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Emerging microencapsulation technologies for dairy and functional foods: From encapsulation materials to bioactive delivery

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ABSTRACT

The increasing demand for functional dairy foods has intensified interest in microencapsulation as a strategy for protecting probiotics, polyphenols, vitamins, minerals, polyunsaturated fatty acids, essential oils, enzymes and other sensitive bioactive constituents. Direct incorporation of these ingredients into dairy matrices is frequently limited by oxidation, thermal degradation, moisture, light, acidic conditions, digestive stresses and undesirable interactions with food components. Microencapsulation addresses these limitations by entrapping active compounds or microorganisms within food-grade carrier matrices and can improve stability, mask undesirable sensory attributes and regulate release. This review summarizes recent advances in encapsulating materials, conventional and emerging processing techniques, probiotic and bioactive delivery, dairy-product applications, gastrointestinal release and industrial translation. Particular emphasis is placed on milk proteins, protein-polysaccharide composites, spray drying, extrusion, emulsification, electrospraying and single-cell probiotic encapsulation. Current evidence indicates that successful systems should be evaluated beyond encapsulation efficiency and should demonstrate storage stability, appropriate gastrointestinal release, sensory compatibility, biological functionality and scalability in real dairy matrices (Akram *et al.*, 2024; Han *et al.*, 2024; Gruskiene *et al.*, 2021).

Keywords: Microencapsulation, Bioactive compounds, Whey proteins, Gastrointestinal delivery, Etc.

1. Introduction

Functional foods are increasingly formulated to provide physiological benefits in addition to basic nutrition. Dairy products are particularly attractive delivery matrices because of their nutritional value, physicochemical diversity, widespread consumption and established use as carriers of probiotic microorganisms. However, many functional ingredients are unstable during processing and storage or interact adversely with proteins, lipids, minerals and other food constituents. Polyunsaturated fatty acids are susceptible to oxidation; phenolic compounds may have limited solubility or produce bitterness and astringency; essential oils are volatile and intensely aromatic; and probiotic microorganisms may lose viability during processing, refrigerated storage and gastrointestinal transit. These constraints can limit both technological performance and the intended functional benefit of fortified dairy products (Gruskiene *et al.*, 2021; de Souza *et al.*, 2024) [2, 1]. (Reque *et al.*, 2021; Rajam *et al.*, 2022) [4, 3]

Microencapsulation broadly involves entrapping, immobilizing or coating an active material within a protective matrix. The active material may be concentrated in a core, dispersed through a matrix, entrapped in a hydrogel network or surrounded by multiple layers. In foods, the core can include microorganisms, lipids, vitamins, minerals, enzymes, flavors, essential oils, antioxidants and polyphenols. The wall material reduces contact between the active ingredient and adverse environmental factors and can be designed to control release under selected processing or gastrointestinal conditions. Thus, encapsulation is not merely a preservation step but a delivery-system design problem in which stability, release, food-matrix compatibility and biological functionality are interdependent (Han *et al.*, 2024) [5]. (Fakolaki *et al.*, 2021; Yang *et al.*, 2024) [6, 7] Dairy proteins are particularly relevant to this field because they can function simultaneously as nutritional ingredients and encapsulating materials. Whey proteins and caseins possess surface activity, emulsifying capacity, gel-forming properties and affinity for a variety of bioactive compounds. They can also be combined with polysaccharides to construct composite matrices with improved mechanical, interfacial and gastrointestinal properties. The present review therefore focuses on recent microencapsulation technologies relevant to dairy and functional foods, with emphasis on wall materials, processing techniques, probiotic and bioactive delivery, dairy applications, characterization, gastrointestinal performance and future industrial translation (Akram *et al.*, 2024) [8].

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2. Fundamentals and mechanisms of microencapsulation

The protective performance of a microcapsule depends on its internal architecture, wall composition and interactions among the core, carrier and surrounding environment. Encapsulation can reduce oxygen and moisture transfer, limit volatilization, immobilize reactive molecules and provide a local microenvironment that buffers probiotic cells against acidity, bile salts, dehydration and mechanical stresses. For oxidation-sensitive oils, the principal objective is to minimize contact with oxygen and pro-oxidants; for volatile flavors and essential oils, diffusion through the wall is a major consideration; and for probiotics, the carrier must reduce environmental stress without permanently restricting cell release. (Yang *et al.*, 2024; Vijayaram *et al.*, 2024) [7, 9]

Release may occur through diffusion, swelling, dissolution, erosion, enzymatic degradation, ionic exchange or mechanical disruption. Consequently, maximum capsule stability is not always desirable. A probiotic carrier should resist food storage and gastric conditions but release viable cells in the intestine, whereas a flavor system may be designed to release during oral processing. Modern encapsulation therefore emphasizes a balance between protection and programmed release rather than encapsulation efficiency alone (Han *et al.*, 2024) [5]. (Yang *et al.*, 2024; Zhao *et al.*, 2024) [7, 10]

3. Encapsulating and wall materials for dairy applications

Wall-material selection is one of the most important determinants of encapsulation efficiency, particle formation, storage stability, release behavior and compatibility with the final food. Food-grade carriers are mainly proteins, polysaccharides, lipids or combinations of these materials. An effective wall material should provide appropriate film formation or gelation, acceptable viscosity, compatibility with the core, protection against anticipated environmental stresses and suitable sensory and regulatory characteristics. (Vijayaram *et al.*, 2024) [9]

Milk proteins have particular value in dairy applications. Whey proteins possess strong emulsifying and film-forming properties and can form heat-induced aggregates or gels that entrap sensitive compounds. β -Lactoglobulin can interact with hydrophobic ligands, while whey protein concentrates and isolates are readily incorporated into dairy formulations. Caseins and sodium caseinate are also useful because of their flexible amphiphilic structures, surface activity and ability to stabilize emulsions. A recent comprehensive review emphasized the versatility of milk proteins for encapsulating probiotics and other food ingredients and highlighted their relevance to functional-food formulation (Akram *et al.*, 2024, Jiang *et al.*, 2024, Barbosa *et al.*, 2024; Zhu *et al.*, 2024) [8, 11]

Polysaccharides remain equally important. Maltodextrin is extensively used in spray drying because of its solubility, low cost and ability to form a glassy matrix, although it often requires combination with an emulsifier for hydrophobic cores. Alginate is widely used for probiotic entrapment because calcium-mediated gelation occurs under mild conditions. Pectin, gum arabic, starch derivatives, chitosan and inulin are also common. Inulin is especially interesting in probiotic systems because it can contribute to capsule structure while acting as a prebiotic substrate. Increasingly, protein-polysaccharide composites are preferred because proteins provide interfacial activity while polysaccharides contribute viscosity, gel strength, steric stabilization and environmental resistance. Such complementary interactions are highly relevant to dairy systems and offer a rational route to tailor stability and release (Akram *et al.*, 2024, Bordini *et al.*, 2023, Schofield *et al.*, 2024; Vijayaram *et al.*, 2024) [8, 12]

4. Microencapsulation techniques

Spray drying remains the most industrially important encapsulation technique for dairy applications. A liquid feed containing the active ingredient and carrier is atomized into heated air, producing dried par-

ticles within a short residence time. The process is continuous, scalable and comparatively economical and is already integrated into milk- and whey-powder manufacturing. Feed solids, carrier composition, homogenization, atomization and inlet and outlet temperatures influence particle size, moisture, morphology, encapsulation efficiency and retention of sensitive compounds. Its principal limitation is the combined thermal, oxidative, osmotic and dehydration stress imposed on probiotics and thermolabile bioactives. Protective carbohydrates and proteins can reduce these effects by forming glassy or film-forming matrices around the core. (Anitha & Sellamuthu, 2022; Sbehat *et al.*, 2022, Gullifa *et al.*, 2023; Wang & Zhong, 2024) [13, 14, 15]

Freeze drying is valuable for highly heat-sensitive cultures and bioactives because water is removed by sublimation at low temperature. Nevertheless, freezing can generate osmotic stress and ice-crystal damage, while dehydration can destabilize membranes and proteins. Cryoprotective and lyoprotective ingredients are therefore required. Freeze drying commonly provides high product quality but has long processing times, high capital cost and substantial energy demand, making it less attractive than spray drying for high-volume dairy ingredients. (Wang *et al.*, 2024) [16]

Extrusion is extensively used for probiotic encapsulation. Probiotic cells are suspended in a polymer such as sodium alginate and extruded into a calcium solution, where ionic crosslinking produces hydrogel beads. Mild processing conditions favor cell survival, but conventional beads can be large and porous. Large particles may produce graininess in yoghurt and beverages, while porosity may permit rapid acid diffusion. Coating alginate with other biopolymers can improve barrier properties, although this increases process complexity. (Frakolaki *et al.*, 2021; Rajam *et al.*, 2022) [6, 3]

Emulsification can generate smaller hydrogel particles by dispersing a polymer phase containing the active ingredient into an immiscible continuous phase and subsequently solidifying the droplets. Particle size can be controlled through stirring, phase ratio, polymer concentration and emulsifier concentration. Complex coacervation, in contrast, uses phase separation and electrostatic interactions between biopolymers, often proteins and polysaccharides, to deposit a polymer-rich coating around droplets. It is particularly useful for oils, flavors and other hydrophobic compounds because relatively high core loading can be achieved. (Mousa *et al.*, 2023, Frakolaki *et al.*, 2021; Yang *et al.*, 2024) [17, 6]

Electrospraying is an important emerging technique because it can generate fine particles under low-thermal conditions. An electric field deforms a polymer solution into charged droplets that solidify into micro- or nanoparticles. The technique is attractive for probiotics, vitamins and other thermolabile compounds and can be extended to coaxial configurations for core-shell particles. Its major limitation is throughput. Nevertheless, recent work has demonstrated whey protein-polysaccharide electrosprayed microcapsules that co-encapsulated *Lactiplantibacillus plantarum* and epigallocatechin gallate, illustrating the potential for multifunctional dairy-protein delivery systems (Ma *et al.*, 2025, Jia *et al.*, 2025; Wang *et al.*, 2025) [19, 18]

5. Microencapsulation of probiotics for functional dairy foods

Probiotic encapsulation remains one of the most intensively studied dairy applications. The presence of viable cells at manufacture does not guarantee adequate survival during storage or gastrointestinal transit. Probiotic cells may experience mechanical shear, osmotic change, dehydration, oxygen, acidity, freezing, digestive enzymes and bile salts. Encapsulation can moderate these stresses by creating a protective microenvironment, but effectiveness is strongly strain-dependent. (Sbehat *et al.*, 2022; Sun *et al.*, 2023, Frakolaki *et al.*, 2021; Wang & Zhong, 2024) [14, 20, 6]

Alginate-based systems remain common because of mild gelation conditions, while coatings and composite matrices are used to reduce porosity and improve mechanical resistance. Incorporating inulin or other prebiotic carbohydrates can create synbiotic systems in which

the carrier also provides a fermentable substrate. Dried matrices produced by spray or freeze drying are attractive for shelf-stable probiotic ingredients, but formulation must protect membranes and proteins during dehydration and subsequent storage. (Bordini *et al.*, 2023; Schofield *et al.*, 2024; Vijayaram *et al.*, 2024) [12, 21]

A major recent development is single-cell encapsulation, in which a thin protective coating is constructed directly around an individual probiotic rather than entrapping many cells within a large bead. This strategy may reduce particle size and improve food compatibility while permitting the cell surface to be engineered for gastrointestinal protection. Han *et al.* (2024) [5] described single-cell encapsulation as a promising approach for oral probiotic delivery, although manufacturing scalability, food-grade coating selection, safety and controlled release remain important challenges. Future probiotic research should therefore evaluate not only initial cell counts but also survival during realistic storage, gastrointestinal release and retention of functional activity. (Zhao *et al.*, 2024) [10]

6. Microencapsulation of bioactive compounds for dairy fortification

Microencapsulation is also valuable for non-microbial bioactives. Omega-3 fatty acids are highly susceptible to oxidation, which reduces nutritional quality and generates fishy or rancid flavors. Encapsulation in spray-dried emulsions or coacervate structures can reduce oxygen exposure and surface oil, but protection depends on wall composition, particle porosity, storage temperature and packaging. The encapsulated lipid must subsequently be released during digestion, illustrating the need to balance storage protection with bioaccessibility.

Polyphenols and natural antioxidants can have limited solubility, chemical instability, bitterness, astringency or strong color. Milk proteins are attractive carriers because they interact with many phenolic compounds through hydrophobic and hydrogen-bonding interactions. Encapsulation can improve dispersibility and sensory compatibility, although excessively strong binding may restrict gastrointestinal release.

Essential oils have antimicrobial and antioxidant potential but their volatility, hydrophobicity and intense aroma restrict direct incorporation into dairy foods. Microencapsulation can improve retention and dispersion and can modulate release. A dairy-focused review concluded that encapsulation can help harness essential oils as natural antimicrobial agents, but performance depends on the oil composition, carrier, processing method and dairy matrix (de Souza *et al.*, 2024) [1]. Vitamins and minerals can similarly benefit from isolation from light, oxygen or reactive food components; however, adequate digestive release remains essential for nutritional effectiveness.

7. Application in major dairy products

Yoghurt and fermented milk are major vehicles for encapsulated probiotics and bioactives. Their acidic environment, post-acidification and oxygen exposure can reduce probiotic viability during storage. Encapsulation can improve survival, but hydrocolloid particles may modify viscosity, syneresis and mouthfeel. Fermentation itself can also alter capsule stability through changes in pH and ionic conditions. Gruskiene *et al.* (2021) [2] highlighted fermented milk as a versatile matrix for encapsulated bioactive ingredients while emphasizing the importance of matching the carrier and encapsulation technique to the active compound and product. (Mousa *et al.*, 2023; Guo *et al.*, 2022) [17]

Cheese provides relatively high buffering capacity and a structured protein matrix that may favor probiotic survival, although salt, moisture, ripening conditions and microbial competition can impose stress. Microcapsules must be compatible with cheese texture and biochemical changes during maturation. Encapsulated enzymes and flavors may additionally be used to control ripening or flavor release.

Ice cream and frozen desserts present freezing, ice-crystal and osmotic stresses to probiotics. Encapsulation can reduce direct exposure

to these stresses, but particle size must remain compatible with the expected smooth texture. Fluid milk and dairy beverages require particularly good dispersibility because large or dense particles may sediment. Dairy powders are naturally compatible with dried encapsulated ingredients, but long-term stability depends on residual moisture, water activity, glass transition, oxygen permeability and storage temperature. Reconstitution behavior is therefore an important quality criterion in addition to powder stability.

8. Characterization and evaluation

A robust evaluation of microencapsulated systems should combine structural, physicochemical, microbiological and functional measurements. Encapsulation efficiency is useful but insufficient because a high value does not demonstrate protection during storage or effective release. Particle size and distribution influence sedimentation, dispersibility, gastrointestinal behavior and sensory perception. Scanning electron microscopy is commonly used to assess surface shrinkage, cracks and pores in dried particles, while spectroscopic and thermal methods can reveal wall-core interactions and physical state. (Yang *et al.*, 2024) [7]

For dried systems, moisture content and water activity influence molecular mobility and storage stability. For encapsulated lipids, surface oil and primary and secondary oxidation products should be monitored. For probiotics, viable counts should be measured immediately after processing and throughout storage, followed by appropriate simulated gastrointestinal testing. In vitro digestion is valuable for screening but should not be interpreted as proof of in vivo efficacy.

9. Gastrointestinal release, bioaccessibility and bioavailability

Modern encapsulation research increasingly recognizes that processing stability is only the first stage of delivery. Bioaccessibility refers to the fraction of an ingested compound released from the food matrix and available for intestinal absorption, whereas bioavailability additionally includes absorption, distribution and metabolism. An encapsulated compound can therefore show improved in vitro bioaccessibility without necessarily producing greater systemic availability. (Yang *et al.*, 2024; Schofield *et al.*, 2024) [7, 21]

For lipophilic compounds, release from the carrier and incorporation into mixed micelles are essential for intestinal transport. Excessively stable particles can restrict this process. For probiotics, the objective is different: viable cells should survive gastric conditions and be released in an intestinal environment compatible with activity. Standardized digestion protocols and subsequent in vivo validation are needed because differences in pH, enzymes, bile concentration and digestion time can substantially influence experimental outcomes (Han *et al.*, 2024) [5].

10. Recent advances and emerging technologies

The field is moving from passive physical protection toward precision delivery systems with controlled architecture and environmental responsiveness. Single-cell probiotic coating is a prominent example. Rather than placing multiple cells in large hydrogel beads, protective biopolymer layers are assembled around individual cells. This can reduce carrier mass and particle size and may allow surface properties to be tailored for gastrointestinal survival and interaction. However, high-throughput food manufacturing and regulatory acceptance remain unresolved challenges (Han *et al.*, 2024) [5]. (Jiang *et al.*, 2024; Zhao *et al.*, 2024; Jia *et al.*, 2025) [11, 10]

Electrohydrodynamic processing, including electrospraying and coaxial electrospraying, enables relatively precise particle and core-shell formation under mild thermal conditions. The 2025 study by Ma *et al.* demonstrated that whey protein concentrate combined with polysaccharides could be electrosprayed to co-encapsulate *L. plantarum* and EGCG, with the carrier designed to improve probiotic protection and antioxidant functionality (Ma *et al.*, 2025) [19]. Such work is especially relevant to dairy science because milk-derived proteins can

form the structural basis of the delivery platform. (Jia *et al.*, 2025; Wang *et al.*, 2025) [18, 22]

Multilayer and protein–polysaccharide systems are also expanding because different layers can provide complementary barrier, mechanical and release functions. Microfluidic approaches offer exceptionally narrow particle-size distributions and controlled internal architecture, although low throughput currently restricts routine food manufacture. Three-dimensional food printing may eventually enable spatially organized delivery of probiotics and bioactives in personalized foods, but it remains primarily developmental for high-volume dairy applications.

11. Industrial scale-up, sensory quality and regulation

The gap between laboratory performance and commercial feasibility remains one of the major limitations in microencapsulation research. A formulation optimized on laboratory equipment may behave differently during industrial atomization, drying, mixing or gelation. Commercial systems must provide reproducible particle properties, acceptable process yield and throughput, reasonable ingredient and energy costs and compatibility with existing dairy operations. Spray drying retains a strong industrial advantage because large-scale dairy infrastructure already exists. (Reque *et al.*, 2021; Wang *et al.*, 2024) [4, 16]

Sensory compatibility is equally important. Large hydrogel particles can produce graininess; polysaccharides can alter viscosity and syneresis; proteins may interact with the casein network; and encapsulated oils or plant compounds may still influence flavor and color. Sensory evaluation should therefore be integrated during formulation rather than performed only after technical optimization. Regulatory acceptance also depends on the identity and status of the core and carrier materials, intended use and jurisdiction. Conventional food-grade proteins and polysaccharides generally offer a clearer pathway than novel chemically modified or nanoscale carriers. For probiotic systems, both strain safety and the properties of the delivery material require consideration.

12. Sustainability and future perspectives

Future dairy microencapsulation should increasingly integrate sustainability with functional performance. Whey proteins and other dairy side streams can serve as high-value carrier materials, while pectins, fibers, starches and proteins recovered from other food-processing streams may support circular processing. Nevertheless, a material of natural origin is not automatically sustainable; extraction, purification, drying and storage can carry substantial environmental burdens. Life-cycle assessment and techno-economic analysis should therefore accompany laboratory measures of encapsulation efficiency. (Jiang *et al.*, 2024; Barbosa *et al.*, 2024) [11]

The most important future direction is the transition from optimizing isolated particle characteristics to evaluating the complete product-to-gut pathway. Systems should be assessed for processing survival, storage stability, release, bioaccessibility, sensory acceptance and, where relevant, biological efficacy. Single-cell coatings, multifunctional co-encapsulation, protein–polysaccharide composites and precision electrospraying are likely to remain active research areas. Data-driven formulation may also assist optimization when sufficiently standardized datasets become available. (Wang *et al.*, 2024; Yang *et al.*, 2024) [16, 7]

Industrial translation will ultimately favor systems that provide adequate rather than merely maximal protection while remaining simple, safe and economical. A technically sophisticated multilayer particle has limited commercial value if it requires expensive ingredients, multiple processing stages or produces unacceptable mouthfeel. The most successful next-generation systems will therefore combine food-grade materials, predictable release, sensory compatibility, scalable processing and demonstrable functional benefit.

13. Conclusion

Microencapsulation has developed from a protective processing technique into a versatile delivery platform for functional dairy foods. Proteins, polysaccharides and their composites can protect probiotics, omega-3 lipids, polyphenols, essential oils, vitamins and other sensitive ingredients against processing and storage stresses while improving technological compatibility. Milk proteins are particularly promising because they combine nutritional value with emulsifying, gel-forming and ligand-binding properties (Akram *et al.*, 2024, Reque & Brandelli, 2021; Frakolaki *et al.*, 2021) [8, 4]

Spray drying remains the strongest option for large-scale dairy manufacture because of its throughput and established infrastructure, whereas extrusion, emulsification and freeze drying remain valuable for specific sensitive cores. Emerging techniques such as electrospraying and single-cell encapsulation provide greater control over particle architecture and probiotic delivery but require further scale-up and cost reduction (Han *et al.*, 2024; Ma *et al.*, 2025) [5, 19].

Future research should move beyond reporting encapsulation efficiency and demonstrate performance in real dairy matrices during realistic processing and storage. Gastrointestinal release, bioaccessibility, sensory quality, regulatory feasibility, sustainability and economic viability should be treated as integral design criteria. The central objective is therefore not simply to encapsulate a functional ingredient, but to create a safe and scalable system that protects it when necessary, releases it appropriately and provides measurable value in the final dairy product.

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