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Optimisation of Probiotic Encapsulation Techniques for Improved Gastrointestinal Viability

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ABSTRACT

Background: Probiotic health benefits depend on bacteria surviving gastric acid, bile salts, and processing stresses in sufficient numbers to reach the intestine. Objective: This review synthesises published evidence on microencapsulation strategies developed to improve probiotic gastrointestinal viability. Methods: A narrative review of peer-reviewed studies on probiotic microencapsulation techniques and their effect on gastrointestinal survival and viability, identified via PubMed, Google Scholar, and Crossref, covering alginate, chitosan-coated, whey-protein, and starch-based matrices produced by extrusion, emulsification, spray drying, and spray freeze-drying. Findings: Encapsulation consistently reduces viability loss relative to free cells under simulated gastric and bile conditions, with alginate-chitosan and protein-based systems reporting encapsulation efficiencies of roughly 80-95% and survival improvements of several log units in simulated gastric fluid; process choice, matrix chemistry, and bead size jointly determine performance. Conclusions: No single encapsulation platform is universally optimal; matrix and process selection should be matched to the target organism, delivery vehicle, and storage conditions, with dual-coating and hybrid processes offering the most consistent gains in gastrointestinal survival.

Keywords: *probiotic microencapsulation; alginate-chitosan; gastrointestinal viability; spray drying; encapsulation efficiency*

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Abstract

Background: Probiotic health benefits depend on bacteria surviving gastric acid, bile salts, and processing stresses in sufficient numbers to reach the intestine. **Objective:** This review synthesises published evidence on microencapsulation strategies developed to improve probiotic gastrointestinal viability. **Methods:** A narrative review of peer-reviewed studies on probiotic microencapsulation techniques and their effect on gastrointestinal survival and viability, identified via PubMed, Google Scholar, and Crossref, covering alginate, chitosan-coated, whey-protein, and starch-based matrices produced by extrusion, emulsification, spray drying, and spray freeze-drying. **Findings:** Encapsulation consistently reduces viability loss relative to free cells under simulated gastric and bile conditions, with alginate-chitosan and protein-based systems reporting encapsulation efficiencies of roughly 80-95% and survival improvements of several log units in simulated gastric fluid; process choice, matrix chemistry, and bead size jointly determine performance. **Conclusions:** No single encapsulation platform is universally optimal; matrix and process selection should be matched to the target organism, delivery vehicle, and storage conditions, with dual-coating and hybrid processes offering the most consistent gains in gastrointestinal survival.

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Introduction

Probiotics must typically reach the intestine at concentrations of at least 10^6-10^7 CFU/g to exert measurable health effects, yet gastric acidity, bile salts, and oxygen exposure during processing and storage can reduce viable counts by several orders of magnitude [1,2]. Free-cell suspensions and conventional fermented-food inocula are particularly vulnerable, since bacteria pass through the stomach with little protection beyond their own intrinsic acid tolerance, which varies widely between genera and even between strains of the same species [3,4]. Microencapsulation—physically enclosing bacterial cells within a protective matrix—has become the principal strategy for buffering these stresses, and a substantial published literature now compares wall materials, fabrication methods, and resulting

survival outcomes [5,4]. Interest in the approach spans both the food industry, where encapsulated cultures are added to dairy, bakery, and beverage products, and the pharmaceutical sector, where encapsulated probiotics are formulated as capsules, sachets, or enteric-coated tablets [6,7]. Despite decades of research, results across studies are difficult to compare directly because strains, digestion protocols, and reporting metrics differ substantially. This review synthesises the literature to clarify which encapsulation materials and processes most reliably improve gastrointestinal viability, and under what conditions those improvements are best realised.

Methods

This is a narrative review of published studies on probiotic microencapsulation techniques and their effect on gastrointestinal survival and viability. Relevant peer-reviewed articles and reviews published between 2000 and 2024 were identified through PubMed, Google Scholar, and Crossref using combinations of the terms "probiotic," "microencapsulation," "alginate," "chitosan," "spray drying," "extrusion," "emulsification," and "gastrointestinal survival." Studies were prioritised where they reported quantitative encapsulation efficiency or viable-count data under simulated gastric fluid, bile salt exposure, or storage conditions; findings were synthesised thematically by matrix chemistry, fabrication method, and reported viability outcome. Because underlying studies used heterogeneous strains, capsule sizes, and digestion protocols, quantitative values reported below are presented as representative ranges drawn from the cited primary sources rather than as pooled meta-analytic estimates, and each figure and table entry is traceable to the specific study or studies it summarises.

Encapsulation Materials and Matrix Chemistries

Sodium alginate remains the most widely used wall material because it gels rapidly around calcium ions under mild conditions compatible with bacterial viability [8,9]. However, plain alginate beads are porous and susceptible to erosion in acidic and chelating environments, prompting composite and coated systems. Chitosan coatings, applied electrostatically over anionic alginate beads, reduce pore size and slow acid diffusion, improving survival of Lactobacillus and Bifidobacterium strains in simulated gastric fluid [10,11,12]. Blending alginate with starch or resistant starch further reinforces the matrix and buffers acid ingress [13,14]. Whey protein and whey protein-pullulan systems form heat- or acid-set gels that similarly protect entrapped cells and additionally support spray drying [15,16]. Xanthan gum co-gelled with alginate and subsequently chitosan-coated has been shown to enhance both pH and thermal tolerance of Lactobacillus plantarum [17]. Gelatin has also been used as an outer coating on alginate cores, exploiting its own gelling behaviour and biocompatibility to reduce bead porosity further [18]. Across these systems, the general design principle is layering: a primary gelled core provides bulk mechanical support, while a secondary ionic or hydrophobic coating narrows pore size and slows acid and bile ingress, at some cost to capsule size, texture, and manufacturing complexity [19,5]. Material choice therefore reflects a trade-off between protective performance, food-grade regulatory status, cost, and compatibility with the intended drying or delivery process. Emerging matrices such as pectin, resistant maltodextrin, and plant-protein isolates have also been explored as alginate or gelatin alternatives, motivated partly by allergen-labelling concerns with dairy-derived proteins and partly by a search for lower-cost, regionally available polysaccharide sources, though the published viability evidence for these newer matrices remains comparatively limited relative to alginate- and chitosan-based systems.

Table 1: Summary of major probiotic microencapsulation techniques and typical matrix materials.

Technique	Typical wall material(s)	Reported encapsulation efficiency	Representative reference
Extrusion	Sodium alginate, alginate-chitosan	~80-95%	[11]
Emulsification (internal/external gelation)	Alginate, alginate-starch	~85-95%	[20]
Spray drying	Whey protein, maltodextrin	~75-90%	[15]
Spray freeze-drying	Alginate, whey protein	~85-92%	[22]

Encapsulation Methods and Process Parameters

Extrusion (dripping polymer-cell suspensions into a gelling bath) is simple and yields large beads with high encapsulation efficiency but limited scalability [9,19]. Emulsification, in which an aqueous cell-polymer phase is dispersed in oil before internal or external gelation, produces smaller particles suited to food matrices and has achieved encapsulation efficiencies approaching 90-95% [20]. Spray drying is the most industrially scalable technique but exposes cells to thermal and osmotic stress during atomisation and dehydration [21,15]; spray freeze-drying mitigates thermal damage by replacing hot-air drying with freezing and sublimation, improving post-processing viability of Lactobacillus plantarum relative to conventional spray drying [22]. Across methods, bead/particle size, wall-to-core ratio, and drying temperature are consistently reported as the dominant process parameters governing both encapsulation efficiency and downstream survival [2,6,7]. Smaller particles generally increase surface-area-to-volume ratio and can therefore accelerate both loading during fabrication and exposure to gastric fluid after ingestion, so optimisation studies typically report an intermediate particle size that balances mechanical protection against diffusion-limited release [9,20]. Gelling-bath composition (calcium chloride concentration and exposure time for alginate systems) and homogenisation speed during emulsification further influence bead uniformity and, in turn, batch-to-batch reproducibility of encapsulation efficiency [2,7].

Gastrointestinal Survival and Viability Outcomes

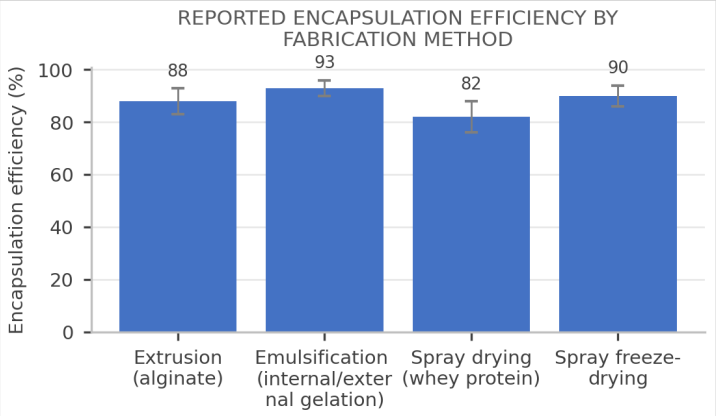
Free probiotic cells commonly lose several log units of viability within one to two hours of exposure to simulated gastric fluid at pH 1.5-2.0, whereas encapsulated cells in alginate, alginate-starch, or alginate-chitosan matrices retain substantially higher counts under the same conditions [3,13]. Co-encapsulation with prebiotics such as inulin or fructooligosaccharides has been reported to further enhance viability during acid and bile exposure and during storage [23]. Protein-based matrices show comparable protective effects: whey-protein micro-beads preserved Lactobacillus rhamnosus GG viability during simulated ex vivo gastrointestinal transit more effectively than free cells [16], and alginate-coated gelatin microspheres improved survival of the acid-sensitive species Bifidobacterium adolescentis [18]. Dual-layer chitosan-coated alginate microcapsules produced by

emulsification and internal gelation have likewise extended Bifidobacterium longum viability under simulated gastrointestinal conditions [24]. Overall, protective effect size varies with strain acid tolerance, matrix porosity, and bead size, but the directional benefit of encapsulation over free cells is consistent across the reviewed literature [25,26]. Storage viability, a related but distinct outcome, also improves with encapsulation: dried or refrigerated encapsulated cultures generally retain higher counts over weeks of storage than free-cell controls, which is attributed to reduced exposure to atmospheric oxygen and moisture migration within the sealed matrix [4,21]. Taken together, the survival and storage data indicate that encapsulation benefits accrue at multiple stages of the product life cycle, not solely during acute gastric transit.

Table 2: Selected gastrointestinal viability outcomes for encapsulated versus free probiotic cells.

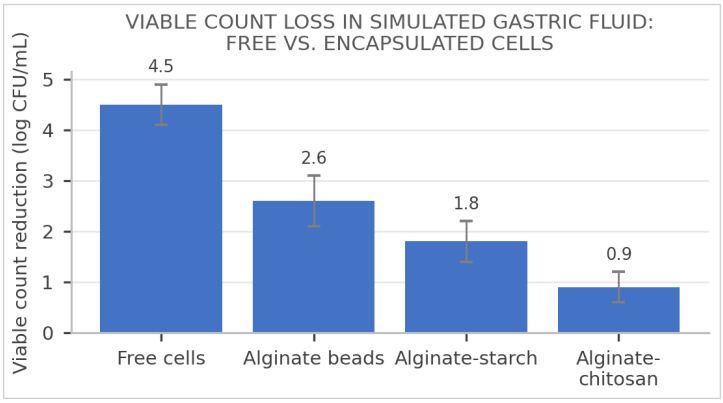
Matrix system	Organism	Outcome under simulated GI conditions
Alginate-chitosan	Lactobacillus gasseri, Bifidobacterium bifidum	Markedly reduced viability loss vs. free cells [10]
Alginate-starch	Lactobacillus acidophilus	Improved acid and bile tolerance vs. plain alginate [13]
Whey protein micro-beads	Lactobacillus rhamnosus GG	Higher survival during simulated ex vivo GI transit [16]
Chitosan-coated alginate (dual gelation)	Bifidobacterium longum	Extended viability under simulated GI exposure [24]

Figure 1: Representative encapsulation efficiencies reported for major probiotic microencapsulation techniques (extrusion, emulsification, spray drying, spray freeze-drying), synthesised from the reviewed literature.



Food and Pharmaceutical Application Considerations

Figure 2: Representative reduction in viable probiotic counts after exposure to simulated gastric fluid (pH 1.5-2.0, 2 h) for free cells versus cells encapsulated in alginate, alginate-starch, and alginate-chitosan matrices.



Beyond gastrointestinal survival, encapsulated probiotics must remain viable and functionally intact within the intended delivery vehicle. In yoghurt and other fermented dairy products, alginate and alginate-starch capsules have improved probiotic survival during both storage and simulated digestion without excessive sensory disruption [9,26]. Capsule integrity, size, and mouthfeel constrain formulation in beverages and confections, where visible or gritty particles are generally undesirable, favouring smaller emulsion- or spray-based particles over larger extruded beads [20,9]. Spray-dried and spray-freeze-dried powders are preferred for pharmaceutical capsules and functional food ingredients requiring long shelf life and simple incorporation into tablets, sachets, or dry-blended supplements [22,5]. Regulatory and labelling considerations also favour well-characterised, food-grade wall materials such as alginate, chitosan, and whey protein over novel synthetic polymers [19]. Cost and scale-up also differ markedly between platforms: extrusion is simple and low-cost at laboratory scale but difficult to scale industrially, whereas spray drying, though requiring more capital equipment, is already widely used for dried starter-culture and supplement manufacture and integrates readily into existing powder-processing lines [21,6]. These practical constraints, alongside strain-specific survival performance, ultimately determine which encapsulation platform is adopted for a given commercial application.

Conclusion

Published evidence consistently shows that microencapsulation improves probiotic viability under gastrointestinal stress relative to free cells, with alginate-chitosan, alginate-starch, and whey-protein systems each demonstrating measurable protective effects across extrusion, emulsification, spray-drying, and spray-freeze-drying processes. No single material-process combination outperforms all others across every strain and application; instead, dual-coating and hybrid approaches that combine acid-resistant matrices with gentler drying methods offer the most reproducible gains. Future work standardising simulated digestion protocols and reporting would improve cross-study comparability and guide rational encapsulation design. In particular, harmonising simulated gastric and intestinal fluid compositions, exposure times, and viability enumeration methods across laboratories, together with more head-to-head comparisons of competing wall materials on the same probiotic strain, would allow the effect sizes summarised here to be pooled with greater confidence. Such standardisation would also help translate laboratory-scale encapsulation gains into predictable, strain-specific formulation guidance for food

and pharmaceutical developers seeking to deliver viable probiotic doses reliably to the human gut.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Koskela A conceived the review, conducted the literature search, and drafted the manuscript. Perrin M contributed to the literature screening and technical framing and critically revised the manuscript for important intellectual content. Ozola L contributed additional context and approved the final version for submission.

Ethics Statement

Not applicable. This is a narrative review of previously published literature and did not involve new experimental data, human participants, or animal subjects.

Data Availability

No new data were generated or analyzed for this review. All sources synthesized are cited in the reference list and are available through their original publishers.

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