



Dairy 4.0: Embracing Digital Technology for Sustainable Farming: A Review

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10.18805/ajdfr.DR-2242

ABSTRACT

In the fourth industrial revolution, digital technologies are being utilized to construct efficient and sustainable dairy farms by combining various technology and resources. It is now more important than ever to embrace innovation and developing technologies in order to tackle the current global concerns by automating and modernizing the operations. However, the industry faces challenges in adopting new technologies, such as limited access to advanced technologies, inadequate infrastructure and a knowledge deficit among farmers. This article gives an overview of the evolution of dairy 4.0 from dairy 1.0. in resonance with the evolution of Industry 4.0. This is a review paper that investigated past literatures to identify the components of Dairy 4.0 that are supportive to sustainable innovation. The Indian dairy industry has transformed significantly due to technological advancements, including automation, precision farming and Industry 4.0 systems. The results show that robotics, 3D printing, artificial intelligence, Internet of Things, big data and blockchain are among the core facilitating technologies of Dairy 4.0. These innovations improve production, efficiency and milk quality, while also aiding breeding, herd management and sustainability. However, ongoing investment in technology infrastructure is necessary to ensure maximum production and productivity.

Key words: Dairy 1.0, Dairy 2.0, Dairy 3.0, Dairy 4.0, Industry 4.0, Sustainability.

Technology is key in solving the problems of food safety and security in the different sectors of the food industry. Inventions and development of high-end technologies have revolutionized the food industry over the last few decades. The most important two fundamental technical aspects that are leading this revolution are Industry 4.0 (I4.0) and Artificial Intelligence (Dopico *et al.*, 2016). I4.0 would usher in a new technology paradigm that would cut across all industrial sectors.

Many other developments impact the way AI operates the gigantic data received from the IoT devices in real-time. The IoT is the vital part of many industries, enabling and upgrading industries through big data (Khan *et al.*, 2017). I4.0 enables producing higher quality goods quickly by leveraging data, internet connected equipment and state-of-the-art technology to process expanded volumes of data and communicate with one another. I4.0 would involve deploying many cutting-edge technologies that could fundamentally disrupt the technological paradigm of the dairy industry (Malik *et al.*, 2024). Some of these technologies are cyber-physical systems, the Internet of things, cognitive computing, big data analysis, *etc.* Out of the world's milk, 23% is produced in India, making the country's dairy industry one of the most promising producer (Janssen *et al.*, 2019). However, in India, the dairy industry needs market development. For this, a significant investment in infrastructure of dairy firms in terms of transportation, chilling, processing, calf feed, *etc.* is necessary (Leitch *et al.*, 2014).

Further, to increase the milk production and set up more dairy units, improving feeding technology is important. Also farm Women should be inspired by various extension techniques and technology adoption to advance more

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How to cite this article: Sangode, P.B. (2025). Dairy 4.0: Embracing Digital Technology for Sustainable Farming: A Review. Asian Journal of Dairy and Food Research. 44(2): 169-178. doi: 10.18805/ajdfr.DR-2242.

Submitted: 13-06-2024 **Accepted:** 07-08-2024 **Online:** 20-09-2024

scientific information for growing livestock production (Bollido *et al.*, 2020).

This can be bought by ensuring that right technology is implemented that supports the development of dairy sector. Further, the operations efficiency in dairy industry can be improved by adopting technology (Kaushik *et al.*, 2023). As industrial revolutions supported the development of the industries in India, so is the evolution of dairy from manual to mechanization to further automation (Zambon *et al.*, 2019). The dairy business in India is a vital sector of the country's economy, with millions of people able to benefit from it and it contributes significantly to GDP (Sarkar *et al.*, 2024).

India is among the highest milk-yielding countries in the world, with the largest population. But then, the huge Indian population hold most of the country's food. Majority of the industry comprises livestock and poultry, but in the recent past, poultry as a percentage has been on the rise.

To break into the market, one has to be mass producing and India is no pushover, as its volume of milk production yearly is registering perpetual growth.

Further, the application of technologies (innovative and digital) like automated control systems are significant to the sustainable development of dairy production (Kozina and Semkiv, 2020). Sustainability refers to the utilization of natural resources or the implementation of a technique or technology in a way that ensures there is no adverse long-term effects on natural resources (Meena *et al.*, 2024). Sustainable farming technology is crucial for enhancing production efficiency and addressing various challenges faced by the industry. The adoption of agricultural technologies, such as robotics in dairy farming and the use of Information and Communication Technology (ICT) for production and management, plays a significant role in improving productivity and sustainability (Sharma *et al.*, 2022). Additionally, waste-free technologies and the introduction of new food processing methods are essential for the sustainable development of dairy enterprises, promoting economic efficiency and resource optimization (Dalisova *et al.*, 2022). Moreover, the utilization of pressure-driven membrane processing systems and Modified Atmosphere Packaging (MAP) can revolutionize the traditional Indian milk product sector, enhancing product quality, reducing costs and ensuring ecological balance (Asgar and Chauhan, 2023). The successful integration of these technologies, as exemplified by the Gujarat Cooperative Milk Marketing Federation Limited (GCMMFL), showcases the positive impact of Information and Communication Technologies (ICT) in the dairy industry, enabling better control and innovation in milk production and distribution (Desai, 2016). Cow's milk is the most commonly consumed type globally, with buffalo, goat, sheep and camel milk following. India leads in worldwide milk production with 22% of the market share, while the United States ranks second in cow milk production, following the European Union (Boukria *et al.*, 2020).

This review work aims at examining the components of Dairy 4.0 specific to cow milk production that support sustainable innovations and their meaning in relevance to

the dairy industry through the literature explored from global adopters.

This research was conducted by the author at Symbiosis Institute of Business Management, Nagpur, Symbiosis International (Deemed University). The research was conducted from the articles published between 2018 to May 2024. In order to conduct this survey, a comprehensive analysis of the key aspects of digital dairy practices systems and the technologies that support them is done. This analysis is based on an extensive review of existing literature and the latest advancements in the field of dairy farm management. Since the objective of this study is to explore the concept of Dairy 4.0, the features of dairy 4.0 in which the framework of digitization aligns, the requirements are identified. Following section discusses concept of industry 4.0 and dairy 4.0.

Industry 4.0

I4.0 relates to the use of technology to digitally change the way industrial companies operate. These tools include IoT analytics, predictive maintenance, additive manufacturing, automation and robots and the industrial Internet of things (Ashima *et al.*, 2021). Productivity acceleration, adoption to fast changing market conditions, optimized quality and creation of new business models are the forces that push organizations towards Industry 4.0 (Nascimento *et al.*, 2019).

I4.0 represents the culmination of the industry's march towards digital. It means real-time decisions, increased productivity, flexibility and agility-nothing less than a complete disruption of how firms will make, build and market things in the future (Mohamed *et al.*, 2018). Fig 1 shows the evolution of Industry 4.0 with the characteristics of each revolution.

Each revolution phase has changed the way different industries functioned. One such industry is dairy industry. The main feature of I4.0 was the adoption of Artificial intelligence, robotics and Internet-of-Things in the manufacturing processes. These technological advancements now have gained momentum and are adopted fast in the dairy businesses also. Rapid technical advancements have resulted in a radical transformation of the Indian dairy

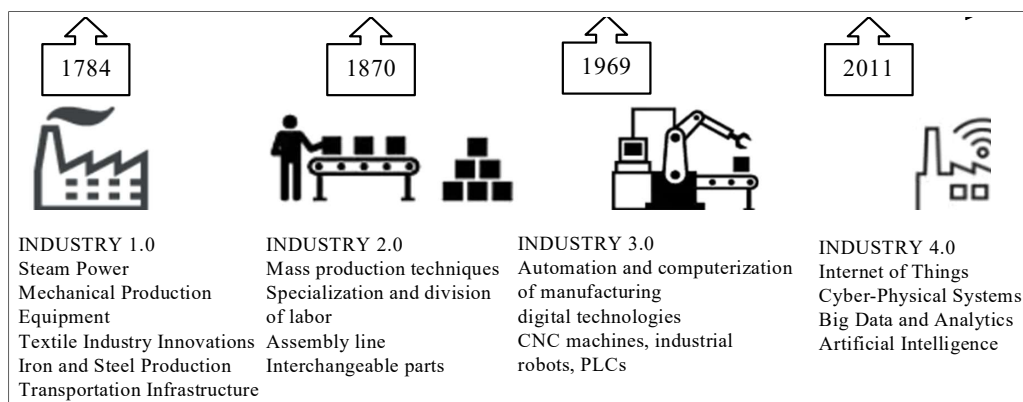


Fig 1: Industry 4.0 evolution.

business. Automation technologies, which simplify many dairy processes, are one such breakthrough (Fedotova *et al.*, 2020). Automation enhances production, reduces the cost of labor and maximizes efficiency. Through a reduction in human contamination and the assurance of precise milking schedules, automated milking systems have significantly enhanced the quality of milk (Hogenboom *et al.*, 2019). Another technological innovation is that of precision farming. Through the application of modern sensors and data analytics, dairy farmers can extend the use of technology toward feed and water optimization, which translates not only to better quality of milk but also to increased production (Neethirajan, 2020). Precision farming also helps in tracking animal health through technology that pinpoints lameness and alerts farmers to diseases so that the animals can be treated in a timely manner for better physical condition (Neethirajan, 2021). These advancements have given rise to the newer version of dairy farm management practices, which today is referred to as Dairy 4.0.

Dairy 4.0

The dairy industry is adapting to the increasing demand for premium dairy products due to several technical advancements and developments together known as “smart dairy farming. Smart dairy factories collect data on the dairy farm using the internet of things and precision forming processes, then use that data to improve milk output through blockchain, big data, artificial intelligence, RFID robotics and the internet of things. This whole system of adoption of innovative technology in line with Industry 4.0 is called “Dairy 4.0” (Gehlot *et al.*, 2022).

Dairy 4.0 does not confine to milk production only. This technology used in breeding has also advanced significantly. By utilizing cutting-edge technology and methods like as artificial insemination and embryo transfer, the producer may increase the number of climate-adapted and disease-resistant cows, thereby increasing milk supply. Enhancements in herd management and sustainability in dairy production are made possible by these genetic advancements (Karavolias, 2023).

Even though the dairy business has evolved with technological breakthroughs and sustainability challenges have been managed, harnessing these innovations for Dairy 4.0 requires continuing investment in technology infrastructure and talent development to keep up with changing customer needs to optimize these benefits.

From Dairy 1.0 to Dairy 4.0, this table offers a comparative summary of the elements and methods related to dairy farming at various phases of industrial development as shown in Table 1.

Dairy 1.0

Dairy is a traditional approach to dairy farming, characterized by minimal mechanization and heavy reliance on manual labour. This system allows animals to graze and feed using traditional methods, with minimal genetic selection.

Table 1: Dairy 4.0 Evolution and comparison of its components.

Component	Dairy 1.0	Dairy 2.0	Dairy 3.0	Dairy 4.0
Mechanization	Limited mechanization, manual labor	Introduction of basic machinery	Adoption of specialized equipment and milking machines	Precision livestock farming, automated milking systems
Feed and nutrition	Traditional feeding practices, grazing	Introduction of formulated feeds	Improved feed formulations, ration balancing	Smart feeding systems, data-driven nutrition management
Breeding practices	Natural mating, limited genetic selection	Controlled breeding, selective breeding	Artificial insemination, pedigree selection	Genomic testing, selective breeding based on genetic data
Milk processing	Basic processing methods (e.g., hand-churning)	Introduction of pasteurization	Standardized processing techniques, refrigeration	Advanced processing technologies, automation
Healthcare practices	Limited veterinary care, herbal remedies	Basic veterinary care, vaccinations	Disease management protocols, routine health checks	Data-driven health monitoring, predictive analytics
Data and information	Manual record-keeping, oral tradition	Paper-based records, rudimentary data collection	Electronic record-keeping, basic data analysis	IoT-enabled farm management, data analytics software
Environmental impact	Minimal awareness, natural waste disposal	Limited environmental regulations, waste management	Compliance with environmental standards, waste control	Sustainable farming practices, environmental monitoring
Labor efficiency	Reliant on manual labor, family-owned farms	Increased reliance on hired labor	Improved labor efficiency, mechanization of tasks	Labor-saving technologies, robotic systems

Milk processing is basic, often involving hand-churning methods. Healthcare practices are rudimentary, with limited veterinary care and a reliance on herbal remedies. Data and information management are primarily manual, with records kept manually or passed down through oral tradition. Attention to environmental impact is minimal and most commonly, the conventional methods of waste disposal are employed. Efficiency of labour is largely manual because many operations are small family farms.

Dairy 2.0

Towards modernization new period of modernization in dairy, includes introduction of basic machinery to supplement human power on-farm Feed and nutrition: Formulated feeds, controlled breeding practices, improved healthcare practices and arrival of technologies such as pasteurization data and information management: Records are still paper-based, but the requirements for data and information management have led to a trend to more basic forms of collection Environmental impact: Recognition is growing about the impact of farming on environmental stewardship, but there are few regulations related to dairy farming Farmers rely heavily on hired labour and is already moving away from family operations.

Dairy 3.0

The big leap across many factors of dairying practice, largely characterized by heavy investment in specialized machinery and milking machines. Improvements in feed and nutrition practices, artificial insemination and pedigree selection, standard techniques and refrigeration, disease management protocols, electronic record-keeping and basic data analysis are made. Environmental impact becomes a concern as farms strive to meet minimum environmental standards with waste control measures in place.

Dairy 4.0

The cutting edge of dairy farming, integrating modern technologies to optimize all aspects of operations while ensuring stewardship of the environment and sustainability. This phase represents the Indian agriculture that has undergone a transformation because to information and

communication technology, especially IoT-based solutions, which have increased productivity and protected the environment (Abed *et al.*, 2024).

Components of dairy 4.0 contributing to sustainable innovation

Robotics

Robotics is an idea that the dairy industry has more recently grown into and it has found several applications in this sector (Prasad, 2017). The most successful application of robotics in the dairy industry is the automatic milking systems. The system does allow a considerable average increase in milking frequency and, hence, higher milk yield through the reduction of labor costs (Bhoj *et al.*, 2022). Among the other benefits associated with the automatic milking systems, they have been identified to mainly increase overall productivity, profitability and sustainability (Cogato *et al.*, 2021). Another recent developed application of robotics in the dairy farm was the need of on-floor cleaning, which addresses the risks associated with addressing cow welfare and helps in the prevention of ammonia emissions (Hassoun *et al.*, 2023). Moreover, sensors placed into the robotic system allow for momentary and accurate collected data. Such data can be used to predict the value of important parameters such as daily milk yield, milk composition and similarly, precise and real-time data collection can be done through sensors included in the robotic system as shown in Fig 2.

A study reported to have measured concentrations of composition and enzymatic activity of milk from dairy farms using robotic and conventional milking systems. They found some variances, which may indicate that the management method had a major impact (Johansson *et al.*, 2017).

3D printing

3D food printing is a manufacturing system that provides flexibility in the shape and composition of food products, added utilization of ingredients and the potential for the creation of food items that meet personalized nutritional needs (Sun *et al.*, 2015), refer (Fig 3). Applications are currently used in the production of chocolate, meat and

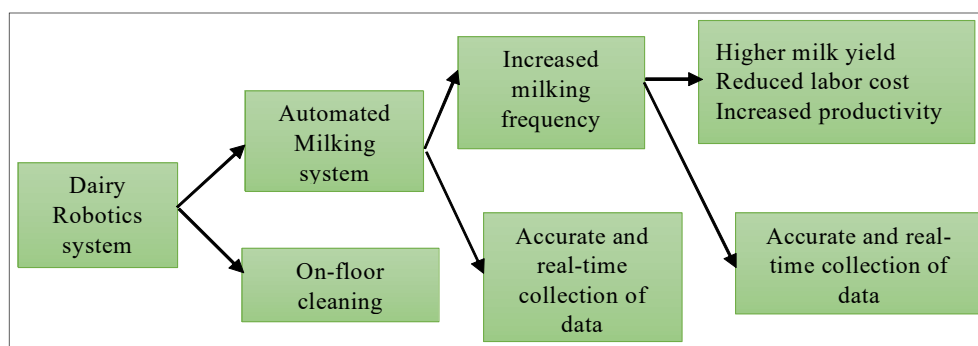


Fig 2: Benefits of robotics in dairy system.

meat analogues, egg white protein products and fruit and vegetable smoothies (Lee, 2021). Unshaped fruits and vegetables or insect proteins were utilized in the creation of 3D printed food, which reduced the excretion of food waste and CO₂ by livestock (Ramachandraiah, 2021). In the recent years, 3D printing of milk-based products has gained the interest of both food companies and researchers. The scope of dairy 3D printing was discussed under five concepts: innovative, futuristic, healthy, efficient and sustainable. The printer's most preferred device for extrusion-based 3D printing material had been the combination of a milk powder paste with whey protein isolate and milk protein concentrate mixed at a precise ratio (Liu *et al.*, 2018). Liu *et al.* (2018) conducted further to prove that the greatest performance levels for the milk protein gel were obtained when liable for a 3D printing material and these provided a 3D object that closely matched the model with a good degree of fidelity. Three-dimensional printed food has even been used to support environmental sustainability (Zhu *et al.*, 2023). The challenges in 3D printer in food printing are represented in Fig 4.

Big data

Big Data analytics is said to have significant applications in dairy farm as presented in Fig 5. It includes the improvement of dairy farm management, milk output prediction, quality improvement and on-farm decision making (Cabrera *et al.*, 2020). The milk output prediction

and Analysis tool is an affordable tool that determines milk output on the individual and group levels of cows through big data (Fuentes *et al.*, 2020). Through strategic management, the application of Big Data in dairy farming has demonstrated remarkable potential in enhancing animal production and health as well as dairy farm profitability. Real-time data collection, integration, management and analysis are provided by the system for both on- and off-farm data, enabling useful applications including nutrition grouping, early clinical mastitis diagnosis and clinical mastitis onset prediction (Kaur *et al.*, 2023). An important area of research for the application of big data is animal health assessment. Since it is a multi-faceted concept, assessing the overall health of animals is a daunting task and researchers usually focus on disease identification.

Internet of things

IoT can collect and send out a wide range of data, including temperature, heart rate and mobility of cows, which give insights into the animals' health, location and behavior-for example when they stand, lay, eat (Choudhary *et al.*, 2020), (Fig 6). The farmer can use this data to make informed decisions about the health, nutrition and frequency of milking of their cows. IoT creates many prospects for gathering and disseminating real-time dairy data. In fact, new studies have proposed to use IoT to automate cow feeding and, as a result, be able to dollop up individual nutrition regimens for cows that are claimed to become

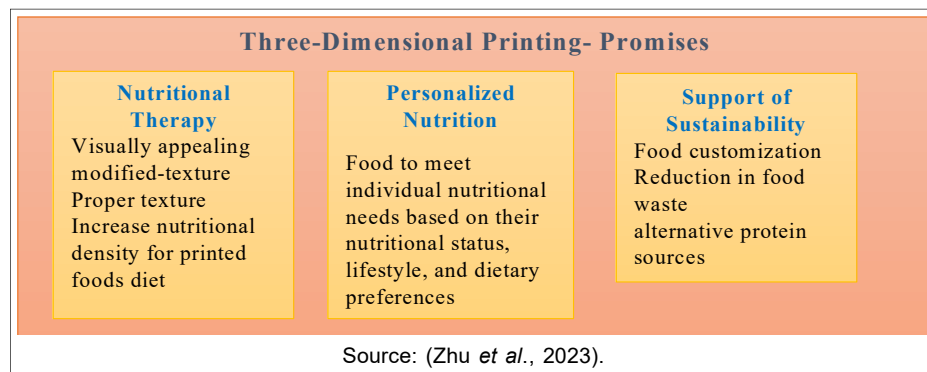


Fig 3: Three-dimensional printing-promises.

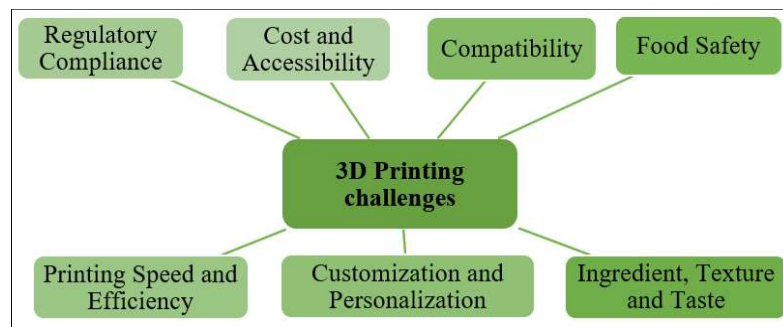


Fig 4: 3D printing challenges.

really helpful in terms of microdosing, as well as foretell the milk output of individual cows more correctly (Cheng *et al.*, 2023). The cows' heart rates and temperatures are recorded by the IoT sensors, which gives information on the cow's health and allows for disease diagnosis and the most adequate treatment and prevention method to be identified.

Artificial intelligence (AI)

AI has mostly been used to evaluate the health and welfare of cows for dairy products (Zhang *et al.*, 2024). This is because the dairy sector has a great demand for reliable, automated and reasonably priced equipment for the examination of dairy products. In dairy farming, AI may extract data from a variety of underutilized sources to streamline tedious and challenging decision-making processes integrated (Taneja *et al.*, 2023). AI determines the best way to care for cows based on the effects of physiological and environmental variables to provide milk with higher quality. Dairy 4.0 also uses AI to improve product quality, customer demand and dairy farming practices (Amin *et al.*, 2018). With the limited shelf life of most goods in the dairy business, demand forecasting is critical. AI has been used to demand prediction and product portfolio risk calculation (Hassoun *et al.*, 2023).

Customers are becoming more and more concerned about food quality, but there aren't many resources available outside of cutting-edge labs and the inspection systems in place can't keep up with the numerous risks to food integrity. It has been proposed that food products use sound vibrations in conjunction with AI to determine adulteration and confirm quality. Fig 7 represents the outcome and impacts of AI.

Block chain

Blockchain is yet another technology that has been revolutionizing different sectors enabling the customers to trace the production and quality of their products (Sinha *et al.*, 2023). In a quest to aid in feeding a growing population across the world using sustainable methods, blockchain technology could be leveraged in the development of smart ecosystems for milk supply chains. Mangla *et al.* (2021) explored how the use of blockchain technology could enhance social sustainability of milk supply chains in Turkey. They found several merits with the use of such technology, like prevention of food fraud, development of rural areas, safeguard concerning the welfare and health of animals and advancement of wholesome food and food security.

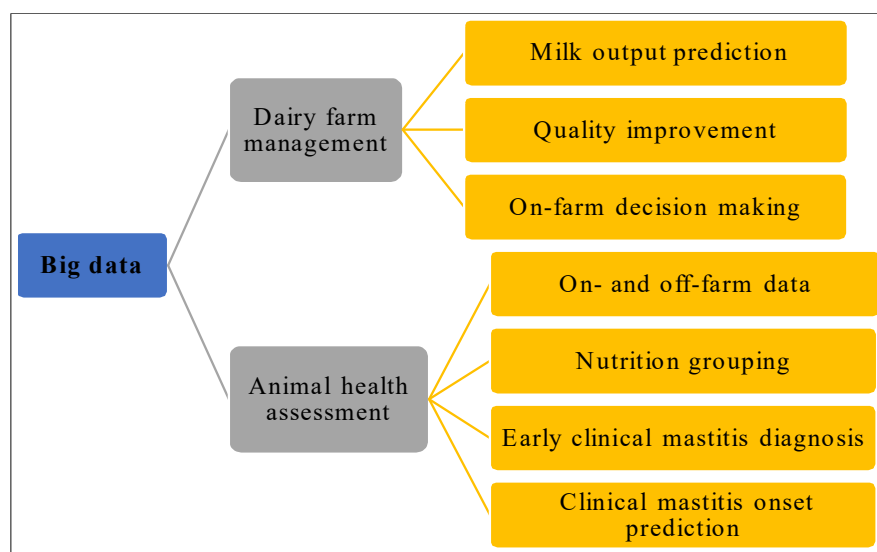


Fig 5: Big Data benefits in dairy system.

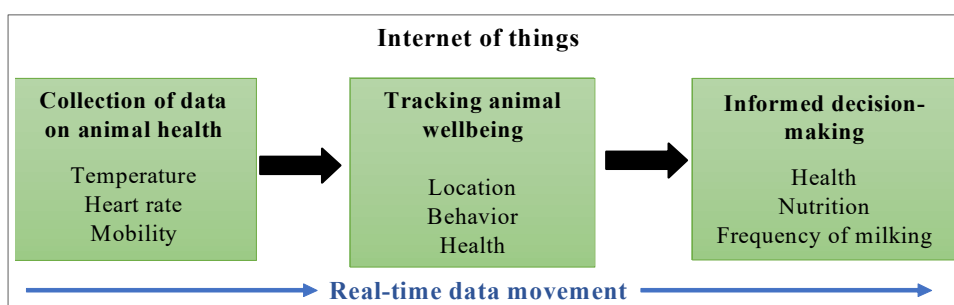


Fig 6: Internet of things benefits in dairy system.

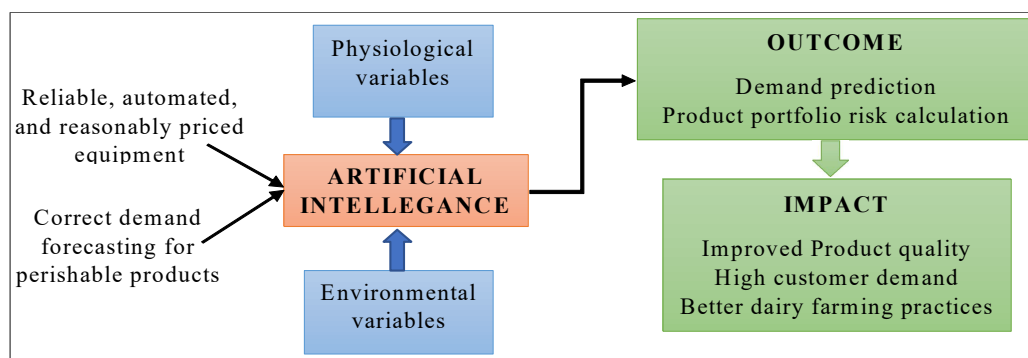


Fig 7: Impact of AI on the dairy system.

Thus, it can be understood that Dairy 4.0 is a significant revolution in dairy industry that is capable of completely transforming the business right from supplier to the customer end.

This paper reviewed articles in the domain of dairy 4.0 in dairy firms and found that there are significant benefits to the dairy stakeholders due to the adoption of technology. The Indian dairy industry has experienced significant transformation due to rapid technological advancements. Automation technologies have simplified dairy processes, enhancing production, labour costs and efficiency. Precision farming, using modern sensors and data analytics, optimizes feed and water, leading to better milk quality and increased production. Smart dairy farming, a system of Industry 4.0, collects data using blockchain, big data, artificial intelligence, RFID robotics and the internet of things to improve milk output profitability by way of advanced data collection, analysis and automation. This technology also aids in breeding, increasing the number of climate-adapted and disease-resistant cows, increasing milk supply and promoting herd management and sustainability. The parameters monitored by IoT sensors include milk production per cow, health indicators, environment conditions such as temperature and humidity and feed intake. RFID tags attached to cows monitor the movement of each particular animal concerning its health record and feeding patterns; all this information will be availed in real-time. Big data analytics processes this huge amount of information, which is picked up from IoT sensors and RFID tags. That analysis could, in turn, identify trends, predict milk production cycles, detect health problems at the outset and find the most promising feeding strategies. Historical data can be used for trend analysis and to make informed decisions on breeding, nutrition and herd management. AI Algorithms can evaluate data to finetune feeding schedules and dietary requirements of each cow, taking variables of milk yield, body condition scoring and health data into consideration. If applied properly, AI-driven predictive models will be able to project milk production, predict diseases at any time with pattern recognition and advise timely interventions accordingly. Blockchain Technology may aid in effective tracing from farms to the consumers, thus ensuring quality and safety in the

consumption of milk. Block chaining can create a very transparent and secure system with regard to tracing every journey of milk from farm to consumer in food safety, quality, control and traceability. For example, blockchain helps farmers record data right from feeding schedules down to health treatment records and even testing the quality of milk, hence creating a reliable audit trail. By mathematical individual cow schedules, robotic milking systems can milk those cows automatically, according to production level-oriented milking, which in turn reduces labor costs while optimizing milking efficiency. However, harnessing these innovations requires ongoing investment in technology infrastructure and talent development.

Smart dairy farming may employ a few of the technologies that characterize Industry 4.0, such as blockchain, big data, artificial intelligence, RFID, robotics and the Internet of Things, which can be deployed to improve milk output and. Here's how these technologies contribute to the same.

Discussion

The development, from very generic beginnings to the present form of Dairy 4.0, is parallel to the development of industry in general-from Industry 1.0 to Industry 4.0. Early forms of dairy farming, much like Industry 1.0, had primitive mechanization, where human labor was the main driving force behind basic efficiency and productivity improvements. Mechanization began with Dairy 1.0 and primarily consisted of mechanical milking machines and simple refrigeration systems. For their time, these were revolutionary, but there is little room for improvement on them. These pioneering innovations thus provided an important groundwork for the succeeding phases in demonstrating what advantages mechanization might bring to bear upon the industry, yet to be sure, most of the production processes were still manually done and followed traditional methods.

After the Industry 4.0 revolution, the Dairy 4.0 is a new paradigm for the milk industry with particular emphasis on the application of new and innovative digital technologies. Some of the technologies that combine to move this stage forward include robotics, 3D printing (Liu et al., 2018), big data, IoT, AI and blockchain, enabling tremendous gains

to be witnessed in sustainability, efficiency and productivity. For instance, robotics has transformed milking methods into automated milking systems that, apart from increasing milking efficiency, also reduce labor and minimize animal stress. These can work day and night to provide consistent high-quality milk production. 3D printing and big data have revolutionized dairy farming by enabling customization and innovation in machinery and parts production. These advancements reduce downtime and improve farm management. Big data analytics and IoT devices provide actionable insights, improving farm efficiency and animal welfare. AI and AI enable predictive decision-making and proactive problem-solving (Dopico *et al.*, 2016). Blockchain technology enhances milk traceability, increasing customer trust and enhancing food safety and quality control. Automation has revolutionized mechanization by eliminating labor-intensive tasks.

Healthcare practices have now moved from being curative to proactive engagement with the use of IoT and AI for early detection and management of diseases. The environmental impact of dairy farming has also been addressed through these advancements. Precision agriculture and automated systems allow for more efficient use of resources, reducing not only waste but also emissions. In light of modern technologies, the highlight of sustainability includes the optimization of operations that reduce environmental impacts to a minimum in dairy production.

Generally, Dairy 4.0 is radically different from its predecessors and advanced with the application of different digital technologies. These have been the novelties that transform productivity, sustainability, and efficiency in all aspects of dairy farming. These are challenges of technological adoption and infrastructure and knowledge gaps; these are things that must be faced if true potential is to be unveiled within the sector of Dairy 4.0. This overview has underlined the need for further research and investment in technology as a means of overcoming these obstacles and further improving the dairy industry.

CONCLUSION

The dairy industry in India faces challenges in implementing modern technology due to lack of access, poor infrastructure and lack of awareness among farmers. This knowledge and skills gap contribute to the disparity in adoption. To address these issues, industry stakeholders should collaborate with legislators, invest in technology and infrastructure and develop training programs for farmers. A cooperative approach can drive the industry towards growth and sustainability. Advanced tracking technologies, such as QR codes, can enhance traceability and transparency, boosting customer confidence and facilitating effective communication between shippers and carriers. Not much of research work is done on the concept of dairy 4.0. Hence, the review of this study is based on the limited literature available. Future research can focus on

conducting primary investigation with dairy owners and analyse their preparedness for dairy 4.0.

Conflict of interest

The authors have no conflict of interests to declare that are relevant to the content of this article.

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