quality deterioration, making it valuable for food safety and quality assessments (Stangierski et al., 2019).

Machine learning algorithms process sophisticated sensory and chemical information to precisely predict and improve the flavor and texture profiles of dairy products. AI applications assist manufacturers in customizing products to suit the preferences of consumers, achieve product consistency, and minimize the reliance on conventional sensory analysis.

6.2. Customized Product Formulation

The process of new product development in the dairy sector is complex and continually evolving, driven by consumers' changing preferences and the demand for specialized products, such as lactose-free options, probiotic-rich products, and enhanced nutritional profiles, such as high-protein and low-fat variants. With rapid advancements in technology, new food processing methods and advanced equipment are changing the development of products. AI is now essential in many areas of food product development, from generating ideas to packaging and managing the supply chain (Kumar et al., 2021). Using AI, companies can improve product quality, streamline production, and respond quickly to consumer needs. This integration enhances the overall efficiency and innovation in creating new food products. AI has various applications in market research, utilizing consumer insights to drive idea generation and concept development. For instance, Goli et al. (2021) analyzed economic and social indicators to determine the significant variables that drive the demand for dairy products in Iran. Similarly, Li et al. (2024) examined the use of an ML method called Latent Dirichlet Allocation to identify consumer sensory preferences that can inform new product development. The researchers gathered large datasets from online product reviews, enabling the algorithm to evaluate both sensory preferences, such as taste, texture,

aroma, and non-sensory preferences, including nutritional benefits and packaging. After determining these preferences, the data was used to design products that would enhance consumer satisfaction, ensuring that new offerings align with the desired product qualities.

AI is increasingly being used to develop innovative intelligent packaging solutions in the food industry, particularly for dairy products (Abekoon et al., 2024). These intelligent packaging systems integrate embedded sensors and various advanced technologies to continuously monitor critical factors that are essential for maintaining the quality and safety of dairy items, including temperature, humidity, and freshness. This advanced technology plays a significant role in determining optimal storage conditions and effectively minimizing food waste throughout the supply chain. It also enhances the overall consumer experience by providing detailed information on the nutritional content and sustainability practices of the product. This information can be accessed by consumers by scanning QR codes on the packaging. This technology not only improves user engagement but also allows for effective traceability, enabling consumers to track the journey of a product from its source to shelves and providing transparency and trust in the food supply chain. Food quality, including the quality of dairy products, can be evaluated by analyzing various components, such as carbohydrates, fats, and proteins (Li et al., 2024). Additionally, moisture content and functional ingredients, such as catechins, caffeine, polyphenols, and anthocyanins, play a significant role in determining food quality. AI and ML technologies can quantitatively assess these components using algorithms, such as linear discriminant analysis (LDA), partial least squares-discriminant analysis (PLS-DA), decision trees, and random forests (RF). These methods analyze the molecular structures of compounds using advanced spectrometry techniques, including hyperspectral imaging (HSI), near-infrared (NIR), visible-near-infrared (Vis-NIR), and mass spectrometry (Yi et al., 2024). Food safety is assessed by measuring the levels

of various contaminants, including pathogens, pesticides, toxins, and heavy metals. AI and ML are instrumental in detecting foodborne pathogens such as *Escherichia coli*, *Staphylococcus aureus*, *Listeria monocytogenes*, and *Salmonella*, as well as fungal toxins such as aflatoxins and heavy metals such as lead, mercury, cadmium, and arsenic. Thus, AI and ML effectively contribute to the measurement of both food safety and quality.

7. Challenges and Future Perspectives

Unlike other techniques, AI has several challenges and limitations to overcome for its implementation (**Table 2**), ranging from

Technological barriers: Although AI offers significant benefits to the dairy industry, several technological barriers can impede its widespread adoption. Technical knowledge and expertise are major obstacles in AI systems. Specialized knowledge is mandatory for proper implementation and efficient operation. Workers should be skilled and trained so that future problems can be tackled without impacting the entire process. If this is not properly considered, the adoption of AI in the dairy industry can be hindered.

Cost of implementation: One of the main factors that is prohibitive for most dairy farmers is the high initial investment in acquiring and maintaining AI technologies. The investment required for AI technologies, including hardware, software, and training, can be a barrier, particularly for smaller farms with limited budgets. Because the margins are very thin for food companies, the cost factor plays a crucial role. This is the point at which most concerns are raised. The cost factor will be viewed with great concern by most farmers because this technique is new to the industry.

Need for comprehensive and high-quality datasets: ML models depend on extensive and diverse datasets to generate accurate predictions. However, the availability of such high-volume, high-quality, dairy-specific data remains limited. Furthermore, real-time processing of large datasets presents additional challenges, as ensuring data quality in real-time applications requires robust infrastructure and sophisticated data cleaning protocols. Addressing this data gap is essential for the reliable application of ML in predicting key indicators, such as herd health, productivity trends, and resource optimization.

Ethical considerations and animal welfare concerns: The proper collection of data in AI implementation requires constant monitoring of animals, which could be a potential source of intrusion into their natural behavior. In addition, the data collected should be shared and handled ethically to ensure that this is beneficial for farm sustainability and, most importantly, for animal welfare. Completely relying on AI could also alter the traditional human-animal relationship. Therefore, it is crucial to ensure human oversight. Decisions made using AI algorithms should also include welfare matrices that will ensure the health and well-being of animals. Furthermore, the primary considerations are the security of the collected data and privacy concerns.

Connectivity and infrastructure challenges: In many developing regions, limited internet connectivity remains a significant barrier to implementing AI in dairy farming. Adequate connectivity is essential for the real-time data transfer, cloud processing, and remote monitoring of on-farm systems. Investments in digital infrastructure are necessary to facilitate smart dairy farming. Addressing this challenge could provide substantial benefits for dairy farmers, allowing them to access the same AI insights available in more developed regions.

Resistance to change: The industry is accustomed to traditional methods and will be reluctant to adopt the change to modern AI techniques. This could be due to several reasons, including obtaining proper technical training, as well as concerns about job loss due to complete automation.

However, AI is expected to influence every stage of the dairy value chain from farm operations and milk quality monitoring to processing, distribution, marketing, consumption, waste management, and even innovation in research and product development. Based on recent studies, the historical progression of AI in the dairy sector has laid a robust foundation for predicting its future trajectory. Initial automation technologies, such as robotic milking systems, introduced in the late 1990s, marked the first wave of AI-enabling tools, followed by widespread adoption of sensor technologies for real-time monitoring of milk yield, animal behavior, and health. As noted in recent literature, the integration of machine learning algorithms has since enabled predictive analytics for mastitis detection, estrus prediction, and feed optimization. The rise of Internet of Things (IoT) devices and cloud-based platforms has further expanded AI's reach beyond individual farms to integrated supply chains and processing units (Neethirajan, 2024). These advancements have led to enhanced efficiency, precision, and sustainability in dairy operations. Emerging research now points to future scenarios where AI systems will not only support real-time, automated decision-making but also self-optimize through adaptive learning models. Developments in computer vision are expected to replace manual animal welfare assessment with continuous, non-invasive monitoring (Zhang et al., 2024). Furthermore, as climate change and resource limitations become more pressing, AI is projected to play a central role in optimizing environmental outcomes through carbon tracking, water use analytics, and sustainable feed management (Neethirajan, 2024; Pathak and Rathore, 2023). Taken together, historical milestones and recent empirical findings underscore AI's growing potential to transform dairy into a more

intelligent, resilient, and sustainable system. Ongoing advancements in AI, along with enhanced integration and tailored applications, are set to revolutionize dairy farming and dairy manufacturing by making it more efficient, environmentally, and financially sustainable.

8. Conclusion

AI has demonstrated transformative effects and impacts in various sectors of the food industry. The dairy industry is experiencing significant progress in the use of AI, which improves efficiency, productivity, and sustainability in many ways. As the global food and beverage artificial intelligence market grows, it is becoming more and more promising to produce high-quality products (Nikolola-Alexieva et al., 2024). Traditionally, dairy farming relied on manual observation and experience-based decision-making, but AI enables real-time monitoring of animal health, precision feeding, and optimized reproduction management. AI automation in milking, disease detection, and farm operations enhances efficiency while reducing human labor. In dairy processing, AI ensures superior quality control through computer vision and sensor-based monitoring, maintaining product safety and consistency. Additionally, AI predictive maintenance minimizes downtime, while AI-assisted product innovation enhances flavor profiling and texture prediction. These advancements not only improve productivity and sustainability but also address critical challenges such as methane emissions, resource optimization, and supply chain efficiency. By transforming traditional dairy methods, AI is driving the industry toward a more efficient, data-driven, and environmentally sustainable future. Furthermore, it is essential to develop advanced frameworks that integrate diverse data sources, including on-farm sensors, environmental data, and supply chain logistics, while maintaining data integrity and cost management. In addition, current challenges in this field need to be addressed.

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Author Contributions

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Alaa El-Din A. Bekhit: Writing -Review & Editing, Validation, Visualization

Nilesh Nirmal: Conceptualization, Methodology, Validation, Resources, Writing -Review & Editing, Visualization, Supervision, Project administration

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Table 1: Application of AI to improve animal performance

Application	Comments	References
Animal health	An artificial intelligence (AI) based software solution developed by Canadian tech mogul EAIGLE Inc. for determining the health status of farm animals.	Congdon et al. (2022)
	Use artificial neural networks (ANNs), machine and deep learning for movement and behavior analysis to predict the health status.	Patil and Ansari (2020)
	AI and radionics tools for improving the efficiency of disease diagnosis	Bouhali et al. (2022)
	Predicting the health status of cattle by measuring deep body temperature using sensors, data analytics, and infrared images.	Ma et al. (2021)
	Control of parasitic infestations and other diseases through predictive AI-based modeling	De Vries et al. (2023); Parija and Poddar (2024)
	Detection of illness/monitoring by the use of real-time global positioning system (GPS) in animals at remote positions.	Rivero et al. (2021)
	Disease detection in cattle through odor by using a gas-sensing algorithm	Haselzadeh (2021)
	Algorithms based on activity monitoring using software “Matlab R2019b” for early detection of various diseases in cattle.	Pavkin et al. (2021)
	Prediction of disease outbreaks using predictive AI models based on animal behaviour, weather conditions, and history of disease occurrence	Congdon et al. (2022)
	Use of robots for cleaning and sanitization of animal sheds to reduce the risk of disease transmission.	Patel et al. (2022)
	Use of robots for vaccine delivery with injection	Ezanno et al. (2021)

	Establishing the relationship between subclinical mastitis and change in the rumination pattern in cows by using an online Sensor System.	Antanaitis et al. (2022)
	Predicting the udder health and detection of subclinical mastitis by using neural networks and deep learning.	Bobbo et al. (2021),
Reproduction	Detection of estrus in cows using CPS/IoT systems in livestock farms.	Dineva et al. (2021)
	AI-based Intelligent monitoring system (IMS) with Augmented Recognition Model for estrus detection in Korean cattle (Hanwoo).	Cho and Kim (2023)
	Ear-attached accelerometer and Ear-sensor accelerometer for estrus detection in dairy cattle	Perez Marquez et al. (2023)
	Intravaginal calving detection device - VelPhone® of Medria, Chateaugiron, France	Horváth et al. (2021)
	Estrus detection in dairy cattle through animal movement and location data acquired by a neck-tag	Wang et al. (2022)
	Prediction of semen quality in Holstein bulls by using Lasso and Gradient Boosting methods.	Hürland et al. (2023)
	Application of machine learning and infrared blood serum spectra for the prediction of reproductive performance of females in the early growth stage in cattle.	Reis et al. (2024)
	Recording and analysis of the ruminating behavior of Gyr heifers by using SCR Heatime® HR system sensors.	Kliemann et al. (2023)
	Prediction of forage production by analyzing UAV (Unmanned Aerial Vehicle)-based RGB images using Convolutional Neural Network.	Castro et al. (2020)

Milk production	Machine learning framework for the prediction of future milk yield and milk composition in cows	Ji et al. (2022)
	Estimation of milk production and assessing milk quality by using Decision tree-based algorithms and artificial neural network-based algorithms.	Slob et al. (2021)
	Prediction of the cows' daily milk yield and stage of production by using a deep neural network.	Themistokleous et al. (2022)
	Application of different artificial neural network algorithms for determining milk production	Bhardwaj et al. (2023)
	Prediction of daily milk production of cattle using various machine learning algorithms	Zhang et al. (2022)
	Automatic recording of milk production at small dairy farms based on the Internet of Things (IoT).	Kaunkid et al. (2022)
	Prediction of Milk Yield under controlled environmental conditions in the cold region of China by Using Neural Network Model	Zhang et al. (2023a)
	Prediction of milk production by using the Gradient Boosting method	Streefland et al. (2023)
	Detection of milk adulteration with whey by using FTIR and deep learning techniques.	Lima et al. (2022)
Nutrition	Predicting the milk in subsequent lactation by analyzing the preceding lactation's daily milk yield using a deep neural network	Liseune et al. (2021)
	Monitoring of feeding behavior in cattle with wearable motion sensors	da Silva Santos et al. (2023)
	Ear-mounted sensors to assess grazing time in sheep.	Lewis Baida et al. (2021)

Triaxial Accelerometer technique for analyzing jaw movement for predicting feed intake. Ding et al. (2022)

Prediction of dry matter intake of Canadian Holstein dairy cows through analysis of milk by mid-infrared reflectance spectroscopy via artificial neural networks. Shadpour et al. (2022)

Estimation of Feeding activities by using wearable sensors recording body movements and postures. Brennan et al. (2021)

Measuring jaw movements by sensing changes in pressure around the nose using a noseband pressure sensor. Chen et al. (2022)

Table 2. Advantages and disadvantages of AI in dairy

Advantages	Disadvantages
Enhanced Productivity and Efficiency: AI automates routine tasks, reduces manual labor, and optimizes decision-making across the dairy supply chain.	Technological Barriers: Lack of technical expertise and specialized knowledge can hinder AI adoption.
Improved Animal Health and Welfare: AI enables real-time health monitoring, disease detection, and reproductive performance assessments.	High Implementation Costs: The initial investment in AI technologies, including hardware, software, and training, is expensive, particularly for smaller farms.
Sustainable Practices: AI helps detect and predict methane emissions, supporting net-zero farming and environmental sustainability.	Data Requirements: AI models require large, high-quality datasets, which are currently limited in the dairy sector.
Quality Control and Product Development: AI-powered computer vision and sensor-based monitoring enhance quality control and product innovation.	Ethical and Animal Welfare Concerns: Constant monitoring may disrupt natural animal behavior, raising ethical concerns. Data privacy and security issues also exist.
Optimized Processes: AI adjusts processing parameters (temperature, pressure, timing) to improve yield, energy efficiency, and product quality. It also enables predictive maintenance for dairy equipment.	Connectivity and Infrastructure Challenges: Limited internet access in developing regions hinders AI implementation.
Supply Chain Optimization: AI improves demand forecasting, inventory management, and logistics, reducing spoilage and improving food safety.	Resistance to Change: The dairy industry is slow to adopt AI due to reliance on traditional methods, job security concerns, and training requirements.

Precision Farming: AI-driven automation in dairy farming enhances efficiency and sustainability.

Data Inaccuracies and Privacy: AI-generated data may have inaccuracies, and privacy concerns arise with sharing personal or farm-related data.

Regulatory Gaps: The lack of clear regulations on AI-driven recommendations, especially in health-related applications, poses risks.

Need for Continuous Investment: Ongoing research, skilled workforce development, and supportive policies are essential, especially in developing regions with limited funding.

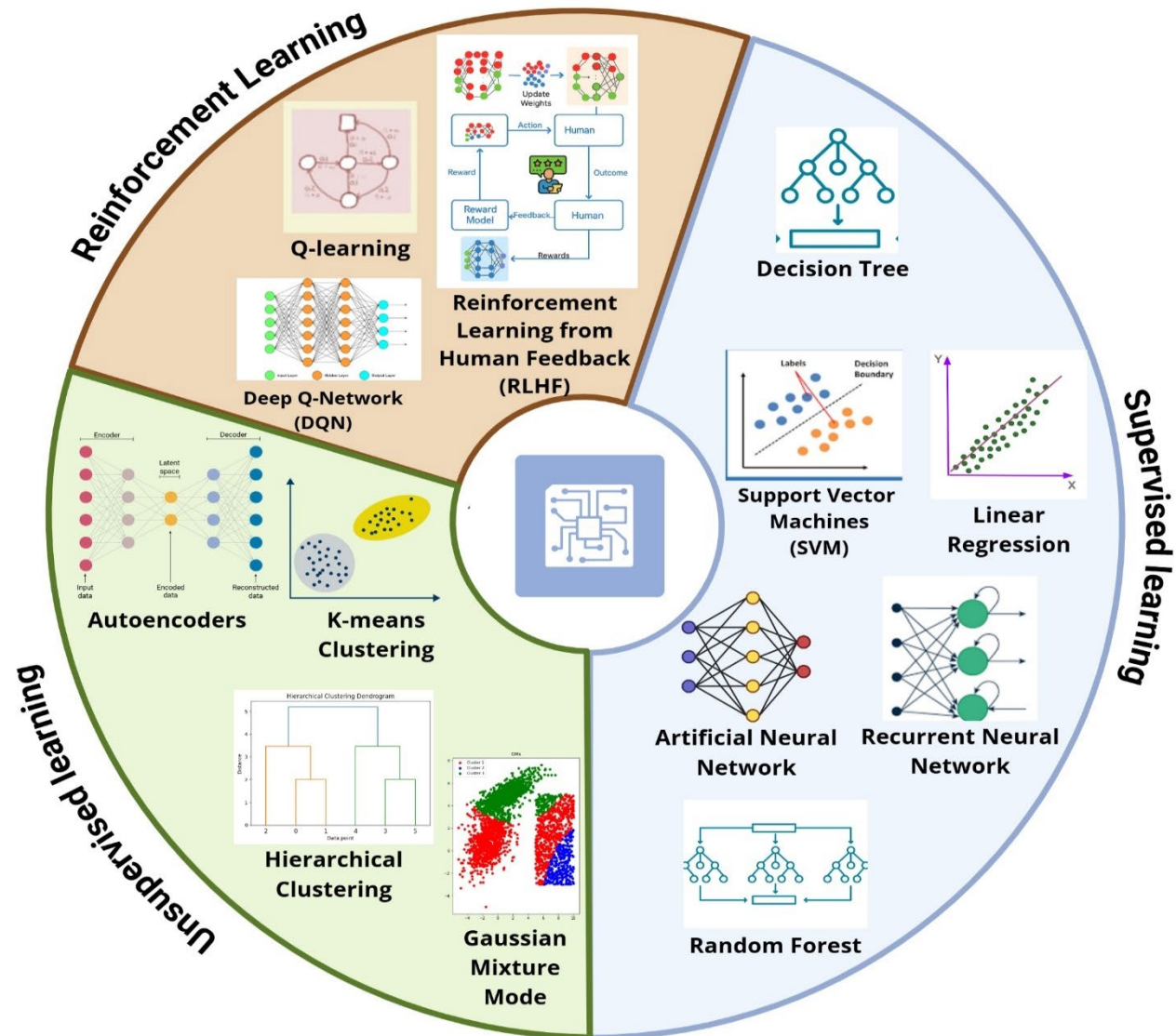


Figure 1. Types of AI algorithms

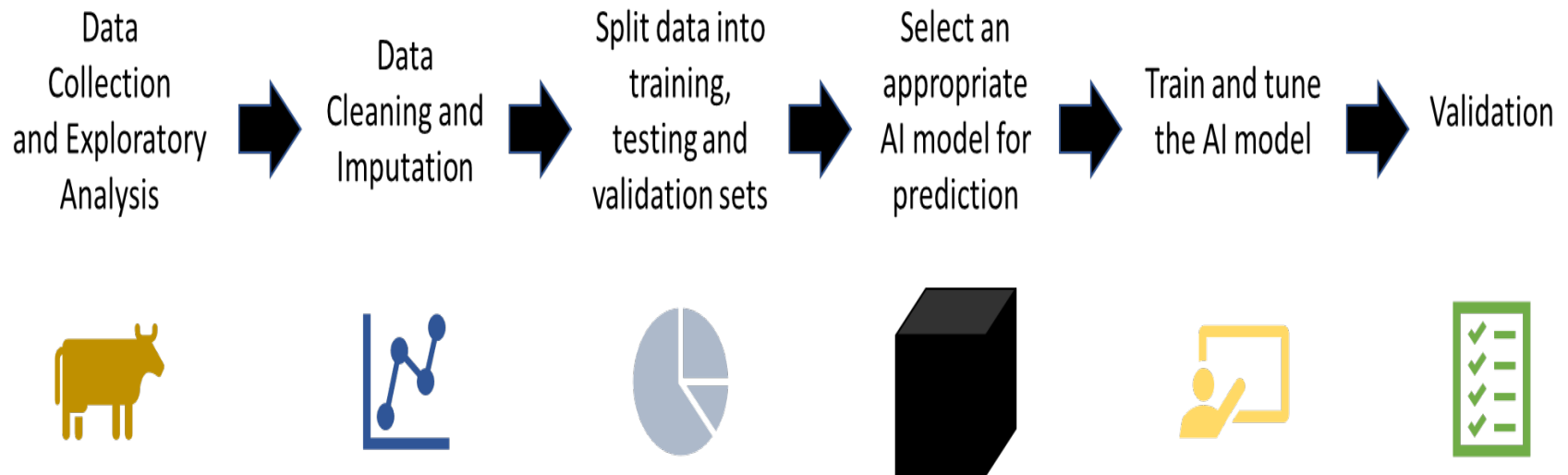


Figure 2. Steps for an AI model to predict animal-level emissions.



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Applications of artificial intelligence in the dairy Industry: from farm to product development

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