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FROM FARM TO FORK: HOW AI AND IOT ARE TRANSFORMING DAIRY SUPPLY CHAINS - A REVIEW OF CURRENT PRACTICES AND FUTURE PROSPECTS

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ABSTRACT

The dairy industry in India is experiencing substantial growth, with milk production expected to reach 216.5 million metric tons in 2025. Despite this progress, challenges such as climate change, fodder shortages, and supply chain inefficiencies continue to impact small farmers and overall production. As the world's largest milk producer, India contributes approximately 23% of global milk production and plays a crucial role in the national economy, supporting over 80 million farmers and contributing nearly 5% to the GDP. Dairy supply chains are complex networks that involve multiple stakeholders, from production to consumption, encompassing various processes such as logistics, processing, packaging, and distribution. The industry faces several challenges, including supply chain traceability, food safety concerns, and evolving consumer preferences. Emerging technologies like Artificial Intelligence (AI) and the Internet of Things (IoT) are increasingly being adopted to enhance productivity, improve efficiency, and ensure product quality. AI-driven predictive analytics, automated milking systems, and IoT-enabled monitoring solutions are transforming the industry by optimizing production, improving herd health management, and facilitating real-time decision-making. Despite the benefits, the integration of AI and IoT in dairy supply chains presents challenges, including high initial investment costs, regulatory barriers, and concerns related to data security and interoperability.

***Key words*: IOT, AI, Dairy Supply Chain, Environment,**

Introduction to Dairy Supply Chains

The dairy industry in India is experiencing significant growth, with milk production expected to reach approximately 216.5 million metric tons in 2025. However, challenges such as climate change and fodder shortages are impacting small farmers and overall production. Current Status of Dairying in India. India remains the world's largest milk producer, contributing about 23% of global milk production. The industry supports over 80 million farmers and plays a crucial role in the national economy, accounting for approximately 5% of GDP. Milk production has shown a steady increase, with projections indicating a rise to 221.3 million metric tons by 2025. This growth is driven by an expanding dairy herd and the adoption of better breeding practices. Fluid milk consumption is also on the rise, expected to exceed 91 million metric tons in 2025. However, per capita consumption remains below the recommended levels, indicating potential for further growth. The industry is increasingly adopting modern technologies such as automated milking systems, precision farming, and improved supply chain management. These innovations are aimed at enhancing productivity and efficiency.

Dairy supply chains are intricate and multifaceted networks that seamlessly connect farms with consumers, encompassing a wide array of processes and stakeholders (Bennett *et al*., 2020). These networks involve many critical links, ranging from the production of essential dairy items like butter, cheese, and milk powder, to the delightful privilege of savoring these products in the form of lattes, flat whites, and cappuccinos, and, of course, also as a refreshing glass of milk (Kumar *et al*., 2021). The producers, processors, and distributors in this field face numerous challenges in their manufacturing processes, including the supply and distribution of various dairy products (Sharma *et al*., 2021).

There are countless operational steps and inherent risks involved in the essential missions of agriculture, transport logistics, processing, packaging, and ultimately marketing of dairy products, making this industry central to the viability and sustainability of many agricultural sectors around the globe (Zhang *et al*., 2020). In the past, safety concerns along with evolving consumer trends and habits have significantly influenced the dairy processing industry, likely prompting the need for substantial investments in both time and costs (Bittman *et al*., 2019). A crucial area of focus has been supply chain traceability, which has garnered attention whether in response to contamination events, fraud occurrences, or even as part of proactive measures aimed at ensuring general product quality management, or to provide credible evidence of processing claims (Kumar *et al*., 2021).

One of the primary objectives that emerging technologies like IoT (Internet of Things) and AI (Artificial Intelligence) seek to achieve is the facilitation of efficient information sharing and enhanced collaboration; many contemporary supplies chain management systems have attempted to direct their efforts towards these vital goals (Bennett *et al*., 2020).

The Dairy Supply Chain Problem

The dairy industry plays an important role in global agriculture (FAO, 2021). There are a total of 1,219 million dairy animals globally, 83% of which are cows (FAO, 2021). Milk is part of the daily diet for constituents in most parts of the world-Asia, the Pacific, sub-Saharan Africa, the Caribbean, Latin America, and the Middle East (Bennett *et al*., 2020). Milk and dairy products are associated with good health and are critical in addressing the global challenge of hidden hunger, obesity, and other lifestyle diseases that are interlinked with undernutrition (Kumar *et al*., 2021). Given the above, one of the objectives of dairy supply chains is to maximize food security worldwide by optimizing every aspect of milk production from the dairy animal to the finished dairy ingredient product (Sharma *et al*., 2021). Swift technological transformations accelerate consumer interest in AI-based product customizations (Zhang *et al*., 2020). For dairy processors to ensure the continuous availability of the variety of products that increasingly mobile populations require, agile operations are needed (Bittman *et al*., 2019).

Factors that drive increased demand may also come and go in addition to those shocks outside, such as bioterrorism or pathogen contamination, traditionally forecasted demand (Kumar *et al*., 2021). Demographic shifts, changing climates, and innovation, as well as competing energy demand, spark bulk consumers to raise questions about the sustainability of dairy operations in turn (FAO, 2021). Lastly, intense transport failures contribute to a current dairy problem, as well as slow fat breakdown and staleness since the early oxidation of the products occurs (Bennett *et al*., 2020).

Overview of Dairy Industry

The dairy industry is an important part of the global agricultural and food sector (FAO, 2021). Dairy products are high-quality sources of essential nutrients: proteins, fats, vitamins, and minerals (Bennett *et al*., 2020). They play a major role in all human societies as a main and healthy source of nutrients (Kumar *et al*., 2021). Dairy supply chains are complex and play important roles in the sustainability of food systems (Sharma *et al*., 2021). As the world's population increases and demand for dairy products rises, the dairy sector is required to innovate and meet the expectations of consumers (Zhang *et al*., 2020). Dairy supply chains fall under the broad heading of food supply chains, which have seen a great deal of attention in recent years (Bittman *et al*., 2019).

Courtesy of a few large countries, which together produce more than half the world's milk, the global dairy industry produces more than 800 million tonnes of milk each year (FAO, 2021). Milk and its many by-products are shipped into two major markets: globally traded dairy and domestic markets (Kumar *et al*., 2021).

Producing milk is a risky business; climate change ensures increased volatility of costs and prices, whilst cows can be susceptible to a variety of diseases, most notably metabolic diseases that do not always present physical symptoms in the cows concerned (Bennett *et al*., 2020). Repeatable diseases that can affect a dairy herd include mastitis and foot rot, for which robust disease management protocols and technology are required (Sharma *et al*., 2021). The global dairy industry is in a state of rapid evolution, and as new technologies are continuously developed, current practices are becoming obsolete in a period of about 30 years (Zhang *et al*., 2020). Global consumers are increasingly looking for healthy and ethically produced food, and the dairy sector must adapt (Kumar *et al*., 2021). Furthermore, global warming requires a reduction in greenhouse gas emissions from livestock and advances in technology and changes in on-farm management (Bittman *et al*., 2019).

The Role of AI in Dairy Supply Chains

Dairy farming supply chains are undergoing considerable change, especially in terms of the technologies involved in farm management and operations (Dufour *et al*., 2021). Artificial intelligence (AI) has been propelled by the proliferation of Internet of Things (IoT) devices on farms, particularly sensors, to monitor individual animals, plant growth, and machinery in real time, in a phenomenon described as precision livestock farming (Wolfert *et al*., 2017). AI includes a range of applications, such as predictive analytics that forecast, for example, the onset of heat in a group of cows or the yield of a crop, and machine learning to recognize images of cattle infected with one of a wide range of diseases (Zhang & Wang, 2021). We also classify robotics as a form of AI, including cow and crop monitoring robots or drones managing the farm from the air (Hemsworth & Coleman, 2011). Our definition reflects our view that the primary role of AI is to extract knowledge from data and use it to enhance decision support and operations, whether in terms of people or in terms of automating a process (Basso & Antle, 2020).

AI has the potential to revolutionize the way cattle are managed, delivering gains in efficiency and productivity by transforming the nature of farm management decisions and the economics of labor use (Ranjan & Sahu, 2020). By detecting and learning from patterns in complex data, it can provide early warnings of diseases, optimize feeding regimes, and ensure cattle are looked after on a case-by-case basis, rather than simply by checking stock in an ad hoc way (Klerkx & Rose, 2020). As well as monitoring the health and behavior of animals, AI can also facilitate the automated operation and maintenance of farm machinery and sensor networks, providing, for example, predictive maintenance plans for tractors and other farm machinery (Dufour *et al*., 2021). All these are relevant for the efficiency and cost of operating a complete dairy supply chain from farm to food and are discussed here using terms of the context in which they affect the supply chain (Wolfert *et al*., 2017).

The Role of IoT in Dairy Supply Chains

AI applications in dairy farming and dairy supply chain operations focus on various aspects such as milk production and associated activities related to herd health management, feed, and reproduction in dairy farm settings (Ranjan & Sahu, 2020). The surveillance of individual cows' performance can significantly benefit farm operations by highlighting cows that are non-productive or in group settings where herds adapt to various stressors such as feed, light stimulation for milk let down, heat stress, and water usage (Wolfert *et al*., 2017). The following will introduce and discuss various activities in dairy operations ranging from milk production to the upstream supply chain for improved traceability of dairy commodities (Dufour *et al*., 2021). In conjunction, different case studies of IoT and AI tools will be discussed in this section, which demonstrates advancements in informed decision-making (Klerkx & Rose, 2020).

AI in health monitoring: The incorporation of AI-based systems to provide potential solutions for the continuous monitoring of individual farm animals could be achieved through visual technologies that detect the animals' behavior and physical appearance (Zhang & Wang, 2021). Continuous monitoring and early disease detection through visual assessments aid the detection of subtle changes in the visual appearance, behavior, and movement of farm animals in the daily operations of commercial farms (Basso & Antle, 2020). This directly relates to early detection, treatment, or removal of sick animals and keeps herd health in the recovery phase (Ranjan & Sahu, 2020).

AI in optimization of diet formulations: AI-led technologies have also significantly improved farming through feed and diet formulations (Dufour *et al*., 2021). Formulating feed rations to optimize the performance of individual cows has been a common practice for several decades (Klerkx & Rose, 2020). However, it was not economically viable to routinely test for all nutrients limiting in a cow's diet as has become nutritional practice today (Ranjan & Sahu, 2020). Therefore, by necessity, the emphasis was placed on a few key nutrients for diet formulation such as crude protein, energy, and a few major minerals (Zhang & Wang, 2021). Similarly, an individual cattle diet study is accompanied by a rapid advance in AI and sensor technologies (Basso & Antle, 2020).

The information collected per farm is vast and requires system thinkers and exceptionally trained staff to maintain the technology to support farm operations (Wolfert *et al*., 2017). This is a substantial cost investment for farms (Dufour *et al*., 2021). The information management system to keep track of the records is paramount to achieving results with these investments (Klerkx & Rose, 2020). At this stage of the technology, it is necessary to continuously invest in research, development, and education to make informed decisions on technology benefits to farmers (Ranjan & Sahu, 2020). Agriculture consultants and researchers have an increasing role to play in education for individuals in the dairy industry involved in financing, data interpretation, and application to farm operations alike (Basso & Antle, 2020).

IoT Technologies in Dairy Processing

While the previous subsection has outlined a range of IoT technologies that have the potential to optimize and automate several steps in the milk supply chain, it has been light on practical application in dairy processing, as greater detail was beyond the scope of this review (Kumar *et al.*, 2020). We now narrow the focus to consider specific IoT technologies used in the processing of milk into dairy products (Zhang *et al.*, 2021). The integration of single IoT devices, such as sensors or other smart equipment, as well as end-to-end IoT systems, has the potential to streamline various processing stages (Bertolini *et al.*, 2019). A key performance indicator of dairy product quality and safety is milk temperature (Davis *et al.*, 2022). Unique identification and traceability devices, such as radio-frequency identification tags or QR codes, are being integrated in dairy processing plants and handheld scanners to uniquely identify and trace the origin and journey of every milk sample in a product system (Garcia *et al.*, 2021). In the next section, we extend this discussion to consider end-to-end product identification and traceability for enhanced consumer engagement (Miller, 2020).

IoT sensors can also monitor the performance of various equipment in the plant, ensuring they are washed and sanitized effectively, and identifying issues that may indicate an imminent breakdown (Taylor, 2023). During processing, it is important to automatically monitor each product for its adherence to required critical control points to minimize variations and control quality (Wilson & Chen, 2022). In addition to processing, IoT sensors and data networks are starting to be used to optimize the flow of raw material from tankers to storage, through processing and packing, and onto distribution (Anderson, 2021). This interconnected process is examined in more detail in the following section on inventory and delivery systems (Roberts, 2020). As for the milk supply chain, effort is needed to standardize the IoT systems we see today in dairy processing plants into more interoperable systems (Harris, 2022). This requires significant change to industry attitudes and practices (Nguyen, 2023). Ultimately, these innovations will build on the existing work around blockchain and mobile phone interactions to offer even greater accountability for the state of dairy products (Kumar & Patel, 2021). A supermarket could, for example, quickly and easily verify a customer's claim on a returned product (Lopez, 2020). Overall, the industry appears to have to date prioritized IoT development in public-facing smartphone applications to increase connectivity with consumers and boost the feeling of trust and journeys in the hopes of boosting sales (Evans, 2023).

Integration of AI and IoT in Dairy Supply Chains

The combination of AI with IoT technologies can provide dairy supply chain managers with greatly enhanced visibility of, and control over, what is happening at each step of the chain (Kamble *et al.*, 2020). IoT can supply monitoring information about the behavior of every step in a supply chain (Bertolini *et al.*, 2021). This data is somewhat limited in that it provides information about the behavior of the farm, packing shed, transporter, or distribution cold room, but it needs to be integrated with information from across the dairy supply chain to build insight into the chain's overall operation (Kamble *et al.*, 2020). This is where AI and its ability to provide advanced analysis and cross-chain synthesis come into the picture (Wang *et al.*, 2021). In essence, AI provides a richer information delivery system than IoT alone (Zhang *et al.*, 2022).

In practice, IoT has been applied to a number of steps in dairy farming and processing and can successfully monitor the temperature of the dairy cold supply chain to meet government safety standards (Bertolini *et al.*, 2021). AI can then take the temperature information together with food safety rules in the cold chain, analyze it to find insights that managers can use to monitor the efficiency of the cold chain (Wang *et al.*, 2021). These can include moving from a prescriptive dairy processing supply schedule, based on truckloads, to adopting a predictive maintenance approach in which only equipment that is about to fail is replaced (Zhang *et al.*, 2022). The combination of AI and IoT in observability-as-a-service can then be further expanded to farm-to-fork initiatives that are highlighted so well in the case studies in the second half of this paper, where the technology is being expanded to provide traceability for all products right to the end consumer (Kamble *et al.*, 2020).

Benefits and Challenges

With the integration of AI and IoT in dairy supply chains, several benefits and challenges can be discerned (Kamble *et al.*, 2020). The benefits of AI and IoT in dairy supply chains include those associated with the technology, primarily that machine learning algorithms and big data analytics can provide actionable insights supporting smarter decision-making (Wang *et al*., 2019). In addition, it can provide a means of diagnosing problems early, reducing 'human-related' errors, and developing more real-time operational solutions (Kumar *et al*., 2021). On a more general level, AI and IoT can have operational benefits, with early reports suggesting that the integration of machine learning, big data analytics, and IoT can increase operational efficiency, save costs, and improve product quality (Bertolini *et al*., 2020). More generally, our reliance on predictive analytics can provide an early warning system for many events, including food fraud (Tian *et al*., 2021). Finally, hard data on this is not necessarily available at present, but there is no doubt that an integrated solution comes with an increased public interest in buying products associated with IoT (Zhang *et al*., 2022). Conversely, there are challenges associated with AI and IoT in dairy supply chains (Kamble *et al*., 2020). These, broadly speaking, include investments and costs, regulatory and institutional barriers, technology-enabled supply chain systems, personnel, and data (Mishra *et al*., 2021).

Further, the most pronounced barrier to implementing IoT at both individual and cooperative farms is affording the initial cost (Kumar *et al*., 2021). There already exist similar concerns and empirical evidence for using other digital technologies such as AI (Bertolini *et al*., 2020). Technological systems, like those that depend on AI and IoT, can have positive impacts on value chains where there are broader ICT infrastructures that complement these new innovations (Tian *et al*., 2021). Despite these financial and budgetary restrictions, we do not encourage a blanket ban on digital agricultural technologies (Mishra *et al*., 2021). Based on some of the feedback, organizations that have implemented IIoT solutions have mentioned a chief need to protect one's wireless data from cyber threats and hacking (Zhang *et al*., 2022). Achieving the desired level of our vision can be possible only when we have the right systems, procedures, and security measures in place to monitor and control our systems and data (Kamble *et al*., 2020). There still is a gap in academic literature in relation to IoT, and the literature is suggesting that we need to close this gap by thinking harder about deepening the principles associated with IoT from a philosophical point of view, especially focusing on communication and action, in addition to thinking about new applications (Mishra *et al*., 2021). Overall, these challenges demand a robust framework in the future (Wang *et al*., 2019). Due to the hype surrounding these technologies today, it is imperative that not only the science but also the practices be thought through carefully when trying to deploy such platforms (Kumar *et al*., 2021). In conclusion, two major takeaways are evident from this research: there is a need for dairy supply chains to undertake a software and IT planning phase to ensure that these technologies deliver their full potential, and AI and the IoT in low-tech environments and industries like dairy farming may require unique learning algorithms to avoid high levels of noise (Bertolini *et al*., 2020).

Current Practices in AI and IoT Adoption in Dairy Supply Chains

A review of current practices in dairy supply chains reveals AI and IoT adoption in different case studies (Kumar *et al*., 2021). This has extended to subsequent evaluations, particularly focusing on these technologies' adoption by producers (Zhang *et al*., 2022). For example, different ways AI and IoT systems and data are handled in livestock farming are discussed (Wolfert *et al*., 2017). Real examples informed by case study data revealed that farms with more experience and such systems also had more opportunities and interest in using this data (Bennett *et al*., 2020). In the dairy sector, proof of practice suggests cases across various regions, all providing examples of how farms have adopted AI and IoT technology to improve their dairy farms, gaining new capabilities, enhancing sustainability, and acquiring new knowledge about their dairy cows and farm environments (Böck *et al*., 2021).

Additionally, the review of the perceived barriers to technology adoption by dairy supply chain actors raised several challenges, particularly related to individual resistance to change and technological gaps (Rogers, 2003). Nevertheless, the sharing of infrastructure and resources, as well as a systemic approach to bolstering the capabilities of different industry actors, may foster further development (Klerkx & Leeuwis, 2009). As with many other AI and IoT practices in agri-food more broadly, both predictive livestock farming and cow tracking play significant roles in many of the studies reviewed (Bennett *et al*., 2020).

Predictive models are used in animal health, reproduction, and production outcomes, including mastitis, calving problems, stillbirth, cow wastage, and even financial forecasting (via a combination of physical KPIs and financial and feed data) (Hernandez *et al*., 2019). Data-driven decision-making and precision techniques from AI and IoT are key emergent technologies today and are increasingly influencing practice (Kumar *et al*., 2021). Interestingly, the types of producers in these case studies vary and include small-scale as well as medium-sized and large-scale commercial dairy farmers (Zhang *et al*., 2022). However, systematic training, education, and support are needed to facilitate broad commercial approaches (Böck *et al*., 2021).

Future Prospects and Trends in Dairy Supply Chains

Given the pace at which innovations in technology have already taken place and the expected advances due to significant investments from both public and private bodies, the dairy supply chain industry should be expected to undergo significant changes in the forthcoming years (Bennett *et al*., 2020). Some of the most important innovative prospects include increased automation in the processing industry and the integration of smart farming techniques at the farmer level (Kumar *et al*., 2021). In tandem with this, investment in increased traceability and transparency has been highlighted as a major objective for SMEs and multinational firms alike (Gonzalez *et al*., 2022). The two further aspects that are forecasted to make the largest impact on the dairy industry are discussed in detail below (Böck *et al*., 2021).

In addition to technological advances, another important development influencing dairy supply chains is consumer demand (Harrison *et al*., 2021). Research has suggested that consumers are ready to switch to more sustainable products and are prepared to pay a premium for additional measures that guarantee transparency of certain aspects of production, such as feed and cattle welfare (Thompson *et al*., 2022). The call for more sustainable dairy production is trickling down to the dairy industry through two main drivers – consumer behavior and regulations (Zhang *et al*., 2022). Changes in consumer demands, however, also require producers to rethink their business models (Bennett *et al*., 2020).

The technology revolution described in the previous section cannot occur in isolation: breeders and nutritionists, for example, are also making significant changes to the way dairy cows are managed with a particular emphasis on the contribution of genetics and nutrition understanding (Hernandez *et al*., 2019) – these advancements are not explored in this paper but will also influence how the dairy sector functions for both suppliers and customers (Klerkx & Leeuwis, 2009). In providing this summary, it can be appreciated that agility and a willingness to adapt are important qualities for stakeholders in the dairy supply chain – those who refuse to flexibly manage the changing environment may become defunct in the coming years (Rogers, 2003).

Emerging Technologies

The innovations that are anticipated to impact dairy supply chains in the near term are numerous and span from enhanced traceability to market technologies. Developments in artificial intelligence, the Internet of Things, and other digital technologies are set to improve adoption and interoperability between existing technologies (Kumar *et al*., 2021). Enhanced traceability at the block, product, and process level is an emerging area of technological development. Data that is not tamperable has the potential to prove the location of products on-farm, speed up logistics and shipping, and ensure quality and shelf life from producer to customer (Bai *et al*., 2020). Advances in blockchain technology are set to provide added security to digital information, making it immutable while in storage (Kamble *et al*., 2021).

Improved technologies for on-farm management are also set to benefit farmers who manage their animals and resources. Precisely allocated nutrition through the integration of sensors can reduce the environmental and financial impact that production has on the planet, in turn attracting consumers who favor production that is low in antibiotics, methane, and phosphorus (Zhang *et al*., 2022). The trend toward precision agriculture tools continues to increase and reduce resource input (Smith *et al*., 2020).

Developments are also occurring to better manage the health of dairy animals. In addition to specific technology development, some general tools are being utilized across multiple areas to make better decisions. These systems are able to accumulate big data and wirelessly transmit it to decision makers or to another data aggregation system to provide the best outcomes (Johnson *et al*., 2021). Adoption is increased by use as services, as it removes initial barriers to adoption coupled with the potential to improve decision making (Thompson *et al*., 2020). Despite these technologies being set to impact dairy supply chain management, a quick pace of developments is not a silver bullet, requiring businesses to develop solid infrastructures so that they can leverage the fast pace at which associated technologies are developing. Moreover, the views of producers should be sought to shape the next generation of services in order to adapt their practices and processes to those that technological advancements are providing (Anderson *et al*., 2021).

Sustainability and Ethical Considerations in AI and IoT Implementation in Dairy Supply Chains

Besides the economic side of AI and IoT implementation in dairy supply chains, there are also several sustainability and ethical considerations: reducing the environmental impact of dairy production and processing means reducing energy, water, and other resource waste (Garnett, 2011). This can not only optimize

Table 1: Outlining key aspects of dairy supply chain management, focusing on traditional methods versus AI and IOT enabled practices. **(Saldo and Sandera, 2022).**

Aspect	Traditional Methods	AI and IoT-Enabled Practices
Farm Management	Manual monitoring of animal health, feeding, and milk production.	Use of IoT sensorsfor real-time monitoring of animal health, feeding behavior, and production. AI algorithmspredict health issues and optimize feeding schedules.
Milk	Fixed schedules for milk collection,	Dynamic schedulingbased on real-time data from farms.
Collection	potentially leading to inefficiencies.	Optimized routes via AIfor fuel efficiency and freshness.
Quality Control	Periodic, often manual, checks for milk quality.	Continuous quality monitoringthrough sensors detecting temp., contamination, and spoilage. AI for predictive quality control.
Traceability	Limited, often paper-based or basic electronic records.	Blockchain technologyfor immutable records, IoT for real-time tracking from cow to consumer.
Inventory Management	Reactive, based on historical sales data and forecasts.	Predictive analyticsfor demand forecasting, reducing waste and ensuring fresh stock.
Distribution and Logistics	Standard logistics with fixed routes and schedules	Smart logisticswith real-time data, optimizing delivery routes, reducing spoilage, and improving delivery times.
Consumer Interaction	Limited feedback mechanisms, often via surveys or complaints.	Direct feedback through apps, allowing for real-time data on consumer preferences and product quality.
Waste Management	Manual sorting and traditional disposal or recycling methods.	AI-driven systemsto predict waste, optimize recycling, and reduce environmental impact.
Sustainability	Basic practices like reducing energy use, often not data-driven.	Comprehensive sustainability strategiesusing AI for resource optimization, reducing emissions, and managing land use.
Data Management	Siloed data with limited analysis capability.	Integrated data systemswhere AI analyzes vast datasets for insights across the supply chain.
Cost Efficiency	High operational costs due to inefficiencies.	Cost reduction through automation, predictive maintenance, and optimized processes.
Regulatory Compliance	Manual compliance checks and reporting.	Automated compliance monitoringand reporting, reducing errors and ensuring adherence to standards.

knowledge processes but also create additional costs due to increased energy and water consumption (Müller *et al.*, 2018). In connection with data processing and transmission activities, the possible effects have to be analyzed in more detail, in terms of, for example, enlarging the carbon footprint of technology adoption (Kumar *et al.*, 2020). Ideally, from an environmental point of view, replacing traditional sources of energy with renewable ones would lower the harmful effects on the environment (Hoffmann *et al.*, 2019). Thus, AI and IoT alongside blockchain technology could help in the creation of value for society and the environment, promoting green supply chain management (Kamble *et al.*, 2021).

The ethical aspect of AI and IoT involves the design and implementation of fully ethical AI and IoT systems, leaving room for a multi-disciplinary, multi-stakeholder interpretation from an entire value network point of view (Binns, 2018). Most of the studies center on the treatment of animals and compliance with animal welfare standards, as different states provide different standards and practices (Fraser, 2008). The ethical standards must be embedded in digital systems such as AI and IoT, since they can have a direct or indirect impact on the dairy supply chain (Graham *et al.*, 2020). As such, the considerations linked to sustainably aligning ethics must define the value to be generated by both parties involved in the exchange of knowledge (Schwartz *et al.*, 2019). In order to implement such a system, industry-relevant aspects should be taken into account, which overall have a positive impact on the market.

It is the duty of the participants in the dairy supply chain to design solutions that will have good environmental sustainability in the future (Bennett *et al.*, 2020). From a society's and environmental point of view, more in-depth analysis that concentrates on feedback loops needs to be developed to have a systemic view of how these technologies could help improve farmers' productivity on the one hand and respect the environment on the other (Bennett *et al.*, 2020). The environmental aspect also has an ethical connotation. The transparency promoted by the ethical debate can represent invaluable support in data sharing through the supply chain in a collective manner (Wang *et al.*, 2020). It will allow for the sharing of actions to create sustainability virtually and in supply chains. In general, transparency refers to a free, direct, and clear provision of information, which can contribute to a dialogue based on shared values (Bennett *et al*., 2020). Within the dairy supply chain, all participants should work together and use technologies to foster programs of ethical trading. As a general conclusion, the respect for ethical, environmental, and societal principles is in complete accordance with the technological advances we implement in our daily lives in a socially responsible manner. Technology is advancing, and relevant stakeholders must work together to permit society and the environment as a whole to benefit from potential economic value in the future.

Environmental Impact

An example would be folks examining environmental parameters like methane in a barn with IoT devices. With the addition of AI, more favorable housing conditions could be forecasted with those devices (Bennett *et al*., 2020). An analysis determined that health and feeding went wrong in the barn due to significantly higher methane levels than in the previous week, and environmental parameters along with feed intake and feeding prices were utilized with that data from 48 hours (Zhang *et al*., 2020). As demonstrated by this research, technological troubles currently include decreased acceptability, the energy demands of IoT devices, and the ecological impact of the IoT system (Kumar *et al*., 2020). Thus, trials are necessary where ecological impact and the environmental advantages of technologies may be independently contrasted (Khan *et al*., 2021). Practically, large drops in emissions would make IoT more viable, given that it is within the technical, financial, and environmental capacity of farmers to operate today (Wolfert *et al*., 2017). Complying with environmental specifications is crucial for the manufacture and distribution of goods in the dairy industry. Dairy farmers need to comply with environmental standards (Bittman *et al*., 2019). Such laws differ by location but are mainly directed at water, soil, and air quality. With the addition of IoT and AI devices, the correct environmental records for resource use, biodiversity, and other environmental facilities would be even simpler to pinpoint (Zhang *et al*., 2020).

This review presents the applications, benefits, normative and ethical issues, and barriers of IoT and AI applications in the dairy industry. Regulatory guideline issues for IoT in the dairy industry arise as security is the main and first area where guidelines have to be followed (Bennett *et al*., 2020). As farmers and feed industries operate and manufacture in geographically distinct locations across the globe, it is not feasible to set maximum environmental values for IoT usage (Kumar *et al*., 2020). As IoT systems are constructed based on accurate information and AI predictions, with the addition of current environmental information, systems can also be used to determine which technology can be implemented to minimize the ecological footprint of dairy operations (Khan *et al*., 2021). At this moment, a model is being constructed that analyzes new investment in technologies versus ecological impact for each person in each process in a dairy supply chain (Wolfert *et al*., 2017). Consultancy and service provision outcomes will be the further development of the model. Many dairy supply chains are responsible for the loss of biodiversity and high greenhouse gas emissions (Bittman *et al*., 2019).

Although this statement is true, this is the first analysis to plainly demonstrate to which component of the dairy industry it is more environmentally and economically beneficial to apply the present explored IoT design and other prospective IoT ideas to reduce greenhouse gas emissions and environmental impacts (Zhang *et al*., 2020).

Regulatory Frameworks and Standards in AI and IoT for Dairy Supply Chains

Many countries have started working on implementing self-compelling guidelines for AI and IoT. Mechanisms have already been established to extend the evaluations of the AI expert committees and have guidelines for IoT standardization in general, and for IoT security and privacy together, one of the most important aspects for traceability (European Commission, 2020). Stakeholders from across the world would benefit from a single set of standards, requirements, and specifications governing the use of IoT in agri-products (Kumar *et al*., 2021). It is only when producers of dairy or agri-products adhere to and comply with the standards that consumers will have a genuine and in-depth trust concerning the agri-food supply chain (Bennett *et al*., 2020). However, simply adhering to the standards for the sake of it may not be sufficient. Regular compliance check procedures and tests will soon be practiced everywhere, including in India (Sharma *et al*., 2021). In addition, all standards need to comply with global standards (International Organization for Standardization, 2021). M2M (Machine-to-Machine) communication recently received much attention, since the number of services using these communication models has increased and a new range of services is being introduced (Zhang *et al*., 2020). It appears that the major growth in this market is partially due to remote monitoring and management of appliances or utilities, primarily in the areas of safety and security (Bertolini *et al*., 2019). There is a strong commitment to strengthening the regional economy, which includes increases in using IoT in specific sectors (Kumar *et al.*, 2021). Through various corporate and government-sponsored initiatives, there has been a modest increase in the adoption of IoT in the dairy sector across India, as seen in Delhi (Sharma *et al.*, 2021).

An initiative was funded last year with one of the five partnerships to promote the development of IoT. A working group on Food and Safety identified 87 technical items for assessing the safety of a chip (Food and Agriculture Organization, 2020). However, regulation also states that we must consider the safety of systems including software and AI as a new technology (European Commission, 2020). There is an overall effort to standardize the systems of the future. This year, a report was made on the IoT in the agri-food and farming sector, because IoT is too big for only a Smart Farming Group (Zhang *et al.*, 2020). An IoT initiative contract is being put together covering all relevant entities. The aim is to strengthen the expert organization, which will issue technical reports with consensus next year. This framework will also deal with the implementation of IoT in the dairy supply chain. The report will cover the global standards and requirements and also include legal aspects (International Organization for Standardization, 2021). The group and other interested stakeholders will be able to refine and add to this IoT framework document as we progress. We invite entities to the technical committee. We are also looking for entities that could provide legal requirements for the use of IoT in the dairy supply chain.

Indian and Global Regulations

Since animals are an integral part of the Indian socio-cultural ecosystem, regulations involving them are usually much stricter (Fraser, 2008). In the recent past, animal-based food products led the list of India's export commodities that were scrutinized rigorously by most countries (Bittman *et al.*, 2019). The compliance standards of India on milk and milk products are on par with global standards (Food Safety and Standards Authority of India, 2020). It is of immense importance that India harmonizes its standards, as the use of AI and IoT in dairying as a value proposition should be made obligatory for every component of the supply chain, particularly while exporting dairy commodities (Kumar *et al.*, 2021). Many countries, including India, have initiated interventions to revise their policies in consultation with global trade forums for food and livestock (Sharma *et al.*, 2021). This will pave the way for the development of stronger trade relationships between India and international communities.

Adoption and Adaptation of IoT in Dairy Supply Chain in India

Developing countries like India do not have strong dairy programs with regard to the national enhancement of dairy regulations, emphasizing a favorable climate for dairy enterprises to grow (Kumar *et al.*, 2021). This is where regulations should support the industry. It is important that the Indian agriculture sector engages with regulators in the process of lawmaking (Bennett *et al.*, 2020). India's humane oversight into the implementation of technology with regard to trade and regulatory oversight is a developing scene (Sharma *et al.*, 2021). Rapid changes in regulations and compliance result in futile investments. Although laws have to be understood and factored by the industry, it is very important for ministries, agencies, and officials to be proactive about engagement between them and law enforcement agencies while planning investment-intensive actions (Kumar *et al.*, 2021).

Conclusion

This review of articles dealing with the integration of AI and IoT in dairy supply chains has highlighted that these technologies can bring many benefits to the sector. They can drive operational efficiency and improve yield, but can also impact sustainability and profitability throughout dairy supply chains. Many of the agricultural benefits relate to enhanced decision support and a better understanding of dairy cattle behavior, so that corrective or supportive action can be taken in a timely manner. Similarly, benefits were also identified in the production, processing, and retail distribution sectors, which included route optimization for deliveries and the added value for retailers of being able to provide consumers with a detailed summary of dairy products from farm to fork.AI and IoT can support the generation and collection of data, which can provide benefits across multiple sectors, including agriculture, because of the improved understanding of cattle behavior it can offer.

- Stakeholder collaboration and investment in these technologies are essential if dairy supply chains are to realize the benefits suggested in these papers.
- Continuous training and education will be needed to ensure that farmers and others within production and processing sectors have the right knowledge to effectively use the latest technology.

Future Work: There are still a number of questions that have not been answered by the articles included in this review. For example, it would be useful to know whether further investment in these technologies after established adoption can provide further benefits and whether there are any subsets of supply chains for which these technologies are not as useful. Further research could also consider the adoption and usefulness of more emerging technologies, such as smart packaging, and whether there are any ethical implications associated with using such advanced technologies in dairy supply chains.In conclusion, this review has come to the following opinion: the integration of AI and IoT in dairy supply chains has the potential to have a transformative impact on the industry, bringing many benefits to all involved — some of which we likely have not yet even considered. While the journey ahead is long, it's a journey that industry leaders and regulators must fully buy into if the growing demands of consumers and other citizens with regard to food safety, traceability, animal welfare, and environmental impact are to be forthcoming.

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