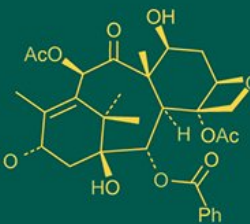
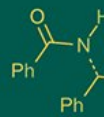
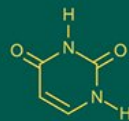
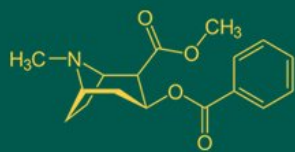


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The new era of functional dairy products current science and emerging technologies: A comprehensive review

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Abstract

Functional dairy products are foods in which the nutritional attributes of dairy matrices are combined with physiologically active components or processing-derived functions intended to provide benefits beyond basic nutrient supply. Milk is intrinsically rich in high-quality proteins, calcium, vitamins, minerals and a range of bioactive molecules, while fermentation and controlled processing can generate additional peptides, organic acids, exopolysaccharides and other metabolites. The functional dairy sector has consequently expanded around probiotic, prebiotic, synbiotic and postbiotic products, bioactive peptide-enriched foods, vitamin- and mineral-fortified dairy foods, omega-3-enriched products, fibre-containing products and dairy foods containing plant-derived bioactives. Among these, yoghurt and fermented milk are the most established delivery systems, but cheese, whey beverages, milk drinks, frozen dairy foods and traditional products such as paneer are increasingly being investigated. Evidence indicates that selected probiotic strains and fermented dairy foods can influence gastrointestinal function, microbial ecology and some immune or metabolic outcomes; however, effects are strain-, dose-, matrix- and population-dependent. Milk-derived peptides show antihypertensive, antioxidant, antimicrobial, immunomodulatory and enzyme-inhibitory activities in experimental systems, but translation from *in vitro* activity to clinically meaningful effects remains a major research challenge. Technological constraints include loss of probiotic viability, interactions between functional ingredients and the dairy matrix, oxidation of sensitive compounds, undesirable flavour or texture, and inadequate stability during storage. Microencapsulation, controlled-release systems, foodomics, metabolomics and precision fermentation offer new opportunities. This critical review examines the scientific basis, product categories, health potential, technological challenges, safety, regulatory issues, research gaps and future prospects of functional dairy products, with particular emphasis on evidence quality and the distinction between demonstrated benefit and plausible functionality.

Keywords: Functional dairy products, probiotics, prebiotics, synbiotics, postbiotics, bioactive peptides, fermented dairy products

Introduction

The role of foods in human health has expanded from the traditional concept of nutrient provision to a broader view in which selected foods and food components may influence physiological functions. Functional foods occupy this intersection between nutrition and health. Dairy products are especially attractive functional-food matrices because milk combines a nutritionally dense composition with a buffering protein system, fermentable lactose, minerals, fat globules and technologically useful proteins. Fermentation further modifies the matrix and may release peptides or generate microbial metabolites with biological activity (Hill C *et al.*, 2014; Gibson GR *et al.*, 2017; Salminen S *et al.*, 2021; Marco ML *et al.*, 2017; Marco ML *et al.*, 2021; Ali MA *et al.*, 2022) [1, 2, 3, 4, 5, 6].

The functional dairy category is not homogeneous. A probiotic yoghurt containing a defined live strain, a vitamin-D-fortified milk, a fibre-enriched yoghurt, a peptide-rich fermented milk and a postbiotic beverage may all be described as functional, but the scientific basis and evidence required to support their proposed benefits differ substantially. The International Scientific Association for Probiotics and Prebiotics (ISAPP) has emphasized that the term probiotic should be restricted to live microorganisms demonstrated to confer a health benefit

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when administered in adequate amounts; similarly, prebiotic and postbiotic terminology requires defined criteria (Hill C *et al.*, 2014; Gibson GR *et al.*, 2017; Salminen S *et al.*, 2021). Dairy-based probiotic beverages have become an important area of product development, and recent AJDFR literature identifies stability, safety, technological characteristics and regulatory considerations as major issues in commercial probiotic dairy beverages (Elango A, 2025). Contemporary reviews likewise emphasize that the potential health value of functional dairy foods depends on the specific microorganism, food matrix, processing history, dose, storage conditions and consumer population rather than on the product category alone (Jang HJ *et al.*, 2024; He JT *et al.*, 2023; Pannerchelvan S *et al.*, 2024; Quintieri L *et al.*, 2024). The present review therefore takes a critical rather than purely descriptive approach. It examines functional ingredients, delivery matrices, mechanisms of action, technological limitations and evidence quality, and identifies research priorities needed to translate promising laboratory findings into robust, commercially viable and scientifically substantiated dairy foods [1, 2, 3, 7, 8, 9, 10, 11].

Scope and Conceptual Framework

Functional dairy products can be understood as conventional dairy foods deliberately designed or formulated to deliver a documented physiological function in addition to their ordinary nutritional role. Functionality may originate from native milk constituents, microbial fermentation, addition of functional ingredients, or combinations of these approaches (Marco ML *et al.*, 2017; Marco ML *et al.*, 2021; Ali MA *et al.*, 2022; Jang HJ *et al.*, 2024).

A critical distinction should be made between a bioactive constituent and a clinically demonstrated functional food. A peptide can inhibit angiotensin-converting enzyme *in vitro* without producing a measurable blood-pressure effect after digestion. Similarly, a probiotic strain may survive well in yoghurt but fail to produce a particular clinical benefit in a target population. Therefore, evidence should be evaluated across a continuum from chemical characterization and *in vitro* activity to animal studies, human intervention trials and reproducible product-level outcomes (Quintieri L *et al.*, 2024; Nielsen SDH *et al.*, 2024; Mohanty DP *et al.*, 2016; Korhonen H and Pihlanto A, 2006; Clare DA and Swaisgood HE, 2000; Nielsen SDH *et al.*, 2017) [4, 5, 6, 7, 11, 12, 13, 14, 15, 16].

Major Functional Components of Dairy Products

Probiotics

Probiotics are live microorganisms that, when administered in adequate amounts, confer a health benefit on the host (Hill C *et al.*, 2014). Dairy foods are among the most widely used delivery systems because the matrix can protect microorganisms from some environmental stresses and provides a familiar, nutrient-rich vehicle. Commonly investigated genera include *Lactobacillus sensu lato*, *Bifidobacterium* and selected other lactic acid bacteria. Importantly, probiotic efficacy is strain-specific and should not be inferred simply from genus or species membership (Hill C *et al.*, 2014; He JT *et al.*, 2023; Sanders ME *et al.*, 2019) [1, 9, 17, 9].

Dairy matrices may improve probiotic survival through buffering capacity and physical protection by proteins and fat. Nevertheless, acidity, oxygen, hydrogen peroxide, storage temperature, interactions with starter cultures and competition for nutrients can reduce viability. Consequently,

probiotic dairy development requires evaluation of viable counts at the end of the stated shelf life rather than only immediately after manufacture (He JT *et al.*, 2023; Tripathi MK and Giri SK, 2014; Champagne CP *et al.*, 2011; Vinderola G *et al.*, 2022; Aryana KJ and Olson DW, 2017) [9, 18, 19, 20, 21].

Prebiotics

A prebiotic is a substrate selectively utilized by host microorganisms that confers a health benefit (Gibson GR *et al.*, 2017). Common food ingredients investigated in dairy products include inulin-type fructans, fructooligosaccharides and galactooligosaccharides. In dairy systems, prebiotics can contribute both physiological functionality and technological effects such as water binding, viscosity modification and mouthfeel. These properties can be advantageous but may also alter fermentation kinetics and sensory quality (Gibson GR *et al.*, 2017; Gibson GR and Roberfroid MB, 1995; Roberfroid MB, 2007; Slavin J, 2013) [2, 22, 23, 24].

Synbiotics

Synbiotic products combine live microorganisms with substrates that are intended to support beneficial microbial activity. The concept has evolved from simple combinations toward more evidence-based formulations in which the probiotic and substrate should be compatible and the combination should provide a demonstrated health benefit (Gibson GR and Roberfroid MB, 1995; Swanson KS *et al.*, 2020). Dairy yoghurt and fermented milk are attractive synbiotic vehicles because fermentation, acidity and the food matrix can be controlled relatively precisely [22, 25].

Postbiotics

Postbiotics are preparations of inanimate microorganisms and/or their components that confer a health benefit (Salminen S *et al.*, 2021). Interest in postbiotics has increased because non-viable preparations can potentially offer greater stability than live cultures and may simplify some processing constraints. However, postbiotic products require characterization of the source microorganism, production process, composition and demonstrated biological effect. The term should not be used simply as a marketing synonym for heat-killed bacteria or fermentation extracts without evidence of benefit (Salminen S *et al.*, 2021) [3].

Milk-derived bioactive peptides

Milk proteins contain encrypted peptide sequences that can be released during gastrointestinal digestion, enzymatic hydrolysis or microbial fermentation. Caseins and whey proteins are important sources. Reported activities include angiotensin-converting enzyme inhibition, antioxidant activity, antimicrobial effects, immunomodulation, mineral binding and inhibition of selected metabolic enzymes (Quintieri L *et al.*, 2024; Nielsen SDH *et al.*, 2024; Mohanty DP *et al.*, 2016; Korhonen H and Pihlanto A, 2006; Clare DA and Swaisgood HE, 2000; Nielsen SDH *et al.*, 2017; Korhonen H and Pihlanto A, 2007; Pihlanto A, 2006; Habib HM *et al.*, 2025; Mudgil P *et al.*, 2024) [3, 11, 12, 13, 14, 15, 16, 27, 28, 29, 30].

The discovery of thousands of peptide sequences has been facilitated by peptidomics, mass spectrometry and database approaches. Recent work has emphasized the need to distinguish sequences with demonstrated activity from those whose activity is predicted solely from computational

analysis. Bioavailability, gastrointestinal stability, absorption and target-site exposure remain critical barriers to translating peptide activity into clinical functionality (Nielsen SDH *et al.*, 2024; Habib HM *et al.*, 2025; Mudgil P *et al.*, 2024)^[12, 29, 30].

Fortified nutrients and functional lipids

Dairy foods are commonly fortified with vitamin D, calcium and other micronutrients. Functional lipid modification has included omega-3 fatty acids and conjugated linoleic acid. Such strategies can improve the nutritional profile, but oxidation, flavour stability, bioavailability and regulatory limits must be considered. The success of fortification therefore depends on both the biological relevance of the nutrient and its stability in the final product.

Plant-derived bioactives and dietary fibre

Fruit extracts, polyphenols, carotenoids, herbs, spices and dietary fibres are increasingly incorporated into dairy products. These ingredients can provide antioxidant or other potential biological activities, while also increasing product diversity. However, phenolic compounds may bind dairy proteins, change colour and produce bitterness or astringency. Functional formulation must therefore optimize bioactivity together with sensory acceptance and shelf stability.

Functional Dairy Product Categories

Functional yoghurt

Yoghurt is one of the most established functional dairy matrices. Its acidic environment, protein gel structure and broad consumer familiarity make it suitable for probiotics, prebiotics, synbiotics, fibres, vitamins, minerals, plant extracts and other bioactives (Pannerchelvan S *et al.*, 2024; Lourens-Hattingh A and Viljoen BC, 2001; Shah NP, 2007; Ranadheera CS *et al.*, 2010). A recent comprehensive review identified probiotics, prebiotics, synbiotics, antioxidants, vitamins, minerals, proteins and other bioactive compounds as major components of functional yoghurt and emphasized potential effects on digestive, immune and metabolic health (Pannerchelvan S *et al.*, 2024)^[10, 31, 32, 33].

The critical issue is that yoghurt should not be considered therapeutically interchangeable across formulations. Starter cultures, added probiotic strains, sugar concentration, total solids, storage duration and dose can differ substantially. Consequently, health outcomes reported for one formulation cannot automatically be generalized to another.

Probiotic fermented milk beverages

Fermented milk beverages provide a convenient liquid vehicle for probiotic delivery. They can be produced using conventional starter cultures alone or in combination with selected probiotic strains. Advantages include ease of consumption and scalable manufacturing; limitations include acid stress, post-acidification and viability loss during storage (Elango A, 2025; Tripathi MK and Giri SK, 2014; Champagne CP *et al.*, 2011)^[8, 18, 19].

Non-fermented probiotic milk beverages

Non-fermented milk drinks containing probiotic cultures offer an alternative where manufacturers wish to retain a milk-like sensory profile. Their development requires particular attention to oxygen, refrigeration, sedimentation, flavour stability and the compatibility of probiotic cultures

with the non-fermented matrix. Reviews comparing fermented and non-fermented dairy probiotic products indicate that both formats have potential, but each presents distinct technological constraints (Jang HJ *et al.*, 2024)^[7].

Functional cheese

Cheese has a relatively complex protein-fat matrix that may protect microorganisms and bioactive compounds. Probiotic cheeses, reduced-fat cheeses and cheeses containing fibres or plant bioactives have therefore been investigated. The main challenge is to maintain viable functional cultures without disrupting ripening, flavour, body, texture and safety. In ripened cheeses, microbial ecology is particularly complex, making it difficult to attribute a health outcome to a single organism (Champagne CP *et al.*, 2011; Gobbetti M *et al.*, 2019)^[19, 34].

Functional paneer and traditional dairy products

Traditional dairy products provide opportunities for regionally relevant functional innovation. Paneer, for example, can potentially carry dietary fibre, plant bioactives, probiotics or other ingredients. However, its high moisture content, acid-heat coagulation process and short shelf life make functional formulation different from yoghurt. Functional ingredients should be assessed for their effects on curd formation, moisture retention, texture, cooking behaviour, microbial stability and consumer acceptance. The development of such products may be particularly relevant to the Indian dairy sector.

Whey-based functional beverages

Whey is a valuable source of lactose, minerals and high-quality whey proteins. Whey beverages can therefore be designed as carriers of probiotics, peptides, fibres and plant bioactives while contributing to by-product valorization. Their acidic or neutral formulations can be adjusted according to the target microorganism and desired sensory profile. Whey proteins themselves also contain bioactive peptide sequences and functional proteins such as lactoferrin and alpha-lactalbumin (Quintieri L *et al.*, 2024; Nielsen SDH *et al.*, 2024; Korhonen H and Pihlanto A, 2007)^[11, 12, 27].

Mechanisms Underlying the Potential Health Effects

Gut micro biota modulation

One of the principal proposed mechanisms of probiotic and prebiotic dairy foods is modulation of the intestinal microbial ecosystem. Mechanisms may include competitive interactions with pathogens, production of organic acids and antimicrobial metabolites, changes in substrate availability, modulation of microbial metabolites and interactions with epithelial and immune cells (Marco ML *et al.*, 2017; Gibson GR and Roberfroid MB, 1995; Reid G *et al.*, 2017)^[35, 22]. However, changes in relative abundance of selected taxa should not automatically be interpreted as improved health. Functional outcomes and clinically relevant endpoints are more informative than taxonomic shifts alone.

Intestinal barrier and immune interactions

Fermented dairy foods and selected probiotic strains may interact with epithelial cells and immune pathways. Proposed mechanisms include modulation of tight-junction proteins, production of microbial metabolites and effects on innate and adaptive immune signaling (He JT *et al.*, 2023; Reid G *et al.*,

2017; Sanders ME *et al.*, 2018). Evidence is promising but highly strain- and population-dependent [9, 35, 36].

Antihypertensive activity

Several milk-derived peptides inhibit angiotensin-converting enzyme *in vitro*, and some fermented dairy products have been investigated in relation to blood pressure (Nielsen SDH *et al.*, 2024; Mohanty DP *et al.*, 2016; Korhonen H and Pihlanto A, 2006; Clare DA and Swaisgood HE, 2000; Nielsen SDH *et al.*, 2017). The critical limitation is that enzyme inhibition measured under laboratory conditions does not establish physiological efficacy. Peptide digestion, absorption, plasma stability and dose at the target tissue must be considered [12, 13, 14, 15, 16, 21].

Antioxidant and anti-inflammatory activity

Milk peptides and plant-derived compounds may scavenge reactive species or influence cellular signaling in experimental systems. Fermentation can modify peptide profiles and release new metabolites (Quintieri L *et al.*, 2024; Korhonen H and Pihlanto A, 2007; Habib HM *et al.*, 2025). Nevertheless, antioxidant capacity measured by chemical assays is not equivalent to a clinically meaningful reduction in oxidative stress. Human intervention studies remain necessary [11, 12, 27, 29].

Metabolic health

Dairy peptides and fermented products have been investigated for effects on lipid metabolism, glucose regulation and dipeptidyl peptidase-IV activity. Recent research using probiotic fermentation of milk from different animal species has identified peptides with DPP-IV inhibitory potential, illustrating the potential of fermentation as a route to functional peptide generation (Aryana KJ and Olson DW, 2017). Such findings remain mechanistic until supported by human studies [21].

Bone health

Dairy foods naturally contribute calcium, phosphorus and protein, while vitamin-D fortification can further improve nutritional adequacy. Some milk-derived peptides may also influence mineral binding or bone-related pathways (Quintieri L *et al.*, 2024; Nielsen SDH *et al.*, 2024) [11, 12]. The strongest evidence for bone health should therefore be considered in the context of the whole nutrient package of dairy foods rather than attributed exclusively to a single bioactive molecule.

Technological Development of Functional Dairy Products Selection and stabilization of probiotic cultures

Culture selection should consider documented health effects, gastrointestinal tolerance, technological performance, compatibility with starter cultures, sensory impact, genetic stability and safety. The desired viable count must be maintained through processing and the declared shelf life (Hill C *et al.*, 2014; He JT *et al.*, 2023; Tripathi MK and Giri SK, 2014) [9, 18].

Microencapsulation

Microencapsulation can protect probiotic cells and sensitive compounds against acidity, oxygen, heat and storage stress. Materials investigated include alginate, proteins, polysaccharides and lipid-based systems. Encapsulation can also alter release during gastrointestinal digestion. However,

encapsulation may increase cost, change mouthfeel or reduce the number of viable cells released from the food matrix if not optimized.

Controlled release and delivery systems

Controlled-release systems seek to protect bioactives during processing and release them at the intended stage of digestion. Such approaches are especially relevant to peptides, polyunsaturated lipids and plant phenolics. Food-grade systems must demonstrate safety, stability, reproducibility and regulatory acceptability.

Fermentation optimization

Fermentation conditions determine acidification rate, peptide release, flavour development, texture and microbial viability. Parameters include inoculum level, temperature, fermentation time, oxygen availability and substrate composition. Modern approaches increasingly combine conventional fermentation with omics tools to characterize microbial metabolism and product functionality (Ali MA *et al.*, 2022; Habib HM *et al.*, 2025; Gänzle MG, 2015).

Sensory Quality and Consumer Acceptance

Functional foods succeed commercially only when consumers are willing to eat them repeatedly. Dairy matrices are highly sensitive to changes in acidity, sweetness, viscosity, colour and aroma. Plant extracts may introduce bitterness or astringency; minerals may create metallic notes; fibres can increase thickness; probiotics may alter post-acidification; and omega-3 enrichment can create oxidation-related flavours.

Product optimization should therefore use sensory analysis alongside functional assays. A product with excellent antioxidant activity but poor acceptability is unlikely to deliver meaningful population-level benefit. Consumer studies should also evaluate willingness to pay, perceived health value, label comprehension and trust in health claims.

Safety Considerations

Functional dairy products must meet the safety requirements of conventional dairy foods while addressing additional risks associated with the functional component. For probiotics, issues include strain identity, opportunistic pathogenicity, antimicrobial resistance determinants and safety in vulnerable populations (Hill C *et al.*, 2014; He JT *et al.*, 2023; Doron S and Snyderman DR, 2015). For plant extracts and concentrated bioactives, toxicological and interaction data may be required. For peptide concentrates, the source protein, production method and purity need consideration.

Postbiotics may reduce some viability-related risks, but their safety cannot be assumed solely because the preparation is non-viable. Production conditions, residual components and the biological activity of the preparation must be characterized (Salminen S *et al.*, 2021) [6, 7, 11, 12, 13, 14, 15, 16, 27, 28, 29, 30, 3, 45].

Regulatory and Health-Claim Considerations

Regulation of functional foods differs among jurisdictions. A central principle is that the presence of a functional ingredient should not automatically be equated with a disease-prevention or treatment claim. Scientific substantiation should correspond to the wording and strength of the proposed claim.

For Indian dairy products, manufacturers should consider applicable requirements of the Food Safety and Standards Authority of India (FSSAI), including standards for dairy products, permitted ingredients, additives, fortification and claims. Internationally, regulatory expectations also emphasize truthful labeling and adequate evidence. The exact regulatory position should always be checked against the version in force at the time of product development and submission.

Emerging Direction

Precision fermentation and strain engineering

Advances in microbial genomics and fermentation technology may enable more targeted production of peptides, vitamins, exopolysaccharides and other functional metabolites. Such approaches could improve consistency but will require rigorous safety and regulatory assessment.

Personalized nutrition: Individual responses to probiotics and fermented foods may vary with age, diet, genetics and gut microbiota. Personalized nutrition could eventually guide selection of functional dairy products for specific physiological goals. Current evidence, however, remains insufficient for routine individualized functional-dairy prescriptions.

Artificial intelligence and predictive food design

Machine learning can support peptide discovery, prediction of fermentation outcomes and optimization of formulations. Recent work has specifically highlighted the use of AI and machine learning in the discovery and evaluation of fermented milk bioactive peptides. The principal requirement is high-quality, standardized training data and experimental validation.

Postbiotic and paraprobiotic dairy foods: Non-viable microbial preparations may allow functional products with

improved thermal and storage stability. This is particularly attractive for products where maintaining live-cell counts is difficult. Future research should determine which postbiotic components are responsible for specific effects and establish dose-response relationships.

Conclusion

Functional dairy products represent a scientifically important and commercially expanding interface between dairy technology, nutrition and health. Dairy matrices naturally provide high-quality proteins, minerals and other bioactive constituents, while fermentation and formulation can add probiotics, prebiotics, synbiotics, postbiotics, peptides, fibres, micronutrients and plant-derived bioactives. Yoghurt and fermented milk remain the most mature functional dairy formats, but cheese, whey beverages, milk drinks and traditional products offer substantial opportunities.

The strongest limitation in the field is the gap between mechanistic potential and product-specific clinical evidence. Functional claims should therefore be linked to precisely characterized microorganisms or compounds, appropriate doses, validated stability and human outcomes. Future progress will depend on strain-level identification, standardized analytical methods, gastrointestinal and bioavailability studies, well-designed human intervention trials, improved delivery technologies and integration of foodomics with precision nutrition.

For the dairy industry, the most promising strategy is not simply to increase the number of functional ingredients, but to design products in which the dairy matrix, processing conditions, functional component and intended physiological outcome are deliberately aligned. Such evidence-based development can improve both scientific credibility and consumer trust while creating opportunities for innovative, sustainable and value-added dairy foods.

Table 1: Major classes of functional dairy products and principal functional components

Product category	Major functional component	Potential functionality	Principal technological challenge
Probiotic yoghurt	Defined live probiotic strains	Gut and immune functions	Viability, post-acidification
Prebiotic yoghurt	Inulin, FOS, GOS	Selective microbial utilization	Texture, sweetness, fermentation
Synbiotic yoghurt	Probiotic + prebiotic	Combined microbiota-directed effects	Compatibility and stability
Postbiotic dairy beverage	Inactivated cells/components	Microbial metabolites and cell components	Standardization and characterization
Functional cheese	Probiotics, peptides, fibre	Microbial, peptide and nutritional functions	Ripening ecology and sensory quality
Whey functional beverage	Whey proteins, probiotics, peptides	Protein nutrition and bioactivity	Flavour and mineral balance
Fortified milk	Vitamin D, calcium, micronutrients	Nutrient adequacy	Stability and regulatory limits
Bioactive-peptide dairy	Milk-derived peptides	ACE/DPP-IV inhibition, antioxidant potential	Bioavailability and dose
Plant-bioactive dairy	Polyphenols, carotenoids, herbs	Antioxidant and other potential effects	Bitterness, colour, protein interactions
Functional paneer	Fibre, probiotics, plant bioactives	Nutritional and potential physiological benefits	Texture, moisture and shelf life

Table 2: Evidence hierarchy for evaluating functional dairy products

Evidence level	What it demonstrates	Interpretive limitation
1. Composition/identity	Presence and concentration of functional component	Does not demonstrate health benefit
2. <i>In vitro</i> assays	Biochemical or cellular activity	May not predict digestion or human response
3. Bioaccessibility/digestion	Stability and release during digestion	Does not establish clinical efficacy
4. Animal studies	Physiological effects <i>in vivo</i>	Species and dose may limit translation
5. Human intervention	Clinical or physiological outcome	Quality depends on design, strain and dose
6. Independent replication	Consistency across studies/products	Still requires relevance to target population

Table 3: Key quality attributes for functional dairy product development

Attribute	Suggested measurement	Why it matters	Critical interpretation
Probiotic viability	CFU/g or CFU/mL at manufacture and end of shelf life	Confirms delivery of live cells	Count at consumption is more informative than initial count
Bioactive peptide content	LC-MS/MS, HPLC, peptide database matching	Confirms identity and concentration	Sequence presence does not prove bioavailability
Prebiotic stability	Chemical assay and digestion model	Confirms persistence and utilization potential	Health effect requires selective utilization evidence
Physicochemical stability	pH, acidity, viscosity, syneresis, oxidation	Protects product quality	Functional ingredient may alter matrix properties
Sensory acceptability	Validated hedonic/descriptive methods	Determines consumer feasibility	Biological activity cannot compensate for poor acceptability
Microbiological safety	Standard food safety microbiology	Ensures product safety	Functional status does not reduce safety requirements
Shelf-life performance	Repeated measurements over intended storage	Confirms stability	Must reflect realistic cold-chain conditions

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