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Postbiotics in dairy foods: Production, bioactive components, health benefits and future prospects

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Abstract

Postbiotics have gained considerable attention as a new generation of functional ingredients in dairy foods due to their stability, safety, and potential health-promoting properties. Unlike probiotics, postbiotics do not require viable microorganisms to exert biological effects, making them attractive for dairy products that undergo processing and extended storage. This review summarizes current knowledge on the production, composition, applications, and health implications of postbiotics in dairy systems. A comprehensive review of published literature from 2010 onwards was undertaken, with emphasis on recent advances in dairy-based applications and postbiotic research. Postbiotics are generally produced through microbial fermentation followed by controlled inactivation techniques such as heat treatment, sonication, enzymatic lysis, or high-pressure processing. Their major bioactive constituents include organic acids, bacteriocins, exopolysaccharides, bioactive peptides, enzymes, vitamins, and cell wall components, which collectively contribute to antimicrobial, antioxidant, anti-inflammatory, and immunomodulatory activities. Dairy products such as fermented milk, yogurt, kefir, cheese, buttermilk, ice cream, and functional beverages have emerged as promising carriers for postbiotic incorporation. Experimental and emerging clinical evidence suggests that postbiotics may support gut barrier function, regulate immune responses, inhibit pathogenic microorganisms, and contribute to metabolic health. In addition, they offer technological benefits by improving product safety, stability, and shelf life. Despite these advantages, challenges related to standardization, compositional characterization, regulatory frameworks, and limited human intervention studies remain significant. Future research should focus on establishing clear dose-response relationships, validating health effects through well-designed clinical trials, and developing standardized production systems to facilitate the successful integration of postbiotics into next-generation dairy foods.

Keywords: Postbiotics, dairy foods, yogurt, cheese, fermented milk, functional foods, bioactive metabolites, gut health

1. Introduction

Functional foods have become a central theme in modern nutrition because consumers and researchers increasingly seek foods that go beyond basic nourishment to deliver targeted physiological benefits. Within this landscape, probiotics, prebiotics, synbiotics, and more recently postbiotics have each represented a distinct strategy for shaping host health through the microbiome and its metabolites (Gibson *et al.*, 2017; Swanson *et al.*, 2020; Salminen *et al.*, 2021) [8, 33, 29]. Among these, postbiotics are attracting exceptional interest because they may provide many of the health and food-system advantages of probiotics while avoiding the viability-related vulnerabilities that complicate product design, storage, and distribution (Aguilar-Toalá *et al.*, 2018; Aggarwal *et al.*, 2022) [2, 1].

Dairy foods are especially relevant to this transition because they are among the oldest and most successful vehicles for microbial functional ingredients. Fermented milk, yogurt, kefir, cheese, and cultured beverages already provide favorable matrices for microbial metabolites and can often preserve or even enrich bioactive fractions during processing and ripening. As a result, postbiotics fit naturally into dairy technology, where manufacturers are seeking shelf-stable, safe, and scientifically defensible functional ingredients that remain effective across variable processing and storage conditions (Mafe *et al.*, 2026) [19].

The growth of postbiotic science has also been driven by a conceptual clarification that was lacking in earlier literature. Before the ISAPP consensus, the field used overlapping terms such as inactivated probiotics, Para probiotics, ghost probiotics, lysates, and fermentation metabolites, which created confusion in both experimental interpretation and regulatory communication. The consensus definition helped resolve that ambiguity by emphasizing that a postbiotic must be a defined preparation of inanimate microorganisms and/or their components that confers a health benefit on the host (Salminen *et al.*, 2021) ^[29].

This review aims to synthesize current knowledge on postbiotics in dairy foods with a critical, journal-ready perspective. The focus is on how postbiotics are produced, what they contain, how they act, how they can be incorporated into dairy matrices, what evidence exists for health benefits, and what barriers remain for translation into reliable commercial products.

2. Review Methodology

2.1 Literature search strategy

A PRISMA-inspired approach was used to organize the review. Search concepts included postbiotics, dairy foods, fermented milk, yogurt, kefir, cheese, lactic acid bacteria, bioactive metabolites, gut health, functional foods, and dairy biotechnology. Searches were conceptually aligned with Scopus, Web of Science, PubMed, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. Priority was given to peer-reviewed reviews and landmark original studies from 2010 onward, with special emphasis on 2020 to the present for dairy application studies (Page *et al.*, 2021) ^[22].

2.2 Inclusion and exclusion criteria

Included studies were peer-reviewed review papers, systematic reviews, original research articles, and consensus documents relevant to postbiotics, paraprobiotics, microbial metabolites, and dairy applications. Studies had to address definition, production, characterization, biological effects, food applications, or safety. Excluded sources were non-peer-reviewed items, editorials, conference abstracts, duplicate records, and records lacking verifiable bibliographic information.

2.3 Data extraction and quality assessment

For each eligible article, the following information was extracted: authors, year, organism or strain, production or inactivation method, dairy matrix, reported bioactive components, functional outcome, and study model. Because the literature spans mechanistic, technological, and clinical work, study quality was assessed qualitatively rather than by a single quantitative score. Strongest weight was given to consensus statements, systematic reviews, and studies in high-impact journals in dairy science, food science, microbiology, and nutrition.

2.4 PRISMA flow diagram

A journal-ready PRISMA-style flow should report records identified, duplicates removed, records screened, full texts assessed, studies excluded with reasons, and studies included in qualitative synthesis. The PRISMA 2020 framework provides the standard format for this reporting and should be adapted to the final manuscript submission format (Page *et al.*, 2021) ^[22].

3. Concept and Definition of Postbiotics

The concept of postbiotics evolved from the realization that beneficial effects associated with probiotics are not

necessarily dependent on viable cells. Early terms such as Para probiotics and non-viable probiotics were used inconsistently, often referring to heat-killed bacteria, lysates, or fermentation products without a clear unifying framework. ISAPP addressed this by defining postbiotics as a preparation of inanimate microorganisms and/or their components that confers a health benefit on the host (Salminen *et al.*, 2021) ^[29].

This definition has three practical implications. First, a postbiotic must be a preparation, meaning it is intentionally produced and characterized. Second, it must contain inanimate microbial material or components rather than live cells. Third, it must demonstrate a host benefit, which means that not every bacterial lysate qualifies automatically. The distinction matters in dairy science because fermented products may contain multiple bioactive fractions, but only those with verified benefit should be called postbiotics (Mafe *et al.*, 2026) ^[19].

The relationship among probiotics, prebiotics, synbiotics, para probiotics, and postbiotics is best understood as a conceptual progression from live microorganisms to substrates that support them, then to combinations, and finally to non-viable microbial preparations that themselves exert a biological effect. This evolution reflects a broader move toward precision in functional food science rather than a simple replacement of one term with another.

4. Production of Postbiotics

4.1 Microorganisms used

Lactic acid bacteria are the most common source of dairy postbiotics because they are already central to milk fermentation and are generally regarded as safe. Frequently used taxa include *Lactobacillus spp.*, *Lactiplantibacillus plantarum*, *Lactocaseibacillus casei*, *Lactococcus lactis*, *Streptococcus thermophilus* and *Bifidobacterium spp.* (Jahedi *et al.*, 2025) ^[13]. Strain specificity is critical because even closely related strains can produce markedly different metabolite profiles and immunological effects.

Bifidobacteria are particularly relevant to dairy applications because they are oxygen sensitive and can be difficult to maintain as live probiotics during manufacturing and storage. In such cases, inactivated bifidobacterial preparations may provide a practical route to preserve functional potential without demanding viability at shelf life or point of consumption (Gibson *et al.*, 2017) ^[8].

4.2 Production technologies

Postbiotics can be generated through classical fermentation or by combining fermentation with inactivation or disruption methods. Heat treatment and pasteurization are the most common because they are simple, scalable, and effective at inactivating cells while retaining many heat-stable components such as peptidoglycan, teichoic acids, and some bacteriocins. Tyndallization can provide incremental inactivation, but it is less standardized in modern industrial practice.

Non-thermal and semi-thermal approaches are increasingly studied. Sonication may disrupt cells and release intracellular material, high-pressure processing can alter membranes and liberate active fractions, and enzymatic lysis can selectively generate defined peptide or cell wall fractions. These methods may improve bioactivity in some systems, but they can also alter composition unpredictably, so process control is essential (Ji *et al.*, 2023) ^[14].

4.3 Factors affecting production

The final postbiotic profile depends strongly on strain selection, growth phase, growth medium, pH, oxygen

availability, temperature, and duration of fermentation. In dairy systems, substrate composition matters because milk proteins, lactose, minerals, and fat all influence microbial metabolism and downstream bioactive generation (Żółkiewicz *et al.*, 2020) ^[41]. The inactivation process is equally important because the same strain may yield different functional properties depending on whether it is heat-killed, sonicated

pressure-treated, or enzymatically lysed (Figure 1).

For industrial translation, postbiotic production should be treated as a controlled bioprocess with measurable outputs, not as an incidental by-product. That means defining composition, potency, and safety parameters for each product rather than assuming equivalence across preparations.

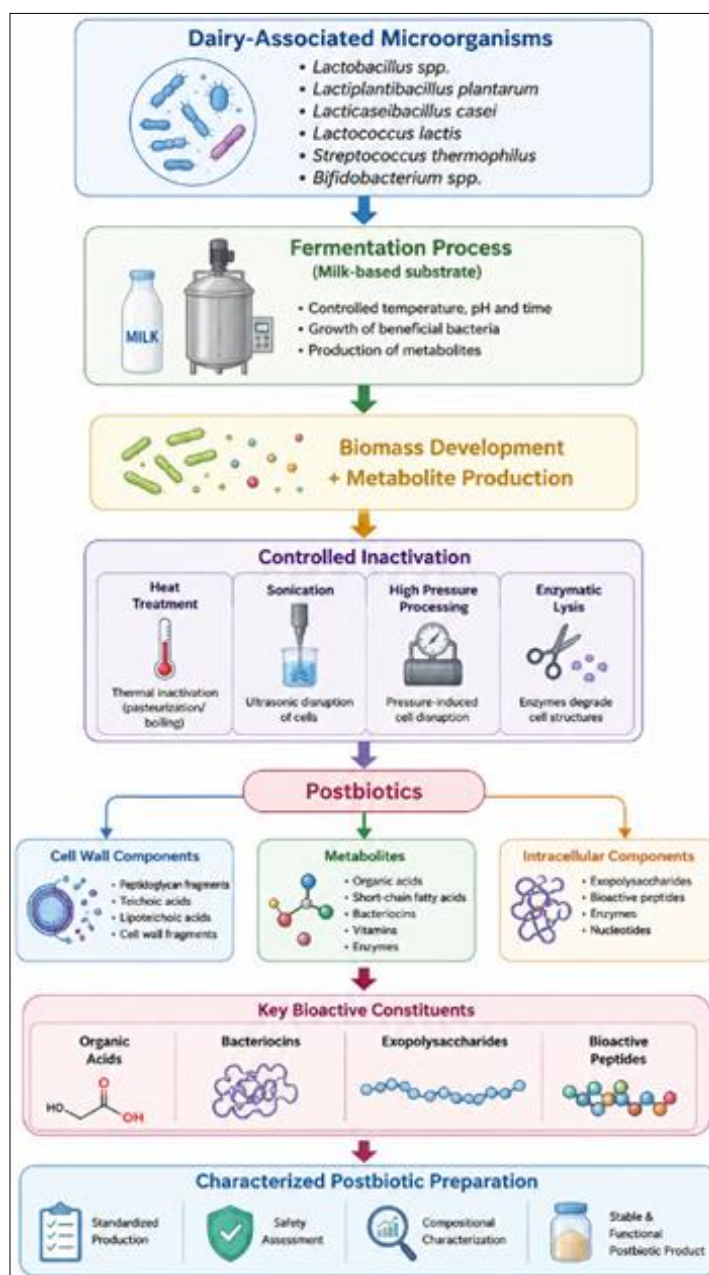


Fig 1: Production pathway and generation of bioactive postbiotic components from dairy-associated microorganisms.

5. Major Components of Postbiotics

Postbiotics are chemically diverse and often multi-component. Their composition includes organic acids, short-chain fatty acids, bacteriocins, exopolysaccharides, peptidoglycan fragments, teichoic acids, cell wall fragments, bioactive peptides, enzymes, and vitamins. Their biological effects often arise from synergy rather than one dominant molecule (Hijová *et al.*, 2024; Yeşilyurt *et al.*, 2021) ^[10, 39]. Organic acids and short-chain fatty acids contribute to antimicrobial activity and help lower pH, creating unfavorable conditions for spoilage and pathogenic bacteria. Bacteriocins, especially from LAB, are among the most important food-preserving postbiotic constituents because they can directly

suppress target organisms. Exopolysaccharides may improve product texture and water-holding capacity in dairy foods while also influencing immune pathways (Homayouni *et al.*, 2023) ^[12].

Peptidoglycan and teichoic acid fragments are especially relevant to immune signaling because they interact with host pattern-recognition receptors. Bioactive peptides generated by proteolysis during fermentation may contribute antioxidant, antihypertensive, or immunomodulatory functions (Scarpellini *et al.*, 2021) ^[30]. Since many studies measure postbiotics as crude extracts, the field still needs better fractionation and structure-function mapping to assign biological activity to specific components.

6. Applications in Dairy Foods

6.1 Fermented milk

Fermented milk is one of the most logical targets for postbiotic development because it already contains fermentation-derived bioactive compounds and can support further enrichment. Postbiotic supplementation can improve microbial stability and may contribute to product safety by suppressing undesirable flora (Wu *et al.*, 2024) ^[38]. Because fermented milk is consumed broadly and accepted as a health-oriented product, it provides a realistic commercial route for first-generation postbiotic foods.

6.2 Yogurt

Yogurt has received the most attention among dairy matrices because it is globally consumed, technologically compatible with added bioactives, and relatively easy to standardize. Studies on fortified yogurts suggest that postbiotic powders or inactivated preparations can improve acidity and maintain acceptable rheology and water-holding capacity, though sensory impacts must be monitored carefully (Tarique *et al.*, 2022) ^[34]. Yogurt therefore serves as both a delivery platform and a model system for understanding postbiotic-matrix interactions.

6.3 Kefir

Kefir is a particularly interesting matrix because its mixed microbial ecology naturally generates a spectrum of metabolites and may already function as a quasi-postbiotic system. Its complexity could be an advantage for bioactivity, but it also complicates standardization. Compared with yogurt and cheese, kefir remains underexplored in terms of defined postbiotic enrichment and health validation (Pihurov *et al.*, 2021) ^[25].

6.4 Cheese

Cheese offers a dense protein-fat matrix that can protect bioactive compounds during storage and ripening. Postbiotic applications in cheese often focus on biopreservation, especially inhibition of *Listeria monocytogenes* and *Staphylococcus aureus* in fresh or soft cheeses. Recent evidence indicates that the preparation method of the postbiotic strongly influences antibacterial effectiveness in cheese applications (Khani *et al.*, 2026; Sharafi *et al.*, 2022) ^[15, 31].

6.5 Buttermilk

Buttermilk is a promising but relatively neglected vehicle for postbiotics. Its mild flavor, fluid format, and sustainability appeal may make it suitable for functional ingredient development (Taşkoparan, 2025) ^[35]. The main research gap is the lack of controlled studies on how postbiotic fractions behave during storage and whether they retain measurable bioactivity in this matrix.

6.6 Ice cream

Ice cream is technologically complex because freezing, fat dispersion, and high sugar content can influence postbiotic stability and distribution. It may be an appealing carrier for consumer-friendly functional positioning, but the evidence base remains limited. In this matrix, sensory quality is likely to be as important as bioactivity (Gao *et al.*, 2021) ^[7].

6.7 Functional dairy beverages

Functional dairy beverages may be the most commercially flexible postbiotic format because they can be formulated

with precise dosing and marketed for convenience. These products also allow combination with fibers, vitamins, or plant-derived bioactives (Taşkoparan, 2025) ^[35]. However, their success will depend on clear evidence of efficacy and careful flavor management.

7. Health Benefits of Postbiotics

7.1 Gut health

Postbiotics may promote gut health by enhancing epithelial integrity, supporting mucus production, and reducing pathogen attachment. These effects are especially important for populations where live probiotic survival is uncertain or undesirable (Ji *et al.*, 2023; Liu *et al.*, 2022) ^[14, 18]. Many beneficial outcomes likely reflect host recognition of microbial-associated molecular patterns rather than classical colonization.

7.2 Gut microbiota modulation

Although postbiotics do not populate the gut, they can influence microbiota composition indirectly by lowering pH, suppressing pathogens, and shifting local ecological conditions. In other words, they modulate rather than colonize. This distinction should be preserved in any health claim (Liu *et al.*, 2022; Smolinska *et al.*, 2025) ^[18, 32].

7.3 Immunomodulatory effects

Cell wall fragments, lipoteichoic acids, and other microbial structures can interact with immune receptors and alter cytokine signaling. Depending on preparation and dose, postbiotics may stimulate protective immune responses or help rebalance dysregulated immunity (Yeşilyurt *et al.*, 2021) ^[39]. Mechanistic interpretation must remain cautious because immune effects are highly context dependent.

7.4 Anti-inflammatory activity

Several postbiotic preparations reduce pro-inflammatory mediators in model systems and appear to influence NF-κB-related signaling. Such effects are attractive for gut and metabolic health, but the literature often mixes different preparations and disease models. Strong anti-inflammatory claims should therefore be tied to specific preparations and validated endpoints (Zdybel *et al.*, 2025) ^[40].

7.5 Antioxidant effects

Peptide-rich and metabolite-rich fractions can display measurable antioxidant activity, sometimes through direct scavenging and sometimes through host-response modulation. However, chemical antioxidant assays do not always correlate with *in vivo* benefit (Rezaie *et al.*, 2024) ^[28]. The field needs better linkage between *in vitro* antioxidant potential and physiological outcomes.

7.6 Antimicrobial properties

Antimicrobial action is one of the most robustly supported functions of dairy postbiotics. Organic acids, bacteriocins, and membrane-active components can inhibit spoilage and pathogenic microorganisms, improving shelf life and food safety. This function may be as important technologically as any direct health effect (Rad, 2022) ^[27].

7.7 Metabolic health

Evidence suggests potential effects on glucose regulation, lipid metabolism, and energy balance, likely mediated through gut barrier support, inflammatory modulation, and microbiota interactions. Yet the available human evidence is

too limited to support generalized claims (Al-Habsi *et al.*, 2024) [3]. The strongest current conclusion is that postbiotics are promising, not proven, metabolic modulators.

7.8 Allergy prevention

Some experimental studies suggest that postbiotics may aid immune maturation and reduce allergic sensitization. This area is clinically important but still early-stage. It will require age-specific, dose-specific, and preparation-specific trials before meaningful application in pediatric nutrition (Homayouni, 2021) [11].

7.9 Cardiovascular health

Potential cardiovascular benefits include blood pressure modulation, lipid-lowering effects, and systemic anti-inflammatory activity. Dairy-derived bioactive peptides are especially relevant here, since fermentation can release peptide sequences with angiotensin-converting enzyme inhibitory potential. However, the clinical translation remains modest (Mousavi *et al.*, 2024; Fuente-Muñoz *et al.*, 2025) [20, 5].

7.10 Potential anticancer effects

Anticancer findings are mostly preclinical and should be interpreted with caution. Reported mechanisms include apoptosis induction, antiproliferative signaling, and immune modulation. These observations are scientifically interesting but far from sufficient to support disease-prevention claims in commercial products (Nowak *et al.*, 2022) [21].

8. Mechanisms of Action

Postbiotics act through a network of partially overlapping mechanisms. They can strengthen the epithelial barrier, support tight-junction integrity, and increase mucosal resilience. They can also interact with innate immune receptors and modulate inflammatory pathways. In parallel, they exert direct antimicrobial effects and create ecological conditions that disfavor pathogens (Teame *et al.*, 2020) [36]. These mechanisms should not be collapsed into a single explanation such as “postbiotics improve immunity.” Rather, different preparations may work through different mechanisms, and the same preparation may act differently depending on host age, diet, health status, and dose. This complexity is precisely why postbiotic science needs mechanistic standardization and better biomarker-driven trials (Teame *et al.*, 2020; Ji *et al.*, 2023) [36, 14].

9. Advantages over Probiotics

Postbiotics have several clear advantages in dairy applications. They are more stable during processing and storage, do not require viability, and can be used in products that undergo heat treatment or long shelf life. They also reduce concerns about probiotic translocation or survival in vulnerable consumers. From an industrial perspective, they are easier to standardize and potentially simpler to register as defined ingredients (Yeşilyurt *et al.*, 2021) [39].

These advantages do not make them universally superior to probiotics. Live microorganisms may still be preferable where colonization, competitive exclusion, or active fermentation in the gut is desired. The most realistic strategy may be complementary use of live probiotics and postbiotic fractions in designed formulations (Pandey *et al.*, 2025) [23].

10. Safety and Regulatory Aspects

Safety assessment must begin with strain history and manufacturing control. A postbiotic preparation should be screened for pathogenicity determinants, contaminating

microbes, residual toxins, and unwanted metabolites. Because postbiotics are not live, they may be safer for some consumers, but safety cannot be assumed from non-viability alone (Guglielmetti *et al.*, 2025) [9].

Regulatory frameworks remain fragmented. Depending on jurisdiction, a postbiotic may be treated as a food ingredient, novel food, supplement, or biologically active product. Clear labeling should identify the source organism, inactivation method, and intended functional role. Marketing claims should not outrun evidence, especially for disease-related outcomes (Vinderola *et al.*, 2022) [37].

11. Challenges and Limitations

The biggest limitation is lack of standardization. Different studies use different strains, media, extraction procedures, and inactivation methods, making cross-study comparison difficult. Another limitation is incomplete compositional characterization: many postbiotic preparations are described functionally but not chemically. Clinical evidence, especially in dairy formats, is still sparse (Pandey *et al.*, 2025) [23].

Scale-up is another problem because industrial processing can alter bioactive profiles. Sensory impact also matters, since dairy consumers will reject products that sacrifice flavor or texture for abstract health claims. Finally, regulatory uncertainty continues to delay commercialization and credible health communication (Pattapulavar *et al.*, 2025) [24].

12. Future Perspectives

Future progress will likely depend on precision functional foods, omics-based characterization, and better host-response profiling. Personalized nutrition may allow postbiotics to be matched to consumer needs, such as gut health, immune support, or metabolic management. Dairy matrices will continue to be important because they are familiar, versatile, and technically robust (Liang *et al.*, 2023) [17].

A particularly promising direction is the development of combined probiotic-postbiotic systems, where live cultures and their functional metabolites coexist in one product or production chain. Artificial intelligence may also help identify optimal strain-process-matrix combinations and predict sensory and functional performance. Sustainable valorization of dairy by-products as substrates for postbiotic production is another area with both environmental and economic appeal (Pattapulavar *et al.*, 2025; Franco, 2024) [24, 6].

13. Research Gaps

The field needs standardized definitions of potency and dose, better structure-function relationships, validated biomarkers, more dairy-specific intervention trials, and long-term safety data. It also needs to separate technological functions, such as biopreservation, from host-directed health effects. Without that separation, the literature will continue to mix food preservation claims with biomedical claims (Amobonye, 2025; Mafe *et al.*, 2026) [4, 19].

14. Conceptual Framework

A practical conceptual framework is: microbial strains → fermentation → postbiotic production → characterization → incorporation into dairy foods → consumption → gut barrier and microbiota interactions → immune/metabolic effects → health benefits. This framework is useful because it makes clear that the final health outcome depends on the quality of each upstream step. It also highlights why process control and product definition are essential for future translation (Guglielmetti *et al.*, 2025) [9].

15. Conclusion

Postbiotics are emerging as a highly promising category of functional ingredients for dairy foods because they combine technological stability with plausible biological activity. Their appeal lies in solving key problems that limit probiotics, including viability loss during processing and storage, while also enabling broader formulation options. At the same time, the field is still maturing and should not be oversold. The next phase of research must move from general enthusiasm to precise definitions, standardized manufacturing, compositional analysis, and well-designed human studies. If these requirements are met, postbiotics could become a major pillar of next-generation dairy innovation.

16. Declaration of Competing Interest

The authors declare no competing interests.

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