

TRANSFORMATION OF THE DAIRY INDUSTRY (2000–2030): FROM A TRADITIONAL FOOD SYSTEM TO MOLECULAR AND DIGITAL PRECISION

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Abstract

This paper presents an overview of the structural, technological, and bioindustrial evolution of the dairy industry during the period 2000–2030, with a particular focus on its transformation from a traditional food system into a biotechnologically and digitally integrated production model. The analysis encompasses the transitional phase from 2000 to 2010, characterized by the intensive development of membrane technologies, advanced separation processes, and the industrial standardization of dairy components into functional ingredients with high added value. The period from 2010 to 2020 was marked by the expansion of the circular economy concept, the valorization of dairy by-products, and the development of functional dairy matrix systems based on interactions between nutrients and the biological activity of food. During the 2020–2030 phase, the industry has been transforming toward a “Dairy 4.0” model, founded on the integration of artificial intelligence, digital technologies, precision fermentation, biofractionation, and automated production management systems. In conclusion, the contemporary development of the dairy sector indicates an intensive convergence of nutritional science, biotechnology, and digital systems aimed at improving the functional properties of dairy products, resource efficiency, and the long-term sustainability of production.

Keywords: Dairy matrix, Dairy 4.0, precision fermentation, circular economy, milk processing, functional food.

Introduction

From a historical perspective, milk and dairy products have represented one of the fundamental elements in the development of human nutrition and civilization, providing a significant source of energy and nutritional security since the Neolithic period and the emergence of early agrarian communities (Evershed et al., 2008; Dunne et al., 2012). Archaeological and biomolecular evidence indicates that the introduction of dairy consumption constituted an important adaptive strategy in human evolution, enabling continuous access to high-quality proteins, lipids, and essential micronutrients, thereby contributing to improved nutritional status, demographic expansion, and the development of early agricultural populations (Leonardi et al., 2012).

In the traditional context, milk was predominantly valued as a concentrated source of calcium, phosphorus, vitamins, and highly bioavailable proteins, essential for growth, skeletal development, and the maintenance of physiological and metabolic functions in the human body (Auestad & Layman, 2021; Mulet-Cabero et al., 2024). However, contemporary scientific research has substantially broadened this perspective, with dairy products now being described as complex biological systems exhibiting pronounced functional and nutritional effects on human health (Huppertz et al., 2024). Particular attention has been devoted to the bioactive components of milk, including protein fractions, bioactive peptides, and lipid structures, which may influence a wide range of metabolic, immunological, and physiological processes (Clare & Swaisgood, 2000; Korhonen & Pihlanto, 2006).

Within contemporary dairy science, the concept of the “dairy matrix” has emerged as a key paradigm emphasizing the interactions among nutritional components within their natural structural organization. According to this concept, the health effects of dairy products cannot be fully explained solely by their individual nutrients, but rather arise from their complex

structural, physicochemical, and functional interrelationships (Mulet-Cabero et al., 2024; Huppertz et al., 2024). Recent studies further indicate that the structural organization of the dairy matrix may significantly influence nutrient bioavailability, postprandial metabolism, and the physiological effects of food, representing a substantial shift in the understanding of the role of dairy products in nutrition and public health (Thorning et al., 2017; Lovegrove & Givens, 2022).

Parallel to this scientific evolution, technological advancements in the dairy industry have enabled a transition toward more precise, automated, and biotechnologically advanced systems for production and processing. These transformations include improved membrane separation processes, fractionation technologies, bioprocessing strategies, and the functional modification of dairy components, aimed at optimizing their nutritional, technological, and biological value (Smithers, 2008; Mistry, 2020). During the last decade, the dairy sector has increasingly evolved toward the “Dairy 4.0” concept, which involves the integration of digital technologies, artificial intelligence, automated production control systems, precision fermentation, and sustainable circular economy models (Balthazar et al., 2021; Kapoor & Metzger, 2023).

The transformation of the dairy industry during the period 2000–2030 does not merely represent a process of technological modernization, but rather a systemic shift in the understanding of milk—from a traditional nutritional raw material to a biologically functional and digitally optimized nutritional system. In this context, the present paper analyzes the evolution of the dairy sector, from traditional processing approaches to contemporary concepts of molecular precision, functional nutrition, and digitally integrated production systems.

Evolution of the dairy industry: From industrial standardization to Dairy 4.0

2.1. Industrial standardization and functional transformation of the dairy sector (2000–2010):

The period from 2000 to 2010 represents a pivotal transitional phase in the development of the dairy industry, during which traditional processing technologies were gradually transformed into highly standardized systems oriented toward food safety, functional nutrition, and industrial efficiency (Bintsis & Papademas, 2022). In this context, the global emphasis on hygiene and quality control culminated in the implementation of the ISO 22000 standard in 2005, which integrated HACCP principles throughout the entire food production and distribution chain (ISO, 2005).

In parallel with regulatory standardization, technological advances in membrane processing, ultra-high-temperature (UHT) treatment, and industrial separation technologies enabled substantial improvements in the stability, shelf life, and nutritional controllability of milk, which increasingly came to be regarded as a functional carrier of bioactive compounds (Kumar et al., 2013; Dhillon & Singla, 2024; Blasi & Verardi, 2024). This technological progress contributed to the redefinition of milk from a “fresh food product” into a highly controlled nutritional system with precisely managed properties.

One of the most significant structural shifts during this period was the industrial valorization of whey, which evolved from a by-product of cheese production into a highly valuable raw material for the manufacture of functional ingredients. The isolation and concentration of whey proteins (WPC/WPI) enabled the development of novel applications in sports nutrition, clinical nutrition, and functional foods, thereby laying the foundation for the contemporary understanding of the “dairy matrix” as an integrated nutritional system (Pires et al., 2021; Soumati et al., 2023; Mulet-Cabero et al., 2024).

At the same time, scientific interest became increasingly focused on the selection and industrial application of probiotic microorganisms, particularly strains such as *Lactobacillus rhamnosus* GG and various species belonging to the genus *Bifidobacterium*, with the aim of modulating the gut microbiome and supporting immune function (Reid, 2008; Özer & Kirmaci, 2010;

Marsh et al., 2014). This development led to a significant expansion of the market for fermented functional dairy products, which experienced the fastest growth within the dairy industry during this period.

Concurrently, the period was also characterized by the dominance of the “low-fat” trend, driven by nutritional recommendations advocating reduced intake of saturated fats. This resulted in the intensive development of delipidation technologies, as well as the increased use of hydrocolloids and stabilizers to preserve the texture and sensory properties of dairy products (Knips, 2005; Haug et al., 2007; Zhao et al., 2023).

2.2. Nutritional revolution, the dairy matrix, and the circular bioeconomy (2010–2020): The period from 2010 to 2020 is characterized as one of the most intensive phases in the evolution of the dairy industry, marked by a clear transition from conventional processing toward the molecular and functional engineering of dairy components (Granato et al., 2022). This transformation was supported by advances in nutritional science, process engineering, and systems-based food analysis.

One of the most influential market and technological phenomena during this period was the global expansion of Greek yogurt, which, through the application of advanced separation processes and ultrafiltration technologies, enabled the development of products with high protein density, improved textural stability, and a “clean label” profile (Aryana & Olson, 2017; Paredes Valencia et al., 2018; Lange et al., 2020). This trend further stimulated the industry toward intensified use of membrane technologies for the fractionation of casein and whey protein fractions, aiming at their precise nutritional and functional application.

Simultaneously, substantial scientific progress was achieved in understanding bioactive peptides and their role in metabolic and physiological processes, supported by developments in metabolomics and advanced analytical techniques (Meleti et al., 2025; Luparelli et al., 2025; Waqar et al., 2026). These investigations reinforced the concept of milk as a dynamic source of biologically active molecules rather than merely a static nutritional system.

In parallel, a significant expansion was observed in the valorization of whey as a functional raw material, as well as in the integration of agro-industrial by-products rich in dietary fibers, such as inulin and pectin, enabling the development of a new generation of synbiotic dairy matrices with enhanced health-promoting properties (Ivanović et al., 2017; Iriondo-DeHond et al., 2018; Fluerasu et al., 2025; Mota et al., 2026). This approach represents an important step toward a circular bioeconomy in the food sector, in which waste streams are increasingly transformed into biologically and nutritionally valuable ingredients.

During the same period, a substantial revision of the scientific perception of dairy fats also occurred. Meta-analyses and systematic reviews indicated that the context of the “dairy matrix” significantly modulates the metabolic response, suggesting that dairy fats are not directly associated with increased cardiometabolic risk and may exert neutral or potentially protective effects in certain populations (Thorning et al., 2017; Astrup et al., 2020; Lordan et al., 2020; Bruno et al., 2021).

Toward the end of the decade, the integration of Industry 4.0 concepts gradually began to transform the dairy sector through digitalization, automation, and predictive analytics. The implementation of big data systems, cloud-based production platforms, and sensor technologies enabled more precise monitoring of product quality, production efficiency, and food safety, thereby laying the foundation for contemporary models of personalized nutrition and intelligent management of nutritional systems (Wolfert et al., 2017; Hassoun et al., 2023; Islam et al., 2025).

2.3. Dairy 4.0: Precision nutrition, digital integration, and sustainable production (2020–2030): The period 2020–2030 is characterized as a phase of intensive digital and

biotechnological integration within the dairy sector, in which the focus progressively shifts from mass production toward molecular precision, functional personalization, and enhanced environmental sustainability (Arena et al., 2023; Kaura et al., 2026). In this context, the concept of “Dairy 4.0” describes the synergy between artificial intelligence (AI), the Internet of Things (IoT), sensor systems, and advanced data analytics, enabling continuous monitoring, predictive modelling, and real-time optimization of productivity, animal health, and resource efficiency (Serrano-Torres et al., 2025; Sabale et al., 2026).

Contemporary AI systems in the dairy industry are applied for productivity forecasting, animal behavior analysis, and early disease detection. The application of machine learning and computer vision enables a transition from reactive to predictive farm management based on real biological and environmental data, significantly improving animal welfare and operational efficiency (Hao et al., 2024; García-Méndez et al., 2024).

Table 1. Integrated technological and biotechnological advances in Dairy 4.0 systems (2020–2030)

Technological domain	Key outcomes and scientific contributions	Source
Precision Livestock Farming (AI, IoT, biosensors)	Real-time optimization of nutrition, improved feed conversion efficiency, early detection of metabolic disorders, and significant reduction of methane emissions.	Norton et al. (2019) Benaissa et al. (2020);
AI and IoT monitoring systems	Machine learning for disease detection (including lameness), behavior analysis of livestock and environmental conditions, and optimization of farm decision-making.	Halachmi et al. (2019); Kamilaris & Prenafeta-Boldú (2018)
Precision feeding models	Individualized nutrition leading to reduced methane emissions (5–15%) and improved productivity and nutritional efficiency.	Nielsen et al. (2021); Dijkstra et al. (2018)
Machine learning for production prediction	High predictive accuracy ($R > 0.80$) for milk yield and quality based on climatic and physiological parameters.	Feldmann et al. (2020); Fuentes et al. (2018)
Precision fermentation	Production of casein and whey proteins with structural and functional identity to animal-derived proteins, without the use of animals.	Huang et al. (2021); Gosling et al. (2020)
LCA and sustainability assessment	Significant reduction in greenhouse gas emissions, water use, and land occupation compared to conventional production systems.	Smetana et al. (2022)
AI-based climate and production optimization	Balancing productivity and environmental footprint through integrated models for sustainable livestock management.	Hristov et al. (2018)

In this direction, by 2030 the dairy industry is increasingly positioned as an integrated biotechnological and digital system combining nutritional personalization, automated analytics, molecular precision, and sustainable production.

2.3.1. Future perspectives in clinical nutrition and dairy systems: In future perspectives of nutritional science, it has been proposed that research should further explore the interaction between pharmacologically induced body weight reduction and nutritional strategies aimed at preserving fat-free mass. In particular, in therapies based on glucagon-like peptide-1 (GLP-1) receptor agonists, including semaglutide (Ozempic), clinical studies indicate that a substantial proportion of weight loss may involve reductions in lean mass, representing a potential risk for muscle function and metabolic stability (Batsis & Zagaria, 2018; Ordovas et al., 2018; Rossi et al., 2026).

In this context, it is emphasized that pharmacologically induced weight reduction requires an integrated approach that includes adequate intake of high-quality proteins and structured physical activity, particularly resistance training, in order to maintain muscle protein synthesis

and minimize the loss of fat-free mass (Devries & Phillips, 2015; Phillips & Van Loon, 2011; Morton et al., 2018). Whey proteins, due to their high biological value and richness in essential amino acids - particularly leucine - represent a key nutritional factor in the preservation of lean mass during caloric restriction and rapid weight loss.

Furthermore, contemporary clinical evidence suggests that optimal outcomes in pharmacological weight reduction are achieved through a combined approach integrating pharmacotherapy, nutritional supplementation, and physical activity, thereby improving body composition and reducing the risk of sarcopenia (Morton et al., 2018; Rossi et al., 2026).

Conclusions

The evolution of the dairy industry demonstrates a clear transition from a traditional food system toward a digitally and biotechnologically integrated model. During the period 2000–2030, the development of AI, IoT, precision fermentation, and advanced processing technologies has enabled a transformation toward “Dairy 4.0,” which is based on data-driven decision-making, sustainability, and molecular precision.

These innovations significantly enhance production efficiency, animal welfare, and the environmental performance of the industry. In parallel, contemporary nutritional science emphasizes the need for integrated approaches to maintaining body composition, particularly in the context of pharmacologically induced body weight reduction.

Overall, the dairy sector is evolving toward a highly integrated system that combines nutritional science, biotechnology, and digital intelligence with the aim of improving human health and sustainability.

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