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A Technology Based Dairy Industry Revolution: Dairy 4.0

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Food sustainability is currently confronted with several unprecedented challenges, including climate change, pandemics, geopolitical tensions, and increasing pressure on global food resources. Addressing these challenges requires the development of resilient food systems supported by technological innovation and the adoption of advanced production and processing approaches. The dairy sector is particularly vulnerable to climate change and other global food-system challenges, while simultaneously contributing substantially to greenhouse gas emissions. Nevertheless, dairy products remain important sources of essential nutrients and bioactive compounds, making the sector vital for global food and nutritional security. Ensuring the quality and safety of dairy products requires careful control of critical processing and operating conditions, particularly because dairy products are highly perishable. At the same time, increasing environmental concerns and changing consumer demands have encouraged dairy manufacturers to adopt more sustainable processing methods and innovative technologies. The dairy industry has consequently emerged as a rapid adopter of automation and digital technologies associated with the Fourth Industrial Revolution (Industry 4.0) (Hassoun et al., 2023). Key Industry 4.0 technologies relevant to the food sector include Artificial Intelligence (AI), robotics, smart sensors, the Internet of Things (IoT), Big Data, cloud computing, blockchain, 3D printing, augmented reality, cybersecurity, digital twins, and cyber-physical systems. Their application in agriculture is commonly described as Smart Farming, Precision Agriculture, or Agriculture 4.0, whereas their integration into food-processing facilities has contributed to the development of smart factories. Within the dairy sector, the increasing integration of automation, digitalization, data analytics, and intelligent technologies across production and supply chains is collectively referred to as Dairy 4.0. This

transition has the potential to improve productivity, product quality, traceability, resource efficiency, sustainability, and overall resilience throughout the dairy value chain.

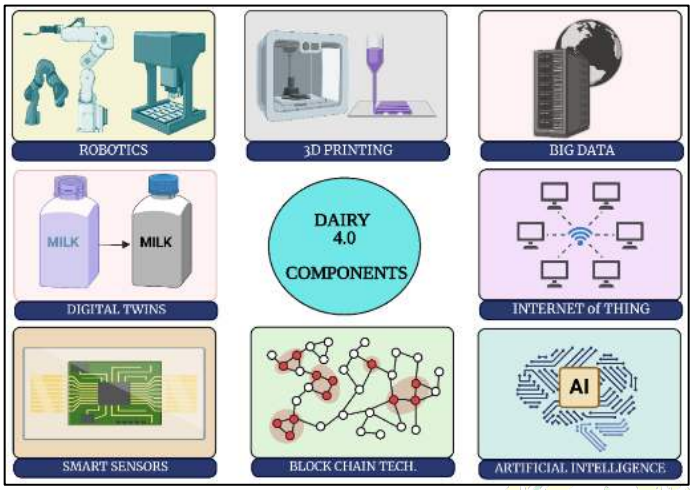

Fig. no. 1: The Components of Dairy 4.0 Industrial Revolution

Artificial Intelligence (AI)

Artificial Intelligence (AI) is an important technology within Dairy 4.0, enabling automation, real-time monitoring and data-driven decision-making. AI can analyse animal behaviour, physiological parameters and environmental conditions to assess dairy cow health and welfare, supporting early disease detection and optimized treatment. It can improve milk yield, milk quality and production efficiency while reducing labour and management costs. AI-based demand forecasting can help dairy industries optimize production and product portfolios, particularly for short-shelf-life products. Computer vision, machine learning and sound-based technologies can support food quality assessment, adulteration detection and cheese-quality monitoring. AI can also assist in improving the sensory characteristics of dairy products. Furthermore, AI-based systems can help manage heat stress in dairy cattle and maintain milk quality under changing climatic conditions. Computer vision can estimate physiological indicators such as respiration and heart rate for predicting milk production and quality. AI combined with aerial imagery can also estimate herd size and methane emissions. Overall, AI has considerable potential to improve productivity, animal welfare, food quality and sustainability in the dairy sector (Hassoun et al., 2023).

Robotics

Robotics integrates mechanical, electrical, electronic, and software technologies to automate tasks ranging from routine operations to complex processes. Its application in the dairy industry has expanded significantly, particularly with the development of Automatic Milking Systems (AMS). These systems automate milking, increase milking frequency, reduce labour requirements, and potentially improve milk production, farm profitability, operational efficiency, and sustainability. Robotics is also being used for floor cleaning, helping maintain farm hygiene, enhance cow welfare, and reduce ammonia emissions. Moreover, sensors incorporated into robotic systems enable continuous and accurate collection of real-time data on animal behaviour and milking activities. These data can be analysed to monitor and predict important production parameters, including daily milk yield, milk composition, and milking frequency. Overall, the integration of robotics, sensors, and data analytics supports efficient, automated, and sustainable dairy farm management (Hassoun et al., 2023).

IoT (Internet of Things)

The Internet of Things (IoT) is a network of interconnected devices that enables real-time collection, exchange, and processing of data. In dairy farming, IoT supports the development of smart and data-driven management systems by providing accurate information for automated monitoring and decision-making. IoT connects physical farm operations with digital platforms through wireless communication and smart sensors. These sensors can monitor important parameters such as cow activity, milk production, animal health, lameness, and body condition. Sensors for monitoring activity and milk yield are relatively well established, whereas technologies for lameness detection and body condition assessment are still emerging. The integration of IoT with data analytics can improve farm efficiency, animal health monitoring, productivity, and management decisions. However, adoption varies among dairy farms and is influenced by economic, technological, social, and behavioural factors. Farmers' acceptance depends on perceived costs and benefits, trust, technical knowledge, infrastructure, and accessibility. Therefore, successful adoption of IoT requires addressing both technological barriers and user-related factors to achieve effective and sustainable digital transformation in dairy farming (Hassoun et al., 2023).

3D Printing

Three-dimensional (3D) printing, or additive manufacturing, is an emerging food-processing technology that uses digital designs to create customized solid and semi-solid food products. Its application in the dairy sector has increased due to the diverse functional and structural properties of dairy ingredients such as proteins and fats. However, these properties also create challenges related to flowability, shape retention, structural stability, and printing accuracy. Dairy 3D printing is being explored for futuristic, creative, healthy, efficient, and sustainable food production. Studies have shown that formulations containing milk protein concentrate (MPC) and whey protein isolate (WPI) are suitable for extrusion-based 3D printing. Milk protein gels have demonstrated good printability, structural stability, and high fidelity to designed shapes. Moreover, hydrocolloids can improve the microstructure, viscoelastic properties, and printing performance of milk protein formulations. Thus, 3D printing offers promising opportunities for innovative, personalized, and functional dairy product development (Sangode, 2025).

Big Data

Big Data refers to large and complex datasets that require advanced technologies for efficient processing and analysis. In the dairy industry, substantial data are generated from milk production, milk quality, animal health, farm operations, environmental conditions, and supply chains. Big Data Analytics can convert these datasets into useful information for improving farm management, predicting milk yield, monitoring animal health, enhancing milk quality, and supporting real-time decision-making. Tools such as the Milk Yield Prediction and Analysis Tool (PAT) can predict milk production at individual-cow and herd levels, providing a cost-effective decision-support approach for dairy farmers. Similarly, the Dairy Brain, which integrates precision agriculture, IoT, and Big Data

Analytics, analyses farm and external data in real time to support nutrient management, early detection of clinical mastitis, and prediction of disease occurrence. Big Data also enables more comprehensive assessment of animal health by combining multiple physiological, behavioural, and environmental indicators. Overall, Big Data Analytics provides a data-driven approach to improving productivity, animal health, resource efficiency, and decision-making, contributing to more efficient and sustainable dairy farming (Sangode et al., 2025).

Blockchain

Blockchain is an important Industry 4.0 technology that can improve the transparency, security, traceability, and efficiency of food supply chains. It uses cryptographically secured, decentralized ledgers to record and share information among supply-chain participants, reducing risks associated with data loss, adulteration, quality deterioration, and limited traceability. When integrated with IoT and other digital technologies, blockchain enables real-time data sharing, auditability, data integrity, and product authentication. In the dairy sector, it can provide traceability throughout the entire milk supply chain, from production and collection to processing, distribution, and consumption. Blockchain can also support monitoring of nutritional quality, adulteration, and contamination. Therefore, its integration into dairy supply chains can enhance food safety, consumer confidence, product authenticity, and sustainability while supporting the development of intelligent and reliable dairy value chains (Hassoun et al., 2023).

Sensor Based Monitoring

The integration of IoT and automation in dairy farming is transforming conventional livestock management through continuous, real-time monitoring of animals, equipment, and farm conditions. IoT-enabled sensors can detect early health problems, monitor feeding behaviour, and support improved animal welfare, thereby reducing veterinary costs and enhancing productivity and milk quality. Regular assessment of Body Condition Score (BCS) and Body Weight (BW) helps evaluate nutritional status, monitor growth, and support informed breeding and management decisions. Automatic Milking Systems (AMSs) further improve farm efficiency by automating milking and enabling individualized cow monitoring and management. In addition, IoT-based systems facilitate real-time monitoring of farm machinery, allowing early detection of equipment failures and minimizing operational interruptions. The integration of robotics further reduces labour requirements while improving productivity and competitiveness. Overall, IoT, robotics, and automation provide an integrated, data-driven approach to herd management, milk production, feeding, equipment monitoring, and environmental control, promoting efficient, sustainable, and modern dairy farming (Tangorra et al., 2024).

Current Scenario and Future Challenges

Despite the potential benefits of Industry 4.0 technologies, several challenges must be addressed for their effective adoption in the dairy sector. A major limitation is the lack of digital infrastructure and reliable connectivity in rural areas, where most dairy farms are located, restricting the use of precision farming, automated milking, and other smart

technologies. The high investment cost of advanced technologies is another significant barrier, particularly for small and medium-sized farms with limited financial resources. This may widen the digital divide between large and small farms, giving larger enterprises a competitive advantage. Furthermore, the adoption of Industry 4.0 requires skilled personnel capable of operating, maintaining, and managing advanced technologies. Providing appropriate training can be difficult for smaller farms due to limited resources and access to skilled workers. Data privacy and cybersecurity are also growing concerns because of increased connectivity and data sharing. Finally, successful implementation requires greater collaboration and coordination among supply-chain stakeholders to integrate digital technologies effectively with existing dairy production and management systems.

Conclusion

In conclusion, digitalization and technological advancements offer significant opportunities to improve the efficiency, productivity, sustainability, and competitiveness of the dairy industry. However, their full potential can only be achieved by addressing key challenges such as inadequate digital infrastructure and connectivity, high implementation costs, shortage of skilled personnel, and limited coordination among supply-chain stakeholders. Overcoming these barriers will require investment in digital infrastructure, affordable and accessible technologies, skill development, and stronger collaboration across the dairy value chain. Addressing these challenges will be essential for ensuring the successful adoption of Industry 4.0 technologies and building a modern, resilient, competitive, and sustainable dairy industry capable of meeting future production and market demands.

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