

Microencapsulation strategies in ruminant nutrition: Advances in formulation, delivery systems, and functional applications

Estrategias de microencapsulación en la nutrición de rumiantes: avances en formulación, sistemas de administración y aplicaciones funcionales

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Abstract

This article aims to present the process of making microcapsules and its benefits within animal nutrition, more specifically for ruminants. The review was carried out through a study of the literature regarding the nutrition of ruminants and the elaboration of microcapsules in order to choose the appropriate procedure that meets the desired purpose. A spreadsheet was elaborated to allow us to gather and summarize all the information found relating to authors, processes, materials, and techniques to later analyze those that were more effective. Following this, the writing of the article began considering the information found that allowed us to recognize the application of different specific methods used in the animal nutrition industry, among which spray drying and spray cooling stand out as successful techniques in the field of encapsulation of compounds of interest to implement improvements in the nutrition of ruminants.

Keywords: Feed additives, encapsulation techniques, bioactive compounds, animal feed technology, nutrient delivery systems.

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Resumen

El presente artículo de revisión pretende dar a conocer el proceso de elaboración de microencapsulados y sus beneficios dentro de la nutrición animal, más específicamente en rumiantes. La revisión se llevó a cabo mediante un estudio de la literatura respecto a la nutrición de rumiantes y la elaboración de los microencapsulados, esto con el fin de escoger el procedimiento adecuado que cumpla con el fin deseado. Se elaboró una tabla que permitiera reunir y resumir toda la información encontrada, relacionando autores, procesos, materiales y técnicas, para posteriormente analizar aquellos que tuvieran mayor efectividad. Seguido a esto, se inició la redacción del artículo teniendo presente la información encontrada, la cual permitió reconocer la aplicación de distintos métodos específicos usados en la industria de la nutrición animal, dentro de los cuales se encuentran el secado por aspersión y el enfriamiento por aspersión como técnicas exitosas en el campo del encapsulamiento de compuestos de interés para ejecutar mejoras en la nutrición de los rumiantes.

Palabras clave: aditivos alimentarios, técnicas de encapsulación, compuestos bioactivos, tecnología de alimentos para animales, sistemas de liberación de nutrientes.

Introduction

Microencapsulation is a technique in which an active material, in any state of aggregation, is coated with a matrix of wall material to protect it and to optimize its bioavailability and utilization within the organism. This coating allows the core material to be released in a controlled manner, through diffusion processes, at a specific site along the digestive tract where it can be absorbed and used effectively (Moschona & Liakopoulou-Kyriakides, 2018). A microparticle is composed essentially of two components: the core material, which corresponds to the active compound with a nutritional or functional effect, and the wall material, which acts as a protective barrier against external agents, thereby maintaining the integrity of the system until it reaches its target site of action (Contreras-Pacheco *et al.*, 2026).

Microcapsules are designed to release the core material at controlled rates under specific conditions, clearly differentiating between pre-ruminal and post-ruminal release phases in the case of ruminants (Contreras-Pacheco *et al.*, 2026). This capability for programmed release enables the encapsulated compound to be protected from adverse environmental factors such as light, oxygen, temperature, pH, acidity, and the presence of other reactive compounds, thereby preserving its chemical stability and biological activity (Thies, 2012). This controlled delivery mechanism is particularly important in ruminants, where the core material must bypass the harsh conditions of the rumen to be effectively absorbed in the lower gut.

Among the principal benefits of microencapsulation are the protection of the core material from critical environmental conditions (such as moisture, temperature, pH, oxidation, and light) and the preservation of the activity of sensitive bioactive compounds, including probiotics, non protein nitrogen, carbohydrates, lipids, vitamins, and proteins (Marcillo-Parra *et al.*, 2021). Furthermore, microencapsulation enables the controlled release of the active principle at a specific site within the organism, facilitating its absorption and reducing adverse reactions such as interference with the ruminal microbiota or premature loss of nutrients due to fermentation (Tolve *et al.*, 2021). By modifying the physical properties of the microcapsule, it is possible to balance the release and bioavailability of the compound, thereby improving its efficacy and reducing the need for frequent or excessive dosing (Tolve *et al.*, 2021).

In the field of veterinary medicine and animal nutrition, microencapsulation has become a key technological tool, particularly in ruminant nutrition (Kiran & Deswal, 2020). Applications include the use of microcapsules containing essential oils, whose effects have been evaluated on milk production and quality in lactating dairy cows. Da Silva *et al.* (2020) supplemented primiparous dairy cows with microencapsulated essential oils and reported beneficial effects on milk yield and composition, which were attributed to alterations in ruminal fermentation and improved nutrient utilization. Similarly, they evaluated microencapsulated selenium in dairy cattle and observed superior mineral

absorption compared with inorganic sodium selenite, with higher transfer of selenium from the supplemented diet into milk.

In this way, microencapsulation represents a highly valuable technology in the animal feed industry, as it enables the development of more efficient nutrient and additive delivery strategies, reducing losses and improving animal performance and health, as well as the quality of animal derived products such as milk and meat. This biotechnological advancement contributes to the sustainability of animal production by optimizing the use of feedstuffs and minimizing metabolic and environmental impacts within the ruminant organism.

Methodology

This mini review was conducted using a structured and reproducible approach that integrates elements of a systematic literature review with a critical narrative synthesis, aiming to provide a comprehensive and analytical overview of microencapsulation strategies in ruminant nutrition. The scope of the review includes studies published up to December 2021, allowing for a consolidated assessment of established technologies and applications prior to recent developments in the field.

Literature search strategy

A comprehensive literature search was performed across Scopus. The search strategy combined keywords related to microencapsulation technologies and ruminant nutrition using Boolean operators.

The core search string included terms such as: TITLE-ABS-KEY ((“microencapsulation” OR “encapsulation” OR “microcapsules” OR “nanoencapsulation” OR “coating”) AND (“ruminant nutrition” OR ruminants OR cattle OR dairy OR rumen OR sheep OR goats OR bovine) AND (“controlled release” OR bioavailability OR “feed additives” OR “rumen protection” OR “bypass nutrients” OR “targeted delivery” OR digestibility)) AND PUBYEAR>2000 AND PUBYEAR<2021 AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “re”)) AND (LIMIT-TO (LANGUAGE, “English”) OR LIMIT-TO (LANGUAGE, “Spanish”)).

Inclusion and exclusion criteria

The following inclusion criteria were applied: (i) original research articles, controlled trials, and comprehensive reviews on microencapsulated nutrients or additives used in ruminants (including bovine, sheep, goats, and camelids); (ii) studies reporting encapsulation materials and techniques, as well as biological outcomes such as production performance, ruminal fermentation, animal health, and milk or meat quality; and (iii) articles written in English, Spanish, or Portuguese, provided that the methodology and results were clearly described.

Articles were excluded if they: (i) focused on microencapsulation for monogastric animals, aquaculture, or human food applications without explicit relevance to ruminant nutrition; (ii) were short communications, editorial comments, or patent documents lacking experimental

data on animal performance or ruminal behavior; or (iii) analyzed encapsulation methods without presenting results related to ruminant physiology, productivity, or product quality.

Study selection and synthesis process

The study selection process followed a structured approach inspired by the PRISMA guidelines. Selection was conducted in two stages. First, titles and abstracts were screened to exclude clearly irrelevant studies, such as those involving non-ruminant species or non-nutritional applications. In the second stage, the full texts of potentially eligible articles were evaluated to confirm compliance with all inclusion criteria and to ensure sufficient methodological and experimental detail.

For each retained study, relevant information was systematically extracted and compiled into a structured synthesis table, including animal species and physiological stage (e.g., lactating dairy cows, growing beef cattle, and ewes); encapsulated compound (e.g., essential amino acids, polyunsaturated fatty acids, vitamin E, selenium, enzymes, and probiotics); encapsulation technique (e.g., spray drying, spray chilling, fluidized-bed coating, coacervation, and emulsion-based systems); wall material composition (lipid-, polymer-, protein-, carbohydrate-based, or multilayer systems); proposed or demonstrated site of release (ruminal or post-ruminal), along with the evaluation method (in vitro simulations or in vivo trials); and the main outcomes reported, such as milk yield and composition, carcass

traits, ruminal pH, volatile fatty acids, methane emissions, digestibility, and health indicators.

This tabular synthesis enabled a systematic comparison across studies and supported the identification of trends, inconsistencies, and knowledge gaps in the literature on microencapsulation in ruminant nutrition up to 2021.

Thematic organization and qualitative analysis

Following data extraction, the selected studies were organized into thematic sections to facilitate a coherent and in-depth analysis. These sections included: (i) formulation of microencapsulated nutrients, focusing on core materials and the rationale for encapsulation; (ii) wall materials and delivery systems, including lipid-based, polymer-based, protein-based, and multilayer matrices; (iii) encapsulation technologies commonly applied in ruminant feed systems; (iv) functional applications and biological outcomes reported in ruminants up to 2021; and (v) limitations, challenges, and emerging trends that suggest future research directions beyond 2021.

Within each section, the analysis combined descriptive synthesis with critical interpretation, emphasizing convergent findings, methodological variability, and unresolved scientific questions. The level of evidence was assessed qualitatively rather than through formal scoring systems, maintaining consistency with the scope and format of a mini review while ensuring a rigorous and insightful evaluation of the field.

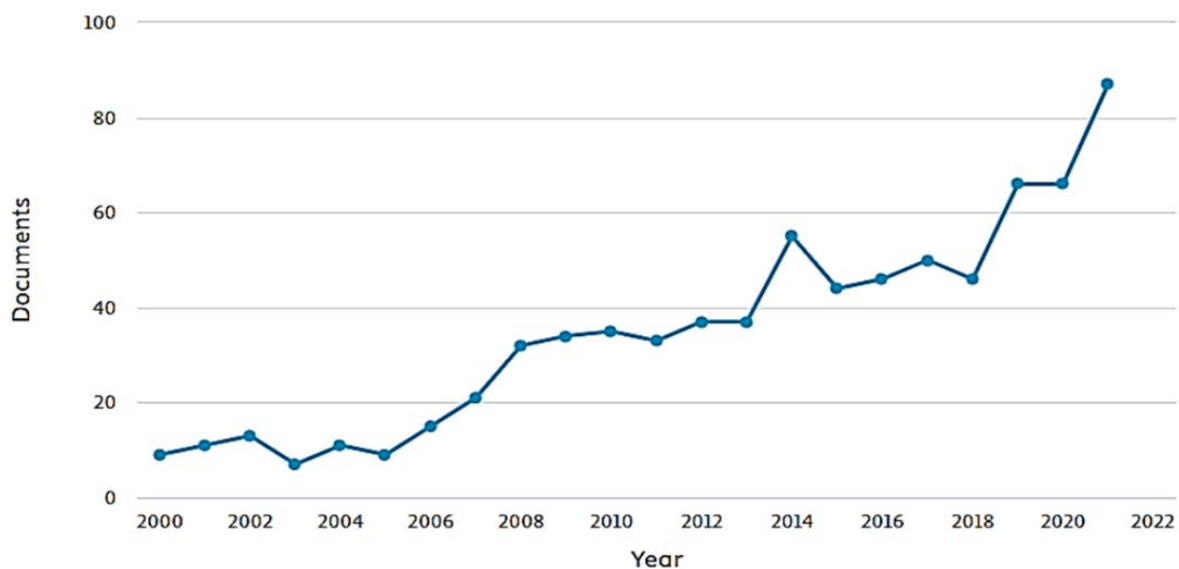
Results and discussion

Figure 1 shows the temporal distribution of publications, revealing a steady increase in research output from 2000 to 2021, with a marked acceleration after 2014. Early studies (2000–2006) were limited in number, reflecting the emerging nature of microencapsulation technologies in ruminant systems.

From 2007 onwards, progressive growth was observed, likely driven by advances in encapsulation techniques and their application in improving nutrient delivery and rumen stability (Tolve *et al.*, 2021).

Notably, the sharp increase in publications after 2018 highlights the growing interest in functional feed additives, rumen-protected compounds, and sustainable livestock production strategies (Park *et al.*, 2018).

Figure 1. Number of documents published per year in Scopus on microencapsulation/encapsulation in ruminant nutrition (2000–2021)



Source. Own elaboration.

Figure 2 depicts the keyword co-occurrence generated using VOSviewer software (version 1.6.5, developed by Van Eck and Waltman, NL). The keyword co-occurrence map delineates a highly interconnected and multidisciplinary research landscape centered on microencapsulation and its applications across biomedical and animal-related systems. The network structure

reveals both conceptual consolidation and translational expansion, characteristic of a field transitioning from fundamental formulation science toward application-driven innovation.

At the core of the map, high-frequency nodes such as particle size, drug delivery system, nanoparticle, and encapsulation function

as dominant intellectual anchors. Their central positioning and extensive linkages indicate that control over physicochemical properties—particularly size, surface charge (zeta potential), and morphology—remains the principal determinant guiding system performance. These variables underpin critical functionalities such as drug release, bioavailability, and biocompatibility, which collectively define the efficacy of encapsulated systems.

The network segregates into four major thematic clusters, each reflecting a distinct yet overlapping research trajectory:

1. Physicochemical and formulation science (blue cluster)

This cluster is densely organized around terms such as drug bioavailability, drug solubility, dispersity, and drug targeting. It represents the mechanistic backbone of the field, emphasizing how formulation parameters influence absorption, distribution, and overall therapeutic performance. The prominence of oral drug administration and nanoparticle engineering suggests a sustained focus on overcoming solubility and permeability barriers.

2. Delivery systems and functional materials (green cluster)

Anchored by terms such as drug delivery system, biocompatibility, polymer, and bovine serum albumin, this cluster reflects advances in carrier design. The frequent appearance of protein-based systems highlights a growing interest in biologically derived materials as encapsulation matrices.

Notably, the inclusion of humans and animals within this cluster underscores its translational relevance, bridging material science with in vivo applicability.

3. Chemical and encapsulation processes (red cluster)

This cluster is centered on encapsulation, chemistry, controlled release, and microencapsulation. It reflects the engineering and process-oriented dimension of the field, including emulsification, gelation, and the development of structured delivery systems.

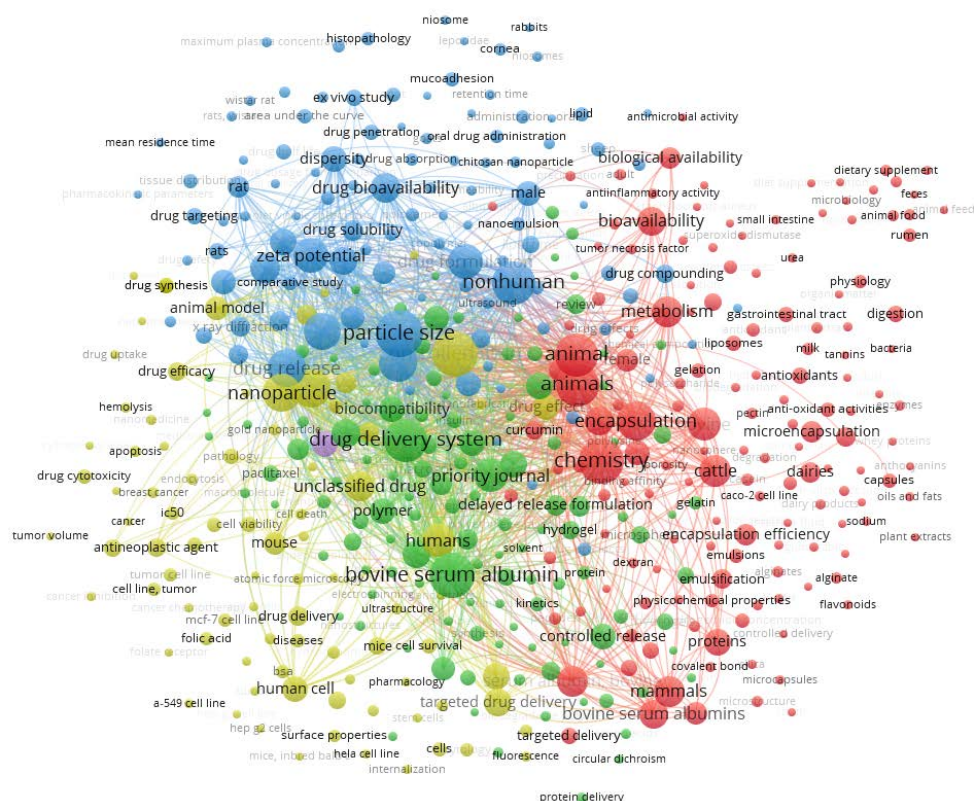
The co-occurrence of terms such as antioxidants, flavonoids, and plant extracts signals a strong trend toward incorporating functional bioactives, particularly those of natural origin. Importantly, nodes such as “animal”, “cattle”, and “dairies” indicate the extension of encapsulation technologies into animal nutrition and agro-industrial applications.

4. Biomedical and therapeutic applications (yellow cluster)

This cluster emphasizes antineoplastic agents, drug efficacy, cell viability, and human cell models, reflecting the biomedical origins of microencapsulation research. The presence of terms such as tumor cell line and apoptosis suggests a strong orientation toward oncology and targeted therapies.

However, its peripheral yet connected position indicates that while biomedical applications remain foundational, they are increasingly integrated with broader delivery system innovations.

Figure 2. Keyword co-occurrence generated using VOSviewer software from papers published between 2017 and 2021



Source. Own elaboration.

Emerging trends and conceptual convergence

A key insight from the map is the convergence between traditionally distinct domains—pharmaceutical sciences, materials engineering, and animal nutrition. The proximity of terms such as animal, metabolism, and bioavailability to core encapsulation terms suggests that principles initially developed for human therapeutics are being actively translated into animal feed systems. This includes the delivery of antioxidants, enzymes, and bioactive compounds to enhance digestion, health, and productivity.

Additionally, the increasing visibility of nanoemulsion, liposome, and hydrogel systems reflects a shift toward more sophisticated and tunable delivery platforms. These systems enable controlled and targeted release, aligning with the broader paradigm of precision delivery.

Another notable trend is the integration of natural compounds (e.g., curcumin, flavonoids, and plant extracts) within encapsulation frameworks, reinforcing the movement toward sustainable and functional additives, particularly relevant in the context of antibiotic-free animal production systems.

Microencapsulation methods and their selection

To select an appropriate microencapsulation method, it is necessary to consider the target site and the physiological conditions under which the core material must be delivered, as well as its compatibility with the wall material. In the animal feed industry, a wide range of encapsulation technologies has

been applied to address key nutritional and metabolic challenges in ruminants, thereby improving the quality of animal-derived products such as milk and meat (Kiran & Deswal, 2020).

Table 1 summarizes the most commonly used microencapsulation methods in ruminant nutrition, along with their main functional characteristics.

Table 1. Microencapsulation strategies in ruminant nutrition: materials, release mechanisms, and functional outcomes

Method	Core material	Wall material	Release mechanism	Functional objective	Key outcome	Reference
Extrusion	Probiotics (Lactobacillus, Bifidobacterium)	Sodium alginate/pectine	Diffusion/enzymatic degradation	Protection of viable	Improved immune response and animal performance	(Melo <i>et al.</i> , 2021)
Liposomes	Curcumin	Phospholipids	Diffusion-controlled	Slow nitrogen release	Improved ruminal performance	(Wu <i>et al.</i> , 2020)
Dispersion	Urea	Poly (3-hydroxybutyrate)	Diffusion	Controlled nitrogen delivery	Sustained nitrogen release without toxicity	(Arjona <i>et al.</i> , 2021)
Lyophilization	Urea	Beeswax	Lipid digestion	Slow nitrogen release	Improved ruminal performance	(de B. Carvalho <i>et al.</i> , 2019)
Lipid encapsulation	Methionine, lysine	Lipid matrix	Lipid digestion	Rumen protection of amino acids	Increased post-ruminal bioavailability	(King <i>et al.</i> , 2021)

Lipid coating	Soybean meal protein	Fat (palmitic/stearic acids)	Lipid digestion	Rumen bypass protein	Increased rumen-undegraded protein	(Campos <i>et al.</i> , 2021)
Fat coating	Glucose	Lipid matrix	Lipid digestion	Energy	Improved milk production and metabolic status	(Li <i>et al.</i> , 2019)
Emulsification + Spray drying	Proteins (ovalbumin, whey, plant proteins)	Polymeric matrix	Diffusion/matrix erosion	Protection against ruminal hydrolysis	Enhanced protein stability	(Tan <i>et al.</i> , 2021)
Emulsification-sonication	Lysine	Arachidic or stearic acids and Tween 60	Diffusion-controlled	Controlled nitrogen delivery	Improved stability and delivery of bioactives	(Albuquerque <i>et al.</i> , 2020)
Emulsification + Spray drying	Tannin extract	Gum arabic-maltodextrin	Diffusion/degradation	Fermentation modulation	Reduced ruminal degradation	(Adejoro <i>et al.</i> , 2019)
Spray drying	Branched-chain VFAs	Mixed materials	Controlled release	Fermentation control	Modified gas production dynamics	(Dias Batista <i>et al.</i> , 2020)
Emulsification	Cu and Se	Lipid matrix	Lipid digestion	Mineral delivery and fermentation modulation	Altered rumen microbial activity	(Arce-Cordero <i>et al.</i> , 2020)
Liposomes	Curcumin	Milk/krill	Enzymatic digestion	Bioavailability enhancement	Improved digestibility and stability	(Wang <i>et al.</i> , 2009)

Source. Own elaboration.

As shown in table 1, spray drying, extrusion, emulsification, and spray cooling are the most frequently employed techniques. The selection of each method depends not only on processing considerations but also on the physicochemical properties of both the core and wall materials, as well as the environmental conditions that the microcapsule must withstand, including pH variations, temperature fluctuations, and enzymatic activity within the gastrointestinal tract (Thies, 2012). The following sections provide a detailed overview of these processes.

Extrusion is a well-established technique in which microcapsules are formed by injecting droplets of a colloidal solution into a hardening bath, leading to the formation of gel-based capsules around the active compound. This method is particularly suitable for ingredients of low volatility and high stability, as the resulting gel network provides a robust and controllable matrix for encapsulation (Melo *et al.*, 2021). Its relatively mild processing conditions also make it advantageous for preserving the functional integrity of sensitive bioactive compounds.

Emulsification involves the dispersion of one immiscible liquid phase into another, typically generating oil-in-water or water-in-oil systems in which the polymer phase contains the active compound. Upon phase solidification, induced by temperature changes, cross-linking, or solvent removal, solid microcapsules are formed within the continuous phase. This technique allows the production of particles with relatively narrow size distributions and improved structural homogeneity (Arjona *et al.*, 2021).

Depending on the operational parameters, external gelation can produce particles in the range of 400 μm to 1 mm, whereas internal gelation enables the formation of smaller and more uniform microcapsules ($\sim 50 \mu\text{m}$), which may enhance release control and bioavailability (Adejoro *et al.*, 2019).

Spray drying remains the most widely used microencapsulation method in the food and feed industries due to its cost-effectiveness, scalability, and ability to produce stable, free-flowing powders with controlled particle size and rapid dispersibility (Hoyos-Leyva *et al.*, 2018; Macías-Cortés *et al.*, 2020). The process involves atomizing a liquid feed into a hot air stream, where rapid solvent evaporation leads to the formation of dry microcapsules. Final particle characteristics depend strongly on process parameters and feed composition. However, a key limitation of spray drying lies in the restricted selection of wall materials, which must withstand high temperatures during processing. Therefore, prior characterization of the core material is essential to ensure adequate thermal stability and high encapsulation efficiency (Zanoni *et al.*, 2020).

In ruminant nutrition, spray-dried microcapsules have been successfully applied to protect proteins from microbial degradation in the rumen. For instance, King *et al.* (2021) demonstrated that microencapsulation significantly improved the resistance of dietary proteins to ruminal hydrolysis, thereby enhancing their post-ruminal availability. In that study, protein sources with simpler molecular structures, such as whey protein and ovalbumin, formed more homogeneous and structurally robust

capsules, exhibiting greater resistance to ruminal microbiota and improved protein retention. These findings highlight the potential of spray drying as a practical and efficient strategy for developing rumen-protected protein systems.

Spray cooling represents an alternative encapsulation technique particularly suited for heat-sensitive or volatile compounds. In this process, a molten lipid matrix containing the active ingredient is atomized into a cooled chamber, where rapid solidification results in the formation of lipid-based microcapsules (Adejoro *et al.*, 2019). This method offers advantages in terms of process simplicity, high retention efficiency, and protection against oxidation and volatilization. The encapsulated core may be hydrophilic or lipophilic, provided that it can be adequately dispersed within the lipid phase.

Microencapsulation in ruminant nutrition

Microencapsulation strategies in ruminant nutrition are predominantly driven by the need to balance ruminal protection and post-ruminal release, which ultimately determines the bioavailability and functional efficacy of the encapsulated compounds. Across the dataset, a clear technological trend emerges, where lipid-based encapsulation systems dominate applications aimed at rumen bypass, particularly for nutrients highly susceptible to microbial degradation, such as amino acids, glucose, and urea.

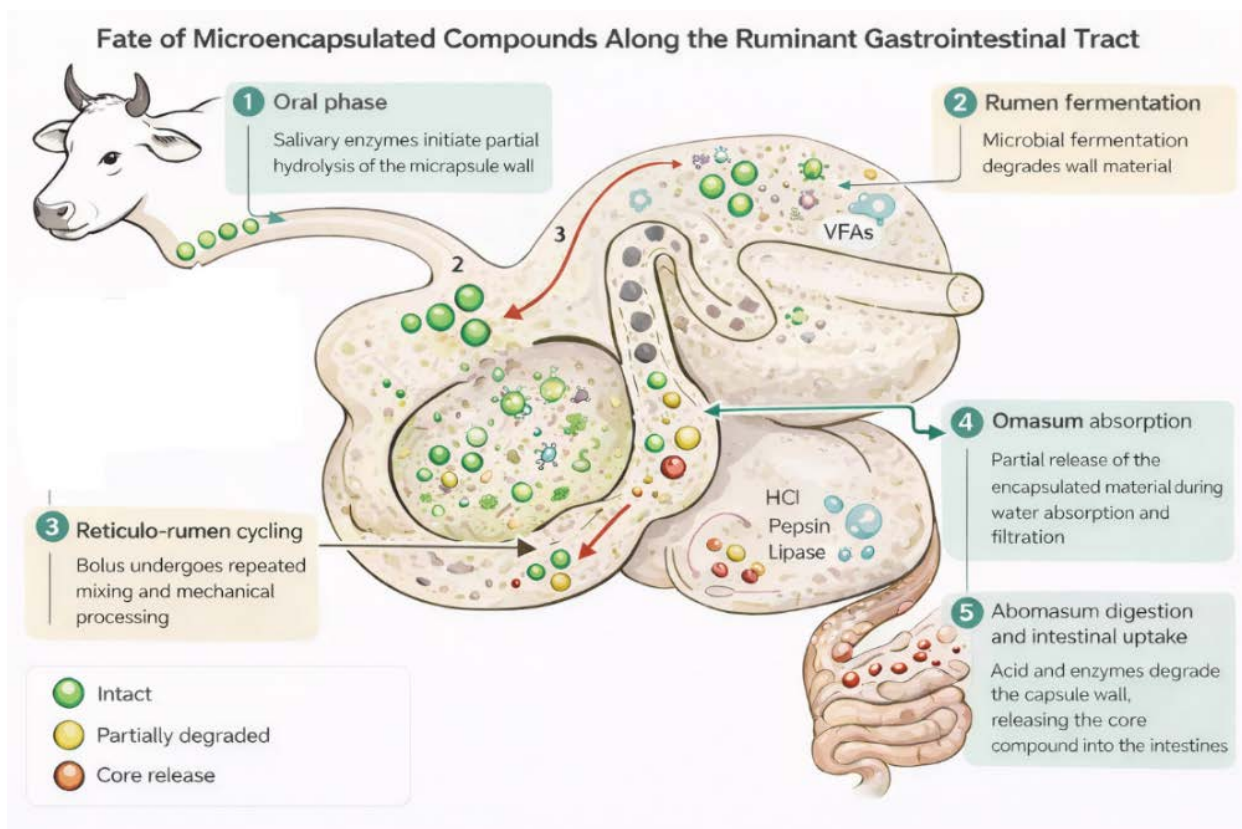
In the context of ruminant nutrition, lipid-based microcapsules produced by spray

cooling have proven effective in protecting minerals and other labile nutrients from ruminal degradation. For example, Arce-Cordero *et al.* (2020) reported that microencapsulated sodium selenite exhibited greater resistance to ruminal reduction compared to its non-encapsulated counterpart, resulting in enhanced selenium transfer into plasma and milk. Animals receiving the encapsulated form showed higher milk selenium concentrations, indicating improved absorption and bioavailability. These results demonstrate the relevance of lipid encapsulation systems for improving the efficiency of micronutrient delivery in dairy production systems.

The effectiveness of microencapsulation strategies in ruminant nutrition is ultimately determined by the dynamic interaction between the encapsulated compound and the complex digestive physiology of the host animal. As illustrated in Figure 3, microcapsules undergo a series of transformations throughout the gastrointestinal tract. Upon ingestion, microcapsules are exposed to salivary enzymes that may initiate partial hydrolysis of surface components (Kiran & Deswal, 2020).

In the rumen, which is the most critical stage, microcapsules are subjected to intense microbial fermentation, where bacteria, protozoa, and fungi can degrade the wall material depending on its composition and resistance (Mizrahi *et al.*, 2021). Simultaneously, the production of volatile fatty acids (VFAs) creates a chemically dynamic environment that further challenges capsule stability.

Figure 3. Fate and functional behavior of microencapsulated compounds along the ruminant gastrointestinal tract



Source. Own elaboration.

The repeated cycling of digesta between the rumen and reticulum enhances mechanical breakdown and microbial exposure, potentially compromising capsule integrity. As the digesta progresses to the omasum, water absorption and mechanical filtration increase the interaction between microcapsules and digestive fluids, facilitating partial release of the encapsulated compounds (Öztürk & Gür, 2021). In the abomasum, acidic pH and enzymatic activity (e.g., pepsin) promote the breakdown of the encapsulating matrix, enabling the release of the core material, which is subsequently absorbed in the intestine.

The efficiency of this process depends critically on the balance between structural resistance in the rumen and controlled disintegration in post-ruminal compartments. If the capsule degrades too early, the active compound is lost due to microbial metabolism; if it is too resistant, nutrient release and absorption are compromised (Carvalho *et al.*, 2019). Therefore, the design of effective encapsulation systems requires precise tuning of material properties and release kinetics to achieve targeted delivery.

Overall, these findings underscore that microencapsulation is not merely a

protective strategy but also a functional delivery system that can enhance nutrient bioavailability, reduce metabolic losses, and improve animal performance. Moreover, its application contributes to more sustainable livestock production by enabling more efficient nutrient utilization and reducing environmental impacts such as methane emissions and nitrogen excretion (Haque, 2018). Future research should focus on optimizing material selection, improving scalability, and validating these systems under long-term *in vivo* conditions to fully realize their potential in commercial ruminant production systems.

The main microencapsulation strategies applied in ruminant nutrition highlight the relationship between encapsulation technique, material selection, and functional outcomes. Lipid-based systems dominate applications aimed at rumen protection, whereas polymeric systems are more frequently associated with controlled release mechanisms.

Lipid matrices, including hydrogenated fats and waxes, have been widely employed due to their hydrophobic nature and resistance to ruminal microbial activity. Studies such as Arce-Cordero *et al.* (2020), Campos *et al.* (2021), and Li *et al.* (2019) demonstrate that lipid-encapsulated amino acids and proteins can effectively bypass ruminal degradation, leading to enhanced intestinal digestibility and improved nitrogen utilization. These findings highlight the high translational potential and industrial scalability of lipid-based systems, which explains their widespread adoption in commercial feed formulations.

However, despite their effectiveness in protecting core materials, lipid-based systems exhibit limited control over release kinetics, as their degradation is largely governed by passive physicochemical processes such as melting and enzymatic lipolysis. This lack of precision may result in suboptimal synchronization between nutrient release and animal metabolic demands, particularly under variable physiological conditions. Consequently, while lipid encapsulation ensures protection, it does not always guarantee targeted delivery, which is increasingly recognized as a key requirement in precision livestock nutrition.

In contrast, polymeric encapsulation systems, including calcium pectinate and polysaccharide-based matrices, offer greater flexibility in modulating release profiles through mechanisms such as diffusion, swelling, and enzymatic degradation. Adejoro *et al.* (2019) showed that biopolymer-based encapsulation of tannins reduced their rapid degradation in the rumen, allowing for a more controlled modulation of fermentation processes. These systems provide a higher degree of tunability compared to lipid matrices, making them particularly suitable for applications requiring controlled or delayed release.

Nevertheless, polymeric systems face significant limitations related to scalability, cost, and mechanical stability, which hinder their widespread application in commercial feed production. Their sensitivity to processing conditions and variability in performance under *in vivo* conditions further complicate their industrial implementation.

This trade-off between functional precision and technological feasibility represents one of the main challenges in the field.

Another relevant trend identified in table 1 is the growing interest in encapsulating compounds aimed at modulating rumen fermentation, including tannins, branched-chain volatile fatty acids, and trace minerals. Arce-Cordero *et al.* (2020) demonstrated that lipid-based microencapsulation of copper and selenium altered microbial fermentation patterns, suggesting that encapsulation can be used not only for protection but also as a tool to strategically influence the rumen microbiota.

These findings suggest that microencapsulation is evolving from a passive protective technology into an active modulation strategy, capable of influencing rumen ecology and metabolic outputs. This shift aligns with current trends in sustainable livestock production, where improving feed efficiency and reducing environmental impacts—such as methane emissions and nitrogen losses—are key priorities.

In addition, emerging systems such as liposomes and nanostructured carriers, as reported by Albuquerque *et al.* (2020), demonstrate the potential for enhancing the stability and bioavailability of bioactive compounds, including antioxidants and phytochemicals. Although these advanced systems are still primarily explored in food and biomedical contexts, their application in ruminant nutrition represents a promising research frontier. However, their adoption remains limited due to economic constraints, regulatory considerations, and scalability issues, which must be addressed before practical implementation.

Overall, the analysis of the available studies indicates that no single encapsulation strategy fully satisfies all functional and industrial requirements. Instead, the field is characterized by a trade-off between protection efficiency, release control, and scalability. Lipid-based systems offer robustness and feasibility but limited precision, whereas polymeric systems provide tunability at the expense of industrial applicability.

From a future perspective, research efforts should focus on the development of hybrid encapsulation systems that combine the structural stability of lipid matrices with the controlled release capabilities of polymers. Additionally, integrating encapsulation technologies with precision feeding strategies and real-time monitoring of animal metabolism could significantly enhance their effectiveness. The use of agro-industrial residues as encapsulating materials or bioactive cores also represents a promising avenue, particularly in the context of the circular economy and sustainable production systems.

Conclusions

Microencapsulation has moved well beyond being a formulation convenience, it is now shaping how we think about nutrient delivery in ruminant systems. What emerges from this review is a field that has matured technically yet is still negotiating the balance between biological effectiveness and industrial reality. Encapsulation clearly improves the stability and post-ruminal availability of sensitive compounds, and

there is consistent evidence that this translates into better nutrient utilization and, in many cases, improved animal performance. At the same time, the rumen remains a highly variable and difficult environment to control, and this continues to challenge the precision that we aim to achieve.

Lipid-based systems have become the practical standard, largely because they work reliably and can be produced at scale. Their success is not surprising—they offer robust protection and integrate well into existing feed manufacturing processes. However, their dependence on passive digestion limits the degree to which nutrient release can be fine-tuned.

Polymeric systems, in contrast, offer a more sophisticated level of control, allowing release to be modulated through well-understood physicochemical mechanisms. Yet, after years of promising experimental results, their adoption remains limited, reflecting unresolved issues related to cost, scalability, and consistency under real production conditions.

What is particularly striking is the growing interest in more complex delivery systems, including liposomes and nano-structured carriers. These approaches open new possibilities, especially for delivering functional compounds with higher specificity and stability. Still, they largely remain within the experimental domain. Moving these technologies toward practical application will require not only technical refinement, but also a clearer demonstration of their value under commercial conditions.

Perhaps the most important takeaway is that there is no single “ideal” encapsulation strategy. Each approach involves trade-offs between protection, release control, and feasibility. The next phase of progress will likely depend on hybrid systems that combine the strengths of different materials and mechanisms, rather than relying on any one solution. Designing such systems will require a more integrated understanding of both material science and ruminant physiology.

Looking ahead, the field would benefit from a stronger emphasis on *in vivo* validation and on linking encapsulation performance with measurable outcomes in animal production. Too often, promising technologies remain at the level of laboratory characterization. Bridging this gap is essential if encapsulation is to become a routine tool in precision nutrition. There is also a clear opportunity to align these developments with sustainability goals, particularly through the use of agro-industrial by-products as encapsulating materials or functional ingredients.

In that sense, microencapsulation is not just about protecting nutrients—it is about rethinking how feeds are designed and how efficiently they are used. Its continued development will play an important role in improving productivity while reducing environmental impact, which is ultimately the direction in which ruminant production systems need to move.

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