Probiotic And Synbiotic Dairy Foods: Current Technological Challenges And Future Innovations: A Review

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Abstract

Probiotic and synbiotic dairy foods have gained substantial attention due to their proven contributions to gut health, immunity, metabolic balance, and overall well-being. This review provides an updated overview of probiotics, prebiotics, and synbiotics, along with their historical development and scientific definitions. Dairy matrices such as milk, yogurt, and cheese offer nutrient-rich environments that enhance the viability and functional performance of probiotics during processing, storage, and gastrointestinal transit. Market trends indicate increasing consumer interest in clean-label, minimally processed, premium, and microbiome-focused products, which is driving rapid growth in the functional dairy sector. Technological challenges including probiotic survival, encapsulation efficiency, formulation stability, fermentation compatibility, and packaging limitations remain key obstacles to product optimization. Emerging technologies such as next-generation probiotics, plant-fiber-enriched synbiotics, CRISPR-based strain engineering, high-pressure processing, and intelligent packaging offer promising avenues for improving probiotic stability and efficacy. Future developments in personalized nutrition, multi-strain synbiotic systems, dairy-based nutraceutical beverages, and regulatory harmonization are expected to shape the next phase of innovation in this field. Overall, probiotic and synbiotic dairy foods hold strong potential as effective, consumer-friendly functional foods, provided that scientific, technological, and regulatory challenges are adequately addressed.

Keywords: Gut microbiota, functional foods, high-pressure processing, dairy technology, food packaging

1. Introduction

The importance of probiotics was brought to light in 2001 when the definition of probiotics was first established. It was redefined as “live microorganisms that, when administered in sufficient amounts, provide numerous health benefits to the host”. This definition was further refined in 2014 by a panel of scientists from the International Scientific Association for Probiotics and Prebiotics (ISAPP) as “this definition encompasses a wide range of microbes and applications, while capturing the essence of probiotics" (Chandrasekaran *et al.,* 2024) [4]. The concept of prebiotics was first introduced in 1995 by Glenn R. Gibson and Marcel Roberfroid, who explained that prebiotics are non-digestible food ingredients that selectively stimulate the growth or activity of one or a limited number of bacteria in the colon, with beneficial effects on the host, thereby improving host health. Later, in 2004, Glenn R. Gibson and Hollie M. Probert proposed three criteria: (i) resisting hydrolysis by mammalian enzymes and gastrointestinal absorption and gastric acidity; (ii) fermented by gut microorganisms; (iii) selectively stimulating the activity and growth of gut bacteria involved in health and well-being. In 2016, the International Scientific Association for Probiotics and Prebiotics (ISAPP) redefined prebiotics as a selectively utilized substrate by host microorganisms conferring a health benefit. The criteria for defining prebiotics are evolving gradually. This review will focus on prebiotics in a broader sense. (Yoo *et al.,* 2024) [27].

Synbiotics are formed when probiotics and prebiotics are coupled. Synergistic effects between probiotics and prebiotics are significant due to the advancement of preserving and introducing living microorganism supplements in the gastrointestinal tract. Synbiotics offer the advantage that probiotics are more readily available in the gastrointestinal tract. (Siddiqui *et al.*, 2023) [22].

Importance of dairy as a delivery matrix (milk, yogurt, cheese)

Dairy products such as milk, yogurt, and cheese are considered ideal delivery matrices for probiotics and synbiotics because they offer a nutrient-rich, protective environment that enhances the survival, stability, and functionality of beneficial microorganisms (Yao *et al.,* 2024) [26]. The natural composition of dairy rich in lactose, casein, whey proteins, minerals, and fats acts as a buffer against stress during food processing, storage, and gastrointestinal transit (Singh *et al.,* 2023) [23]. The near- neutral pH and high-water activity enable probiotics to remain metabolically active, while lactose serves as an energy source, supporting their growth and viability. Fermented dairy products like yogurt provide an acidic yet stable ecosystem where probiotics can coexist with starter cultures and maintain high cell counts (Coelho *et al.,* 2022) [7]. Lactic acid bacteria in raw-milk cheeses: From starter cultures to probiotic functions. Foods, 11(15), 2276.). Cheese, especially semi-hard and hard varieties, offers a more stable microstructure with low oxygen, limited moisture, and longer shelf life, making it one of the most effective carriers for delivering high probiotic loads (Falih *et al.,* 2024) [13]. Furthermore, consumers widely accept dairy- based functional foods, and they align well with the concept of delivering health benefits through everyday dietary habits, strengthening their commercial and nutritional relevance as delivery vehicles for probiotics and synbiotics.

Market and consumer trends

The demand for probiotic and synbiotic dairy products has grown steadily in recent years, driven mainly by increasing awareness of gut health, immunity, and preventive nutrition. Yogurt, fermented milk drinks, and probiotic beverages remain the most popular categories due to consumer familiarity and convenience. Synbiotic formulations are also gaining attention because they offer enhanced functional benefits by combining probiotics with prebiotics (Ali *et al.*, 2022) [1].

Consumers increasingly prefer clean-label**,** minimally processed products, which encourages the use of natural prebiotics and gentle processing technologies. There is also a notable rise in premium and fortified dairy products, including high-protein probiotic drinks and strain-specific formulations. Although plant-based probiotic options are expanding, dairy products remain dominant because of their superior ability to maintain probiotic viability (Chauhan and Rao, 2024) [5]. Personalized nutrition, online retail, and microbiome-focused products are shaping purchasing behavior, while emerging markets such as India show rapid growth due to rising incomes and expanding dairy infrastructure. At the same time, regulatory bodies are placing greater emphasis on accurate labeling and validated health claims, influencing how manufacturers design and market probiotic and synbiotic dairy products.

2. Technological Challenges

a. Viability of Probiotics

Maintaining the viability of probiotic cells throughout processing, storage, and consumption is one of the major technological challenges in developing probiotic and synbiotic dairy products. Probiotics are sensitive to several processing and environmental factors that can reduce their cell count and functional activity.**Survival during processing (heat, homogenization):** Many probiotic strains are heat-labile and cannot withstand pasteurization, high-temperature treatments, or intense homogenization. These processes can damage cell membranes and significantly reduce viable counts (Rabbani *et al.*, 2025) [18].

- **Oxygen sensitivity:** Several probiotic species, particularly *Bifidobacterium*, are anaerobic or microaerophilic (Chen *et al.*, 2022) [6]. Exposure to oxygen during mixing, filling, and storage decreases their stability and survival.
- **Storage stability:** Viability decreases over time due to temperature fluctuations, moisture changes, and interactions with other food components. Probiotics require refrigeration and optimal water activity to maintain the required CFU levels until the end of shelf life (Zavišić *et al.*, 2023) [28].
- **Acidity tolerance:** In fermented dairy products, the acidic environment can stress probiotic cells. Low pH during fermentation and storage may cause membrane damage, reducing their survival before ingestion (Sionek *et al.*, 2024) [24].

b. Encapsulation Technologies

Encapsulation is widely used to enhance the survival of probiotics during processing, storage, and gastrointestinal transit. It provides a physical barrier that protects cells from heat, oxygen, acidity, and mechanical stress commonly encountered in dairy processing.

- **Microencapsulation methods (spray drying, freeze drying, extrusion):** Spray drying is a cost-effective technique that converts probiotic suspensions into dry powder, though high temperatures may reduce viability. Freeze drying preserves cell integrity more effectively by removing water at low temperatures, resulting in higher survival rates. Extrusion involves forming gel beads containing probiotics under mild conditions, offering excellent protection but with higher production costs (Ermis *et al.,* 2022) [12].
- **Protective materials (alginate, chitosan, proteins):** Alginate is one of the most commonly used encapsulating polymers due to its biocompatibility and ability to form stable gels (Siberi Riseh *et al.,* 2021) [20]. Chitosan provides an additional protective coating with antimicrobial resistance and controlled release properties (Asadi *et al*., 2022) [2]. Milk-derived proteins such as whey protein isolate and casein can also be used to encapsulate probiotics, improving their stability and compatibility with dairy matrices.

c. Product Formulation Issues

Product formulation plays a critical role in maintaining probiotic viability and ensuring desirable sensory characteristics in dairy products.

- **pH adjustment:** Probiotics are sensitive to low pH, especially in fermented products such as yogurt. Maintaining an optimal pH during and after fermentation is essential to prevent excessive acid stress and loss of viability (de Souza *et al.,* 2023) [9].
- **Texture and syneresis:** Probiotics can influence the textural properties of dairy products. Issues such as whey separation (syneresis), viscosity changes, or graininess may occur, requiring stabilizers or

  adjustments to fermentation conditions (Arab *et al.,* 2023) [2].
- **Interaction with milk components (lactose, casein):** Milk components can support or inhibit probiotic survival. Lactose serves as an energy source, while casein and whey proteins can form protective microstructures around cells. However, protein- probiotic interactions may also affect texture and fermentation kinetics (Zhao *et al.,* 2024) [29].

d. Fermentation Challenges

Fermentation introduces several challenges that influence probiotic performance and product quality.

- **Selection of strains compatible with dairy cultures:** Probiotic strains must coexist with traditional starter cultures without inhibiting each other or altering expected product characteristics.

- **Co-culturing difficulties:** Differences in growth rates, nutrient requirements, and metabolic activities can complicate co-fermentation, affecting probiotic counts and sensory outcomes (Dhiman *et al.*, 2025) [10].
- **Phage sensitivity:** Bacteriophages can infect starter and probiotic cultures, leading to fermentation failure, reduced viability, or inconsistent product quality (White *et al.*, 2022) [25].

e. Packaging Challenges

Packaging conditions directly influence probiotic survival during storage and distribution.

- **Oxygen permeability:** Many probiotic strains are oxygen-sensitive; therefore, packaging materials must minimize oxygen exposure to prevent oxidative damage and viability loss (Đinh *et al.*, 2025) [11].
- **Light sensitivity:** Exposure to light can accelerate oxidative reactions and reduce probiotic stability, making opaque or UV-protective packaging desirable.
- **Cold-chain requirements:** Most dairy-based probiotics require consistent refrigeration to maintain viable cell counts until the end of shelf life. Temperature fluctuations during storage and transport remain a major challenge.

3. Health Benefits and Mechanisms

Probiotic and synbiotic dairy products provide several documented health benefits, largely mediated through their interaction with the gastrointestinal system and host immune responses.

- **Gut microbiota modulation:** Probiotics help restore and maintain a balanced gut microbiota by increasing beneficial bacterial populations and reducing pathogenic species. Their metabolic activities, such as short-chain fatty acid production, contribute to improved gut barrier function and overall digestive health (Dahiya and Nigam, 2023) [8].
- **Immune enhancement:** Certain probiotic strains stimulate components of the immune system, including macrophages, dendritic cells, and natural killer cells. They can enhance antibody production (particularly IgA) and regulate cytokine responses, contributing to improved resistance against infections (Mazziotta *et al.*, 2023) [17].
- **Lactose intolerance reduction:** Probiotic cultures, especially *Lactobacillus* species, produce β-galactosidase, which assists in lactose digestion.

  Regular consumption of fermented dairy products can reduce symptoms such as bloating, gas, and discomfort in lactose-intolerant individuals (Ibrahim *et al.*, 2021)

  [14].
- **Anti-inflammatory and anti-obesity effects:** Probiotics may reduce systemic inflammation by modulating cytokine profiles and improving intestinal permeability. Some strains also influence

energy metabolism and appetite regulation, contributing to reductions in body weight, fat accumulation, and metabolic markers associated with obesity (Mafe *et al.,* 2025) [16].

4. Emerging Technologies & Innovations

Advances in biotechnology and food processing are creating new opportunities to improve the stability, functionality, and health benefits of probiotic and synbiotic dairy products.

- **Next-generation probiotics (e.g., *Akkermansia, Bifidobacterium longum* BB536):** These strains are gaining attention for their targeted metabolic and immunological benefits. Incorporating next-generation probiotics into dairy matrices requires optimized processing conditions to maintain viability and functional activity (Li *et al.,* 2023) [15].
- **Synbiotic dairy fortified with plant fibers:** Adding natural prebiotic fibers such as inulin, FOS, or resistant starch enhances probiotic growth and survivability while improving gastrointestinal benefits. Such combinations also support clean-label and functional- food trends (Shin *et al.,* 2021) [21].
- **CRISPR-based strain modification:** CRISPR tools enable precise genetic editing to enhance stress tolerance, improve metabolic capabilities, or increase the safety profile of probiotic strains. This technology can produce strains better suited for dairy environments and processing conditions.
- **High-pressure processing (HPP) for improved survival:** HPP is a non-thermal technique that maintains product quality while reducing microbial load. When optimized, it can help preserve probiotic viability and extend shelf life without damaging sensory attributes.
- **Smart/intelligent packaging for probiotic count:** Modern packaging technologies incorporate oxygen scavengers, moisture regulators, or biosensors that monitor probiotic viability. These systems help maintain stability and provide real-time quality information to manufacturers and consumers.

5. Future Prospects

The probiotic and synbiotic dairy sector is expected to expand significantly as consumer awareness and technological capabilities continue to grow.

- **Personalized probiotic dairy products:** Future formulations may target individual microbiome profiles, offering tailored benefits for digestion, immunity, or metabolic health. Microbiome-based diagnostics will support this personalization.
- **Multi-strain and multi-fiber synbiotics:** Combining diverse probiotic strains with multiple prebiotic fibers can provide broader and more robust functional benefits, supporting gut health through synergistic mechanisms.
- **Dairy-based nutraceutical beverages:** Functional dairy drinks enriched with bioactive compounds, vitamins, minerals, and customized probiotic blends will drive product innovation, especially in on-

the-go and clinical nutrition markets.

- **Regulatory challenges (FSSAI, EFSA, FDA):** Stricter regulations require validated evidence for health claims, accurate strain identification, and assurance of probiotic viability at the end of shelf life. Meeting these standards will be essential for product approval and consumer trust.

6. Conclusion

Probiotic and synbiotic dairy foods offer an effective way to deliver health-promoting microorganisms because dairy matrices support good survival and functionality. However, challenges such as maintaining viability during processing, storage, and digestion still limit product performance. Advances in encapsulation, fermentation control, packaging, and emerging technologies are helping improve stability and efficacy. With growing interest in gut health, personalized nutrition, and functional beverages, probiotic and synbiotic dairy products are expected to expand further, provided that regulatory and quality requirements are met.

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