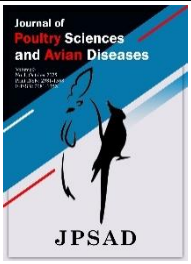
Journal of Poultry Sciences and Avian Diseases

Journal homepage: www.jpsad.com



Next-Generation Feed Additives in Poultry Production: The Role of Encapsulation Technologies in Precision Nutrition

Bahareh Saeed Abadi[1], Ebrahim Soleiman Dehkordi[1], Samad Nejad Ebrahimi[1]*

[1] Department of Phytochemistry, Medicinal Plants and Drugs Research Institute, Shahid Beheshti University, Tehran, Iran

*** Corresponding author email address:** s_ebrahimi@sbu.ac.ir

A r t i c l e   I n f o

Article type:
Original Research

How to cite this article:
Saeed Abadi, B., Soleiman Dehkordi, E., & Nejad Ebrahimi, S. (2026). Next-Generation Feed Additives in Poultry Production: The Role of Encapsulation Technologies in Precision Nutrition. *Journal of Poultry Sciences and Avian Diseases, 4*(4), 1-24.
http://dx.doi.org/10.61838/kman.jpsad.238

A B S T R A C T

The poultry industry is increasingly seeking nutritional strategies that enhance productivity, support intestinal health, and reduce reliance on antibiotic growth promoters. However, many functional feed additives, including vitamins, organic acids, essential oils, probiotics, enzymes, and trace minerals, are susceptible to degradation during feed processing, storage, and gastrointestinal transit, which can limit their stability, bioavailability, and biological efficacy. Encapsulation technologies have emerged as effective delivery approaches to address these limitations by protecting bioactive compounds and enabling controlled or site-specific release within the digestive tract. This literature review summarizes recent advances in encapsulation-based delivery systems for poultry nutrition, with emphasis on microencapsulation, nanoemulsions, spray-dried formulations, and controlled-release platforms. Available evidence suggests that encapsulated feed additives can improve nutrient stability, enhance intestinal availability, support epithelial barrier integrity, modulate gut microbiota, and contribute to improved growth performance and feed efficiency. Encapsulated phytogenics, organic acids, probiotics, enzymes, and nano-formulated minerals also show potential as components of antibiotic-reduction strategies in modern poultry production. Nevertheless, challenges related to manufacturing scalability, cost-effectiveness, regulatory approval, formulation standardization, and long-term safety remain important barriers to wider commercial adoption. Future research should focus on optimizing carrier materials, improving release precision, validating efficacy under commercial production conditions, and integrating encapsulation technologies with precision nutrition strategies. Overall, encapsulation represents a promising approach for improving the efficacy of functional feed additives and supporting sustainable poultry production in the post-antibiotic era.

Keywords: *Microencapsulation; Nanoemulsion; Controlled Release; Poultry Nutrition*

Article history:
Received 4 June 2026
Revised 18 July 2026
Accepted 29 July 2026
Published online 01 October 2026

1 Introduction

The global poultry industry has rapidly expanded over recent decades and plays a key role in meeting the increasing demand for affordable animal protein. This growth has been supported by advances in genetics, nutrition, health management, and production efficiency. Among these factors, feed additives are essential tools for improving nutrient utilization, feed efficiency, intestinal health, and overall flock performance (Bist et al., 2024; Kleyn & Roosendaal, 2024). Historically, antibiotic growth promoters (AGPs) were widely used to enhance growth and control enteric diseases. However, concerns regarding antimicrobial resistance (AMR) have resulted in increasing restrictions on AGPs use and stimulated the development of sustainable alternatives (Nobrega et al., 2021; Rahman et al., 2022). Functional additives, including probiotics, prebiotics, organic acids, phytogenic compounds, enzymes, vitamins, amino acids, and minerals, have gained attention due to their potential to improve nutrient utilization, gut barrier function, microbiota balance, and immune responses (Buonaiuto et al., 2025; Samad et al., 2026). Despite their benefits, the effectiveness of many bioactive additives remains inconsistent under commercial conditions because of poor stability, sensitivity to heat and oxidation, and degradation during feed processing and gastrointestinal transit (Contreras-López et al., 2024; Stamilla et al., 2020). These limitations can reduce bioavailability and prevent sufficient delivery of active compounds to their target intestinal sites (Fontana et al., 2025; Li et al., 2026). Encapsulation technologies have emerged as promising approaches to overcome these challenges by protecting bioactive compounds within protective matrices. These systems can improve stability during manufacturing and storage, enhance gastrointestinal protection, and enable controlled or targeted release in specific intestinal regions (Fontana et al., 2025; Stamilla et al., 2020). Depending on carrier characteristics and release mechanisms, encapsulated additives may improve nutrient availability, gut health, and biological consistency in poultry (Pham et al., 2020; Yang et al., 2015). Although encapsulation is well established in food and pharmaceutical industries, its application in poultry nutrition is still developing. Current research focuses on optimizing encapsulation methods, carrier materials, particle characteristics, and release kinetics to improve additive stability, intestinal delivery, microbiome modulation, immune function, and production performance (Dos Santos et al., 2024; Kolar et al., 2020). Therefore, this literature review discusses recent advances in encapsulation-based delivery systems for poultry feed additives, including microencapsulation, nanoemulsions, spray drying, and controlled-release platforms, with emphasis on mechanisms, applications, benefits, limitations, and future perspectives for precision poultry nutrition.

2 Overview of Micronutrient Challenges in Conventional Poultry Feed

2.1 Physicochemical Instability of Feed Additives

The effectiveness of many functional feed additives is limited by their poor stability during feed processing, storage, and gastrointestinal transit (Saba et al., 2026). Feed manufacturing, particularly conditioning and pelleting, exposes additives to heat, moisture, pressure, and mechanical stress, reducing the activity of heat-sensitive compounds such as vitamins, enzymes, probiotics, and phytogenics (Jaroensaensuai et al., 2022; Mccafferty & Purswell, 2024). Essential oils and other volatile phytogenic compounds are especially susceptible to evaporation and oxidation during processing and storage, resulting in reduced biological activity (Wang et al., 2023). Storage conditions further affect additive stability. Exposure to oxygen, humidity, light, and temperature fluctuations accelerates degradation, particularly in lipid-soluble vitamins, essential oils, and other lipophilic bioactives, thereby reducing the amount of active compound available for absorption (Movahedi et al., 2024; Ramoeletsi et al., 2026; Zhou et al., 2024). The gastrointestinal tract presents additional barriers to additive efficacy. Gastric acidity, digestive enzymes, bile salts, and microbial metabolism may degrade sensitive compounds before they reach their target site, reducing bioavailability and site-specific activity (Fisinin et al., 2017; Hamid et al., 2018; Richards & Malik, 2021). Therefore, protecting functional feed additives and enabling controlled release are essential for improving their efficacy in poultry nutrition (Abdelli et al., 2020; Bialkowski et al., 2023).

2.2 Site-Specific Delivery Requirements

The efficacy of functional feed additives depends not only on chemical stability but also on their ability to reach their specific sites of action within the gastrointestinal tract (Fontana et al., 2025). Because additives differ in structure, stability, absorption site, and biological function, their delivery requirements vary. Organic acids, phytogenic compounds, and medium-chain fatty acids mainly target microbial populations and epithelial function in the ileum and ceca, while enzymes must retain activity until reaching their intestinal substrates (Bedford & Gong, 2018; Liu et al., 2022). Probiotics require protection from feed processing and gastric conditions to survive until reaching the distal intestine, whereas vitamins and amino acids require early release due to absorption mainly in the upper intestine (Burgain et al., 2011; Svihus, 2014). Therefore, heat-sensitive enzymes and probiotics require protection against processing and gastrointestinal stress, while lipophilic compounds require protection from oxidation and poor solubility. Microbiota-targeting additives often benefit from delayed release in distal intestinal regions (Nantapo & Marume, 2025). These requirements emphasize the importance of encapsulation systems capable of preventing premature degradation while enabling targeted delivery, supporting precision nutrition strategies in poultry production (He et al., 2021; Movahedi et al., 2024). Table S1 summarizes the major stability limitations, target gastrointestinal regions, and encapsulation rationale for key classes of functional feed additives used in poultry nutrition.

3 Microencapsulation Technologies

3.1 Principles, Particle Characteristics, and Encapsulating Materials

Microencapsulation is one of the most widely used delivery strategies for improving the stability, handling, and biological efficacy of functional feed additives in animal nutrition (Bao et al., 2023; Desai & Park, 2005). It involves entrapping or coating bioactive compounds within a protective wall material, typically producing particles ranging from a few to several hundred micrometers in diameter (Jyothi et al., 2010). By creating a protective barrier, microencapsulation reduces losses during feed processing and storage, protects sensitive compounds during gastrointestinal transit, and enables controlled release at targeted intestinal sites (Bhusal et al., 2026). In poultry nutrition, this technology has been applied to essential oils, organic acids, probiotics, enzymes, vitamins, phytogenic compounds, and trace minerals (Figure 1) (Kamwa et al., 2024; Zhou et al., 2026). Encapsulation performance largely depends on the wall material, which influences encapsulation efficiency, particle stability, release behavior, and compatibility with feed processing (Flores & Kong, 2017; Mehran et al., 2020). Common encapsulating materials include carbohydrates, proteins, natural biopolymers, and lipid-based matrices (Mahdi et al., 2020; Safeer Abbas et al., 2023). For poultry applications, an ideal encapsulant should be safe, cost-effective, scalable, resistant to feed processing and storage, and capable of releasing the active compound at its intended site of action (Saba et al., 2026).

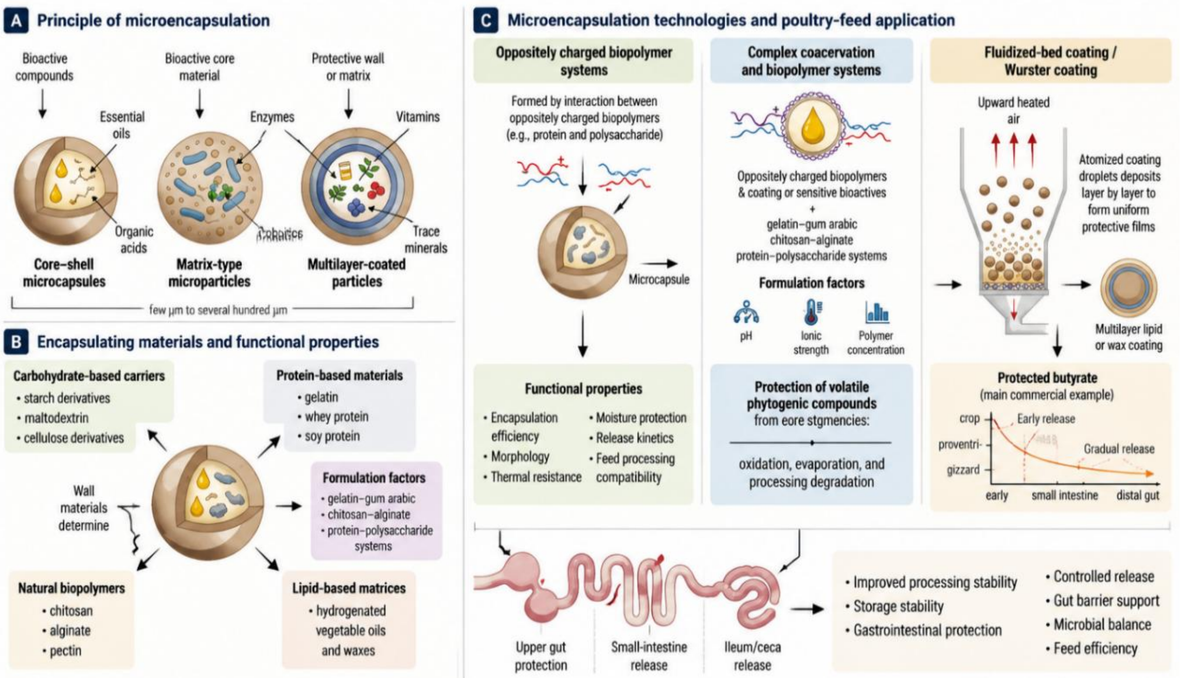


Figure 1. (A) Illustrates core microencapsulation structures, including core–shell microcapsules, matrix-type microparticles, and multilayer-coated particles for protection of bioactive compounds. (B) Summarizes encapsulating materials (carbohydrate, protein, lipid-based, and natural biopolymers) and their influence on functional properties such as encapsulation efficiency, release behavior, and stability under feed processing conditions. (C) Presents major microencapsulation technologies used in poultry feed applications, including oppositely charged biopolymer systems, complex coacervation, and fluidized-bed coating, highlighting their role in protecting sensitive compounds and enabling controlled gastrointestinal release.

3.2 Coacervation and Biopolymer-Based Systems

Complex coacervation is a widely studied microencapsulation technique that relies on electrostatic interactions between oppositely charged biopolymers to form a protective coating around bioactive compounds (Alrosan et al., 2025; Wang et al., 2021; Yousefi et al., 2020). Common systems include gelatin–gum arabic, chitosan–alginate, and protein–polysaccharide combinations (Gali et al., 2023). In poultry nutrition, coacervation is particularly suitable for volatile and chemically unstable additives, especially essential oils that are susceptible to evaporation and oxidation during feed processing and storage (Friedman, 2014; Mo et al., 2022). Naturally derived biopolymers such as chitosan, alginate, and pectin are attractive encapsulating materials because of their biodegradability, biocompatibility, and compatibility with feed applications (Khezerlou et al., 2021). These materials improve gastrointestinal protection and enable more controlled release of bioactive compounds. Alginate effectively protects probiotics and enzymes under acidic conditions, chitosan provides mucoadhesive and antimicrobial properties, and pectin facilitates microbial-triggered release in the lower intestine (Abbaszadeh et al., 2014; Lu et al., 2024; Renukadevi et al., 2025; Ta et al., 2021). Despite these advantages, practical application remains dependent on formulation and processing conditions. Encapsulation efficiency, particle stability, and release behavior vary with polymer composition and processing parameters, highlighting the need for optimization to maintain stability during feed manufacture and ensure predictable gastrointestinal release (Chen et al., 2020; Falsafi et al., 2023; Homroy et al., 2024; Kolar et al., 2020).

3.3 Fluidized-Bed Coating and Commercial Applications

Fluidized-bed coating, including Wurster coating, is one of the most important industrial microencapsulation technologies for feed additives because it offers scalability, continuous operation, and precise control over coating thickness (Bergek et al., 2016). In this process, suspended particles are coated with atomized solutions or molten lipids to form uniform protective layers. Sequential coating with different materials can produce multilayer structures that enhance stability, reduce premature release, and enable controlled gastrointestinal delivery (Bergek et al., 2016; Mahotra et al., 2022; Yan et al., 2025). Protected butyrate products are among the best-known commercial applications of fluidized-bed and lipid-based coating technologies in poultry nutrition (Masiuk et al., 2024). Because free butyrate is rapidly released or absorbed in the upper gastrointestinal tract, lipid-coated formulations are designed to delay release until the small intestine and distal gut (Mátis et al., 2022; Xiong et al., 2024). These formulations, typically based on hydrogenated vegetable fats or waxes, have been associated with improved intestinal morphology, barrier function, microbial balance, and feed efficiency, particularly under enteric challenge conditions (Abdelli et al., 2021; Ma & Faciola, 2024; Mátis et al., 2022). However, their efficacy depends on coating composition, particle size, inclusion level, diet formulation, and experimental conditions (Abdelli et al., 2021; Leonídio et al., 2024; Ma & Faciola, 2024; Mátis et al., 2022).

4 Nanoemulsion Systems

4.1 Principles and Formulation

Nanoemulsions are colloidal delivery systems composed of nanoscale droplets, typically ranging from 20 to 500 nm, dispersed within a continuous phase (Klymchenko et al., 2021). They are thermodynamically unstable but can remain kinetically stable for extended periods when properly formulated (Alam et al., 2021). In most feed-related applications, oil-in-water nanoemulsions are particularly relevant because they allow lipophilic bioactive compounds to be dispersed in aqueous environments and incorporated more uniformly into feed matrices. Owing to their small droplet size, large interfacial surface area, and improved dispersibility, nanoemulsions can enhance the apparent solubility, oxidative stability, and intestinal availability of poorly water-soluble compounds (Banasaz et al., 2020; Butani et al., 2020; Mcclements & Rao, 2011). In poultry nutrition, nanoemulsion technology has attracted increasing attention as a delivery platform for essential oils, fat-soluble vitamins, carotenoids, curcumin, omega-3 fatty acids, and certain mineral or trace-element formulations (Figure 2)

(Mirzaei et al., 2023; Patel & Bhandari, 2014; Pereira et al., 2026).

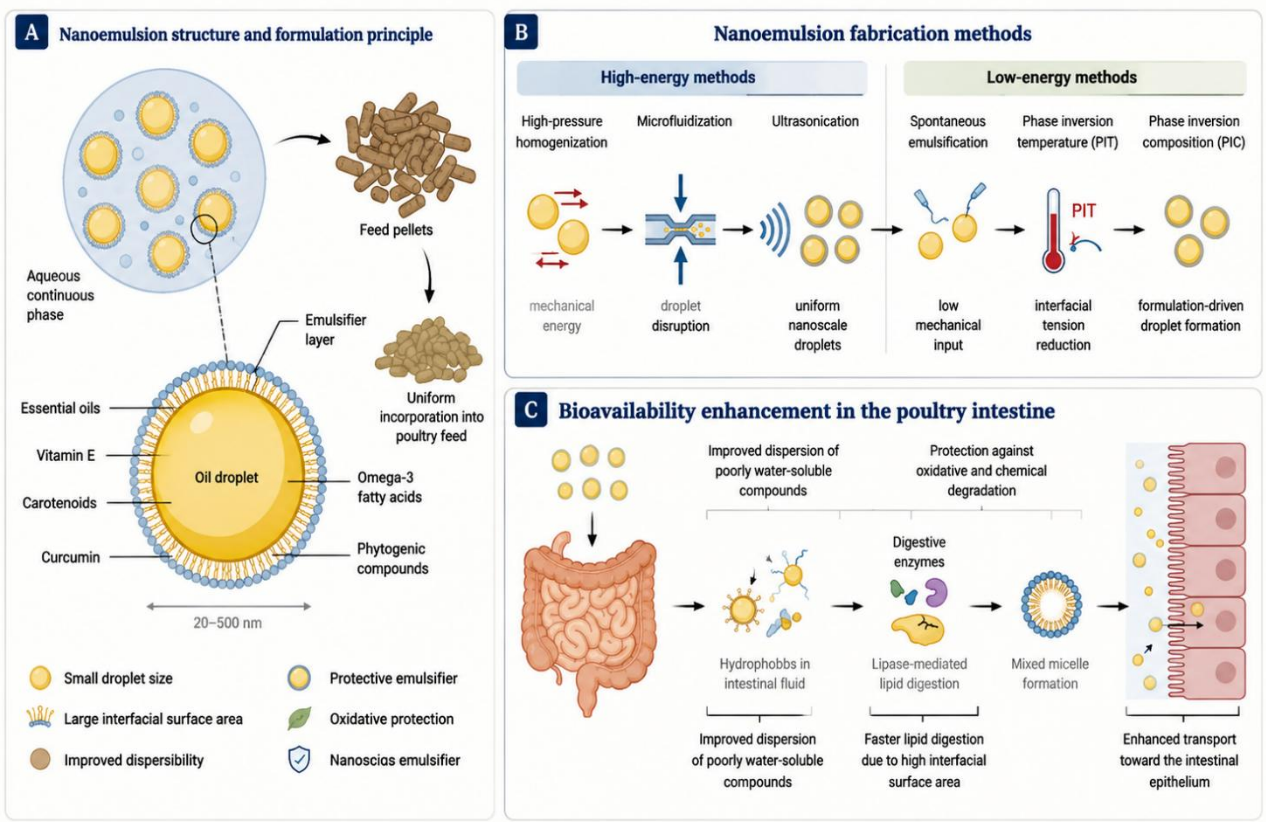


Figure 2. Overview of nanoemulsion systems for lipophilic functional feed additives in poultry nutrition, illustrating nanoemulsion structure, high- and low-energy fabrication methods, and the mechanisms underlying enhanced gastrointestinal stability, bioavailability, and intestinal uptake of bioactive compounds.(A) Nanoemulsion structure showing lipid droplets containing bioactive compounds stabilized by emulsifiers and incorporated into feed. (B) Fabrication methods include high-energy (homogenization, microfluidization, ultrasonication) and low-energy (spontaneous emulsification, PIT, PIC) approaches that form stable nanoscale droplets. (C) Intestinal fate shows improved dispersion, protection from degradation, enhanced lipid digestion, micelle formation, and increased epithelial transport.

Nanoemulsion fabrication is mainly performed through high- or low-energy approaches. High-energy methods, including high-pressure homogenization, microfluidization, and ultrasonication, generate nanoscale droplets through mechanical disruption but may require high energy input and specialized equipment. Low-energy techniques, such as spontaneous emulsification and phase inversion methods, produce small droplets by manipulating formulation composition, interfacial tension, or temperature with lower energy requirements (Ganesan et al., 2018; Gohtani & Prasert, 2014; Wang et al., 2020). The selection of an appropriate method depends on the bioactive compound, oil phase, emulsifier type, desired droplet characteristics, stability, cost, and compatibility with feed processing (Bhatt et al., 2024; Zafar et al., 2024). Emulsifiers and stabilizers are essential for nanoemulsion performance by reducing interfacial tension and preventing droplet aggregation, creaming, and phase separation during storage. Feed-compatible emulsifiers, including lecithin, polysorbates, proteins, and natural biosurfactants, may also influence digestion, micelle formation, and intestinal absorption of lipophilic compounds (Chakravarthy et al., 2024; El-Din et al., 2018). Therefore, nanoemulsion design for poultry applications should consider not only droplet size and physical stability but also safety, palatability, regulatory requirements, feed compatibility, and stability during storage and pelleting (Ewais et al., 2024; Fath El-Bab et al., 2024).

4.2 Bioavailability Enhancement Mechanisms

The principal advantage of nanoemulsions is their ability to enhance the bioavailability of poorly soluble and chemically unstable feed additives (Aboalnaja et al., 2016; De Souza Iacia et al., 2024; Liu et al., 2016; Mustafa et al., 2021). Lipophilic compounds such as essential oils, carotenoids, curcumin, and fat-soluble vitamins exhibit limited dispersion in the aqueous gastrointestinal environment (Aboalnaja et al., 2016; De Souza Iacia et al., 2024; Liu et al., 2016). Incorporation into nanoscale droplets increases the interfacial surface area, promoting interaction with digestive enzymes, bile salts, and intestinal fluids, thereby enhancing lipid digestion, mixed micelle formation, and intestinal absorption (Lee et al., 2024; Lupo et al., 2021). Improved bioavailability results from several complementary mechanisms, including enhanced dispersion of hydrophobic compounds, protection against oxidative degradation, accelerated lipid digestion, and more efficient micellar transport across the intestinal epithelium (Hu et al., 2015; Longo & De Moraes, 2025; Oh et al., 2026; Zhang et al., 2022; Zheng et al., 2021). These mechanisms are particularly relevant for vitamin E, carotenoids, curcumin, omega-3 fatty acids, and essential oil constituents such as thymol and carvacrol (Hsu et al., 2017; Lei et al., 2019; Salvia-Trujillo et al., 2021; Wan et al., 2016). Nanoemulsions may also improve the biological performance of feed additives by modifying their release and intestinal distribution. Nanoemulsified phytogenic compounds and antioxidant formulations have been associated with improved intestinal dispersion, tissue availability, and antioxidant protection compared with conventional formulations (Nasser et al., 2024; Sharma et al., 2025). However, these effects depend on droplet size, lipid composition, emulsifier type, encapsulation efficiency, and the physiological status of the bird (Jayari et al., 2022).

4.3 Applications in Poultry Nutrition

Nanoemulsion systems have been mainly explored in poultry nutrition to improve the delivery of lipophilic and chemically sensitive bioactive compounds (Zuccari & Alfei, 2023). Essential oils and phytogenic compounds, including thymol, carvacrol, cinnamaldehyde, and eugenol, benefit from nanoemulsification due to improved dispersion, protection against oxidation, and enhanced biological activity. Reported effects include improvements in growth performance, intestinal morphology, antioxidant status, immune responses, and gut microbiota balance in broilers (Ji et al., 2023; Mirzaei et al., 2023). Nanoemulsified curcumin and other polyphenols have also been investigated to overcome poor solubility and low bioavailability, potentially enhancing antioxidant and immunomodulatory effects (Fathi et al., 2025; Lepaus et al., 2026). Similarly, nanoemulsion-based delivery of fat-soluble vitamins, carotenoids, and omega-3 fatty acids may improve dispersion, absorption, oxidative stability, tissue deposition, and product quality (Maghsoudi et al., 2022; Qian et al., 2012; Rahim et al., 2025). Nano-formulated minerals, particularly selenium, have shown potential to improve mineral retention, antioxidant activity, immune function, and productive performance; however, their effectiveness and safety depend on particle characteristics, dose, solubility, and tissue accumulation (Alagawany et al., 2021; Hassan et al., 2020). Overall, nanoemulsion delivery is particularly suitable for volatile, lipophilic, oxidation-sensitive, or poorly absorbed additives. However, performance outcomes vary depending on droplet size, emulsifier type, bioactive concentration, inclusion level, diet composition, bird age, and experimental conditions (Aboalnaja et al., 2016; Bendary et al., 2020). Table S2 summarizes the main nanoemulsion and nano-formulated delivery systems discussed in this section and their reported or proposed relevance in poultry nutrition.

4.4 Challenges and Future Perspectives

Despite their potential, nanoemulsion-based feed additives face several limitations for commercial poultry application. Physical instability, including aggregation, coalescence, creaming, Ostwald ripening, and phase separation during storage or processing, remains a major challenge (Teo et al., 2016; Wik et al., 2020). Manufacturing cost and scalability are also critical concerns, as high-energy production methods require specialized equipment, while low-energy approaches remain highly formulation-dependent (Mohite et al., 2023; Panagiotou & Fisher, 2019). The conversion of liquid nanoemulsions into stable, feed-compatible powders adds further complexity. Moreover, nano-formulated additives require careful safety evaluation due to potential differences in absorption, tissue distribution, metabolism, and environmental fate compared with conventional formulations (Committee, 2021; Rao et al., 2017). Future research should focus on developing cost-effective, biodegradable, and feed-compatible nanoemulsion systems with predictable stability and release behavior. Standardized characterization, bioavailability assessment, and commercial-scale trials will be essential to support the practical adoption of nanoemulsion technologies in precision poultry nutrition (Abdullah, 2025; Lee et al., 2011).

5 Spray Drying Applications in Feed Additive Production

5.1 Spray Drying as an Encapsulation Technology

Spray drying is one of the most widely used encapsulation technologies in the food, pharmaceutical, and animal feed industries because of its simplicity, scalability, continuous operation, and cost-effectiveness (Mohammed et al., 2020). In this process, a solution, suspension, or emulsion containing bioactive compounds and wall materials is atomized into heated air, producing dry particles in which the active compounds are entrapped within a protective matrix. The resulting free-flowing powders are stable, easy to store and transport, and readily incorporated into commercial poultry feeds (Rezvankhah et al., 2020; Sonia Indri et al., 2019). In poultry nutrition, spray drying has been applied to vitamins, essential oils, probiotics, enzymes, organic acids, omega-3 fatty acids, and phytogenic compounds (Sonia Indri et al., 2019). Spray-dried particles improve the stability and handling of sensitive additives by protecting them from oxidation, volatilization, moisture, and interactions with other feed ingredients while enhancing flowability and uniform distribution within feed mixtures (Mohammed et al., 2020). Despite these advantages, spray drying presents challenges for heat-sensitive additives. Although drying times are short, elevated temperatures may reduce the activity of probiotics, enzymes, vitamins, and some phytogenic compounds if process conditions are not optimized (D'Amico et al., 2025). Consequently, drying temperature, feed rate, atomization conditions, carrier composition, and solids content remain key determinants of encapsulation efficiency, powder quality, and retention of biological activity (Mirsalami & Mirsalami, 2024).

5.2 Encapsulating Materials and Functional Properties

The performance of spray-dried formulations largely depends on the composition and physicochemical properties of the wall materials. Carbohydrate-based carriers, including maltodextrin, modified starch, gum arabic, and cyclodextrins, are widely used because of their low cost, good film-forming properties, high solubility, and compatibility with large-scale spray drying (Mehta et al., 2022). They improve powder formation, reduce stickiness, and protect volatile or oxidation-sensitive compounds such as essential oils and fat-soluble vitamins (Figure 3). However, carbohydrate-based matrices mainly provide physical protection and generally offer limited control over gastrointestinal release (Corrêa-Filho et al., 2022).

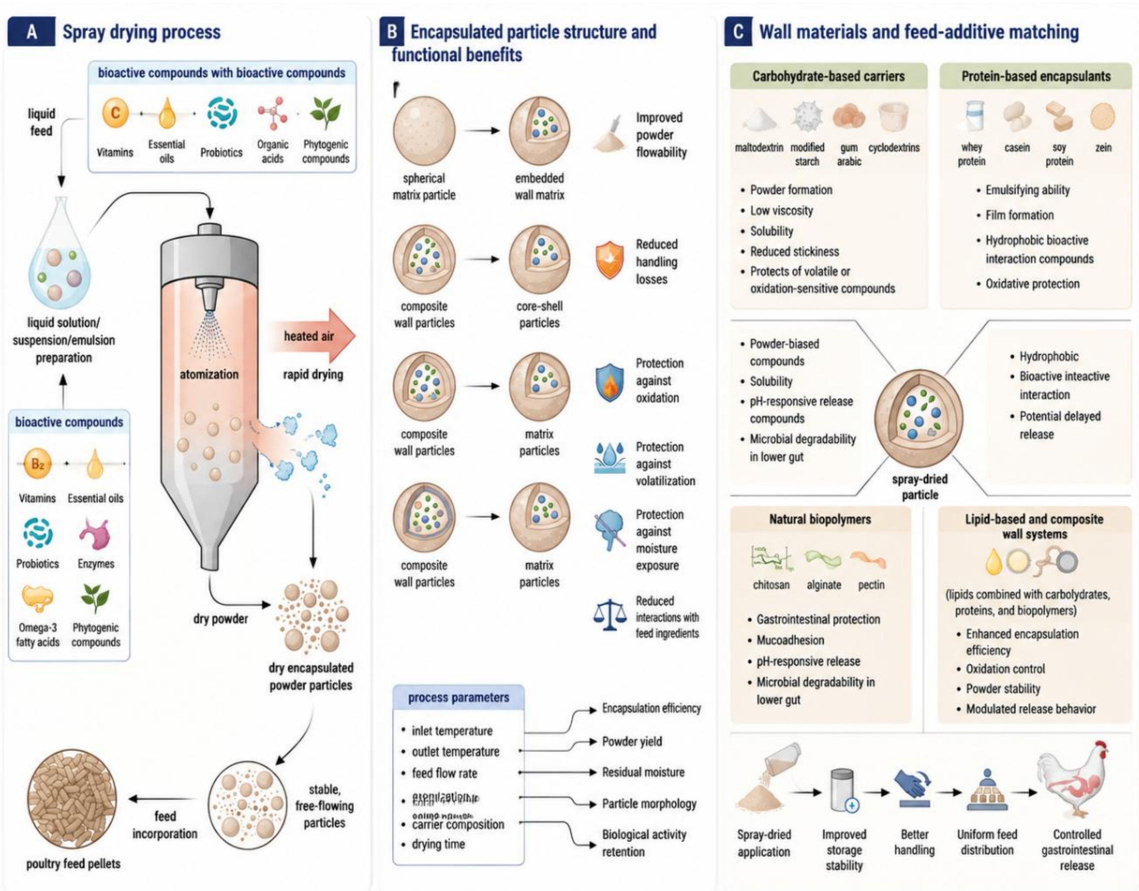


Figure 3. (A) Spray-drying process for converting liquid bioactive formulations into stable, free-flowing encapsulated powders incorporated into poultry feed. (B) Resulting particle architectures and their functional benefits, including matrix, core–shell, and composite wall structures with improved stability, controlled release, and protection against oxidation, volatilization, and moisture. (C) Selection of wall materials for feed-additive encapsulation, including carbohydrate-based, protein-based, natural biopolymers, and lipid-composite systems, enables improved encapsulation efficiency, stability, and controlled gastrointestinal release.

Protein-based encapsulants, including whey protein, casein, gelatin, soy protein, and zein, are widely used because of their emulsifying and film-forming properties and their ability to interact with hydrophobic bioactive compounds (Pateiro et al., 2021). They improve emulsion stability and oxidative protection, while zein and some plant proteins may also provide greater resistance to gastric conditions and delayed intestinal release. However, their commercial use may be limited by heat sensitivity, processing conditions, cost, or allergen-related concerns (Gomes & Sobral, 2022). Natural biopolymers such as chitosan, alginate, and pectin have also been investigated as wall materials or secondary coatings because they provide gastrointestinal protection, mucoadhesion, pH-responsive release, or microbial degradability (Movahedi et al., 2024). These properties make them particularly suitable for probiotics, organic acids, prebiotics, enzymes, and phytogenic compounds requiring targeted intestinal delivery (Khezerlou et al., 2021). Lipid-based carriers and composite wall systems further expand formulation options. Combining carbohydrates, proteins, biopolymers, and lipids can improve encapsulation efficiency, oxidative stability, powder quality, and release behavior (Dahiya et al., 2023). Consequently, wall materials should be selected according to the physicochemical properties of the bioactive compound, the desired release site, feed-processing conditions, regulatory requirements, and commercial feasibility (Fontana et al., 2025). Table S3 summarizes the major wall material categories, their functional advantages, formulation limitations, and applications in poultry feed additive delivery.

5.3 Applications in Poultry Nutrition

Spray-dried encapsulated feed additives have shown considerable potential for improving nutrient stability and biological efficacy in poultry (Figure 4). Essential oils and phytogenic compounds are among the most relevant applications because many of their active components are volatile, poorly water-soluble, and sensitive to oxidation (Corrêa et al., 2025). Spray drying can improve their retention during storage, reduce odor and handling problems, and promote more uniform incorporation into feed. Encapsulated essential oils and phytogenic compounds may therefore provide more consistent antimicrobial, antioxidant, and digestive-support effects than unprotected formulations (Fontana et al., 2025).

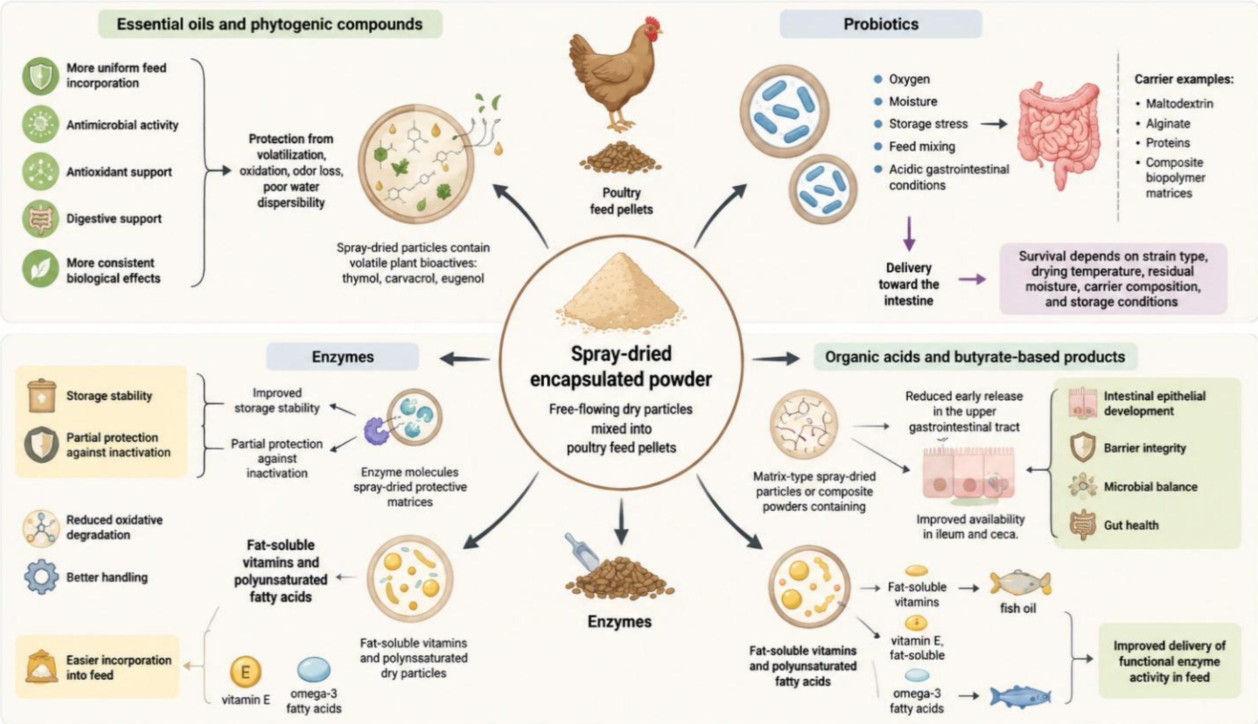


Figure 4. Schematic representation of spray-dried encapsulated powders containing bioactive feed additives (essential oils, probiotics, enzymes, vitamins, organic acids, and fatty acids) and their incorporation into poultry feed. Encapsulation enhances stability, protects against oxidation and volatilization, and enables controlled release in the gastrointestinal tract, improving nutrient availability, gut health, and overall feed efficiency.

Spray-dried probiotic formulations have been developed to improve bacterial survival during storage, feed processing, and gastrointestinal transit. Protective carriers such as maltodextrin, alginate, proteins, and composite biopolymer matrices help maintain probiotic viability and enhance intestinal delivery. However, efficacy depends on strain characteristics, drying conditions, carrier composition, residual moisture, and storage conditions, making strain-specific optimization essential for poultry applications (Muthusamy et al., 2020; Yoha et al., 2022). Organic acids, particularly butyrate, represent another important application of spray-dried delivery systems. Protected formulations are designed to delay upper gastrointestinal release and increase butyrate availability in the ileum and ceca, supporting epithelial development, barrier integrity, and microbial balance (Figure 5) (Deng et al., 2023). Although commercial butyrate products commonly use lipid coating or fluidized-bed technologies, spray drying can also produce matrix-type or composite formulations containing organic acids and phytogenic compounds (De Oliveira et al., 2025).

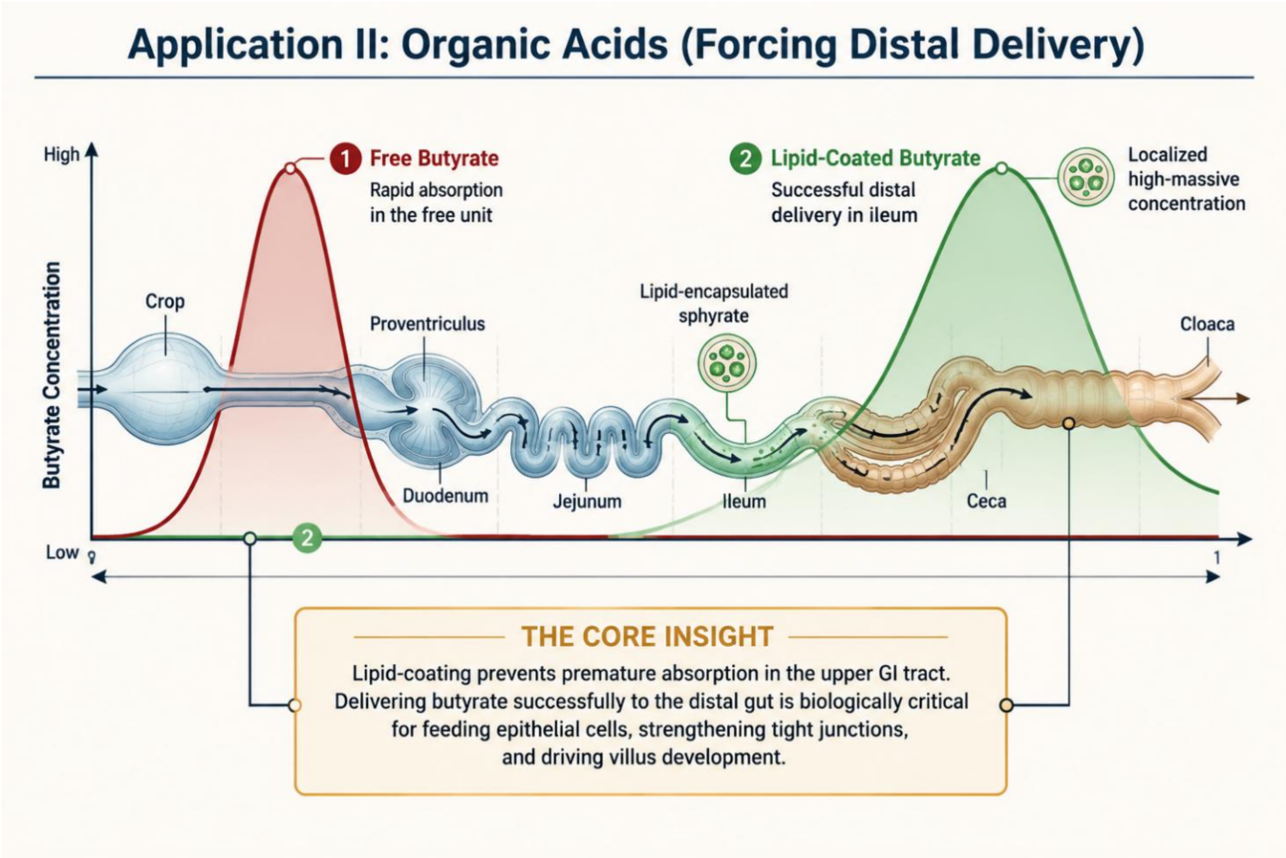


Figure 5. Schematic comparison of free versus lipid-encapsulated butyrate along the poultry gastrointestinal tract. Free butyrate is rapidly absorbed in the upper gut, whereas lipid-coated butyrate enables targeted release in the ileum and ceca, resulting in higher distal gut availability and improved epithelial function, barrier integrity, and microbial balance.

Spray drying is also used for vitamins, enzymes, omega-3 fatty acids, and other sensitive bioactives. It reduces oxidative degradation of fat-soluble vitamins and polyunsaturated fatty acids while improving feed-handling properties. For enzymes, encapsulation enhances storage stability and limits activity loss, provided drying temperatures are carefully controlled (D'Amico et al., 2025). Overall, spray drying is a practical and scalable technology for producing feed-compatible encapsulated additives, although its success depends on optimizing formulation composition, process conditions, and the intended release profile (Dahiya et al., 2023).

6 Controlled Release Systems

Controlled-release systems regulate the timing and site of bioactive release within the gastrointestinal tract, thereby improving additive stability, intestinal availability, and biological efficacy. Among these approaches, pH-responsive systems are particularly relevant because they exploit the natural pH gradients along the avian digestive tract (Dashtestani et al., 2021). Following ingestion, feed additives pass through the acidic proventriculus and gizzard before entering the more neutral intestinal environment, allowing encapsulation systems to remain stable in the upper digestive tract and release their contents at targeted intestinal sites (Lorenzo-Rebenaque et al., 2021). Several pH-responsive materials, including cellulose acetate phthalate (CAP), hydroxypropyl methylcellulose phthalate (HPMCP), alginate, chitosan, and methacrylate-based copolymers, have been investigated for feed applications (Li et al., 2024). These materials protect sensitive compounds from premature degradation and promote release in the small intestine or hindgut, making them suitable for probiotics, organic acids, essential oils, enzymes, and phytogenic compounds (Li et al., 2024). The performance of pH-responsive systems depends on polymer properties, coating thickness, particle size, gastrointestinal conditions, and bird-related factors such as age, diet composition, and health status (Dashtestani et al., 2021). Therefore, formulations should be optimized according to the intended release site and commercial production conditions. Recent studies indicate that pH-responsive encapsulation improves probiotic survival during gastrointestinal transit and enhances the intestinal availability of phytogenic compounds and organic acids (Hashem et al., 2023; Sun et al., 2025). By delaying release until the target intestinal region is reached, these systems may improve gut barrier function, microbial modulation, and feed efficiency. However, additional poultry-specific studies are needed to establish release kinetics, dose–response relationships, and commercial performance (Mátis et al., 2022).

6.1 Enzyme-Triggered and Microbiota-Responsive Release Systems

In addition to pH-responsive technologies, enzyme-triggered delivery systems have attracted increasing attention for targeted nutrient and additive release. These systems utilize wall materials or matrices that are degraded by specific digestive enzymes or microbial enzymes present within the gastrointestinal tract. As a result, encapsulated compounds can remain protected during feed processing, storage, and passage through the upper digestive tract but are released when exposed to the intended enzymatic environment (Figure 6) (Gao et al., 2025).

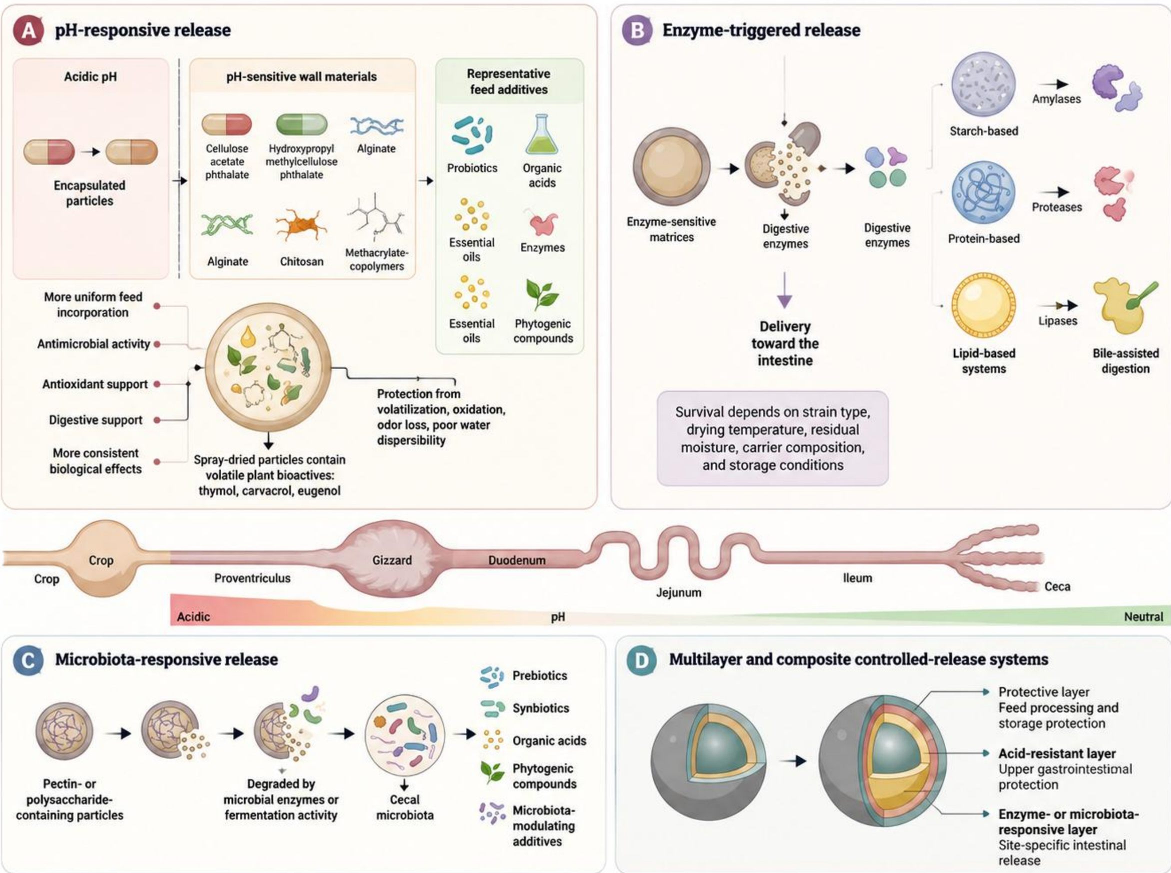


Figure 6. This figure illustrates four controlled delivery strategies for encapsulated feed additives in poultry: (A) pH-responsive release based on gastrointestinal pH gradients using pH-sensitive polymer matrices; (B) enzyme-triggered release mediated by digestive enzymes (amylases, proteases, lipases) enabling substrate-specific degradation of starch-, protein-, and lipid-based carriers; (C) microbiota-responsive release driven by microbial fermentation and enzymatic activity in the lower gut (ceca), promoting liberation of prebiotics, synbiotics, organic acids, phytogenics, and microbiota-modulating compounds; and (D) multilayer and composite encapsulation systems integrating protective, acid-resistant, and stimulus-responsive layers to achieve site-specific intestinal delivery. Together, these systems enable targeted release in the gastrointestinal tract, improving stability, bioavailability, gut barrier integrity, microbiota balance, and overall poultry performance.

Biopolymer matrices based on starch, pectin, alginate, chitosan, and protein-derived materials are widely investigated as enzyme-responsive carriers. Starch- and protein-based matrices are degraded by digestive enzymes, whereas pectin-containing matrices undergo microbial degradation in the ceca, making them suitable for distal intestinal delivery (Burgain et al., 2011). These systems are particularly relevant for probiotics, prebiotics, organic acids, phytogenic compounds, and other microbiota-modulating additives targeting the ileum or ceca (Piva et al., 2007). Microbiota-responsive systems represent a more advanced form of enzyme-triggered delivery. Their carrier matrices remain stable in the upper gastrointestinal tract but are degraded by microbial fermentation or enzymes in the hindgut, enabling targeted release of prebiotics, synbiotics, organic acids, and phytogenic compounds. However, because microbial composition varies with age, diet, and production conditions, these systems require further validation before widespread commercial application (Oni & Oke, 2025). Combining pH-responsive, enzyme-triggered, lipid-based, and microbiota-responsive mechanisms may provide more precise delivery than conventional encapsulation approaches (Fontana et al., 2025). Multilayer or composite systems can provide sequential protection and release, allowing bioactive compounds to withstand feed processing and upper gastrointestinal transit before reaching targeted intestinal sites. Such strategies are expected to support precision nutrition and antibiotic-free poultry production by improving gut health, microbial balance, and nutrient utilization (Azizi et al., 2026). Table S4 summarizes the major controlled-release mechanisms and their applications in targeted delivery of functional feed additives for poultry.

7 Functional Feed Additives and Precision Poultry Nutrition

7.1 Encapsulated Phytogenics and Essential Oils

Phytogenic feed additives (PFAs), including essential oils, plant extracts, and purified phytochemicals, have gained considerable attention as natural alternatives to antibiotic growth promoters in poultry production because of their antimicrobial, antioxidant, anti-inflammatory, and digestive-stimulatory properties (Ayalew et al., 2022). Common examples include carvacrol, thymol, cinnamaldehyde, eugenol, and essential oils derived from oregano, thyme, cinnamon, and clove (Obianwuna et al., 2024; Serra et al., 2021). Despite their biological potential, many phytogenic compounds are volatile, lipophilic, poorly water-soluble, and susceptible to oxidation or thermal degradation during feed processing and storage (Omidian et al., 2025). Premature release or absorption in the upper gastrointestinal tract may further reduce their availability in distal intestinal regions, contributing to inconsistent biological responses (Yang et al., 2015). Encapsulation technologies, including microencapsulation, lipid-based coating, spray drying, and nanoemulsions, improve the stability and delivery of phytogenic feed additives by reducing volatilization and oxidation while enabling more controlled intestinal release (Almassri et al., 2024; Phupaboon et al., 2025). Nanoemulsions enhance the dispersion and bioavailability of lipophilic phytochemicals, whereas lipid- and polymer-based microcapsules provide greater protection during feed processing and gastrointestinal transit (Guo et al., 2025). Encapsulated oregano, thyme, cinnamon, thymol, carvacrol, and related formulations have been associated with improved growth performance, feed efficiency, antioxidant status, intestinal morphology, and gut microbial balance in broiler chickens (Moharreri et al., 2021; Mucha & Witkowska, 2021). They may also suppress enteric pathogens such as *Salmonella sp.*, *Campylobacter* spp., *Clostridium perfringens*, and pathogenic *Escherichia coli*, although efficacy depends on the active compound, encapsulation system, diet composition, and experimental conditions (Sokol et al., 2025). By improving stability and enabling targeted intestinal delivery, encapsulation enhances the consistency of phytogenic feed additives and strengthens their potential role in antibiotic-reduction strategies and sustainable poultry production (Movahedi et al., 2024; Stevanović et al., 2018).

7.2 Encapsulated Organic Acids

Organic acids, including formic, propionic, fumaric, lactic, and butyric acids, are widely used as alternatives to antibiotic growth promoters in poultry nutrition. Their benefits include reduced gastrointestinal pH, inhibition of pathogenic microorganisms, modulation of gut microbiota, improved nutrient digestibility, and enhanced intestinal health (Melaku et al., 2021). Among them, butyric acid is particularly important because it serves as an energy source for intestinal epithelial cells and supports epithelial barrier integrity, immune homeostasis, and intestinal development (Xiao et al., 2023). The practical application of free organic acids is limited by strong odor, corrosiveness, rapid upper gastrointestinal dissociation or absorption, and potential effects on feed palatability (Pearlin et al., 2020). Encapsulation improves handling properties, reduces odor and corrosiveness, protects organic acids during feed processing, and enables gradual release along the intestinal tract, increasing their availability in distal intestinal regions (Mátis et al., 2022). Protected butyrate formulations are among the most commercially important encapsulated organic acids in poultry nutrition. Lipid-coated sodium or calcium butyrate, tributyrin, and related products are designed to delay upper gastrointestinal release and increase butyrate availability in the small intestine and distal gut (Mátis et al., 2022). These formulations have been associated with improved intestinal morphology, epithelial barrier function, nutrient utilization, and feed efficiency in broiler chickens (Abdelli et al., 2020; Mátis et al., 2022). Beyond their antimicrobial activity, butyrate and its derivatives influence gene expression, regulate inflammatory responses, support epithelial renewal, and improve intestinal resilience under enteric challenge conditions (Bedford & Gong, 2018; Li et al., 2026). More recently, multi-component delivery systems combining organic acids with essential oils or phytogenic compounds have attracted interest because of their potential synergistic effects on microbial balance, gut barrier function, and growth performance, reinforcing the role of encapsulated organic acids in antibiotic-free and precision poultry nutrition (Huyben et al., 2021; Islam et al., 2024). Table S5 summarizes the main encapsulated organic acid formulations discussed in this section, with emphasis on their delivery challenges, intended release regions, and functional relevance in poultry nutrition.

7.3 Encapsulated and Nano-Formulated Trace Minerals

Trace minerals such as zinc, selenium, copper, manganese, and iron are essential for growth, immune function, antioxidant defense, skeletal development, and enzyme activity in poultry (Byrne & Murphy, 2022). Although they are traditionally supplied as inorganic salts, their utilization may be reduced by interactions with dietary components, resulting in lower absorption efficiency and greater mineral excretion (Ghasemi et al., 2020). Organic mineral sources, including amino acid chelates, proteinates, and hydroxy trace minerals, generally provide greater digestive stability and bioavailability than conventional inorganic forms (Alagawany et al., 2021; Han et al., 2024). More recently, encapsulation and nano-formulation have emerged as complementary strategies to further improve mineral delivery and precision nutrition (Swain et al., 2021). Encapsulation protects minerals from undesirable interactions during feed processing, storage, and digestion while enabling more controlled gastrointestinal release (Figure 7) (Swain et al., 2021). It may also reduce oxidation caused by reactive metal ions, thereby improving feed stability and preserving sensitive nutrients (Yin, Tong, et al., 2022). These advantages are particularly relevant for trace minerals involved in antioxidant defense and immune function, including selenium, zinc, copper, and iron (Mahmoud et al., 2024).

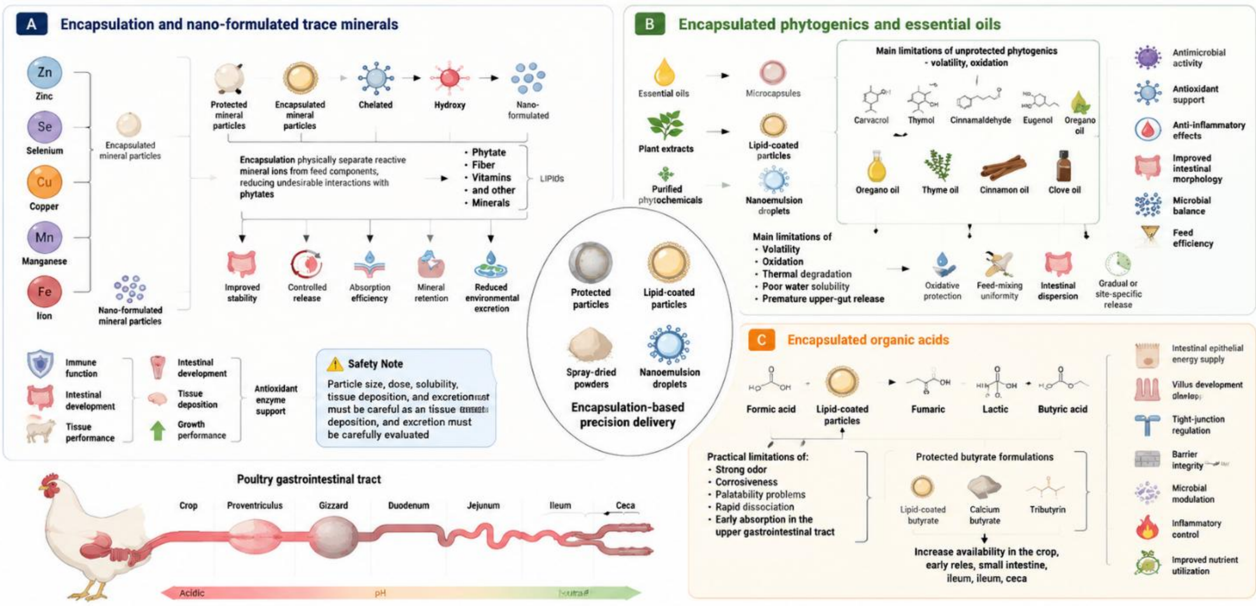


Figure 7. Schematic illustration of encapsulated functional feed additives used in precision poultry nutrition, demonstrating their targeted delivery and their roles in enhancing feed efficiency, intestinal health, microbial balance, immune responses, and overall poultry performance.

Encapsulated selenium, zinc, and copper formulations have shown potential to improve mineral utilization, antioxidant capacity, immune responses, intestinal development, egg quality, and growth performance in poultry (Ferroudj et al., 2026). Selenium nano-formulations have received particular attention due to their role in antioxidant defense, while protected zinc and copper may enhance mineral availability at lower inclusion levels. However, their effectiveness depends on mineral source, particle size, dose, solubility, and diet composition (Asri-Rezaei et al., 2018). Encapsulation and nano-formulation can improve mineral stability, controlled release, retention, and biological utilization, but require careful assessment of safety, tissue accumulation, and environmental effects. Future studies should focus on dose optimization, mineral retention and excretion, tissue deposition, and commercial-scale validation to support sustainable precision mineral nutrition (Yin, Tong, et al., 2022; Yin, Zhai, et al., 2022). Table S6 summarizes the major trace mineral delivery strategies and their relevance for poultry nutrition.

8 Gut Health Management Through Targeted Delivery

8.1 Intestinal Morphology and Barrier Integrity

Maintaining intestinal integrity is essential for nutrient absorption, disease resistance, and poultry performance. The intestinal epithelium functions as a selective barrier regulating nutrient uptake while preventing the entry of pathogens and harmful metabolites. Villus height, crypt depth, and villus height-to-crypt depth ratio are key indicators of intestinal development and absorptive capacity (Adedokun & Olojede, 2019; Jha et al., 2020). Encapsulation improves the targeted delivery of functional additives that support intestinal morphology and barrier function. Encapsulated butyrate, β-glucans, probiotics, phytogenic compounds, organic acids, and micronutrients have been shown to enhance villus development, strengthen tight junctions, reduce inflammation, and improve epithelial resilience (Pham et al., 2020; Xu et al., 2020). Targeted release is particularly important for compounds acting locally in the intestine, where they interact with epithelial cells, mucosal immunity, and the microbiota (Mârza et al., 2025). Butyrate represents a key example, as it provides energy for intestinal epithelial cells and promotes mucin production, epithelial renewal, and tight-junction regulation. Encapsulated butyrate improves its delivery to the lower intestine, enhancing barrier integrity and reducing inflammatory responses (Pham et al., 2020; Xiong et al., 2024). Similarly, encapsulated phytogenics and probiotics may improve intestinal homeostasis by reducing oxidative stress, pathogen pressure, and microbial imbalance.

8.2 Microbiome Modulation

The gastrointestinal microbiota plays a key role in nutrient metabolism, immune development, pathogen resistance, and overall poultry health (Figure 8). A balanced microbial community supports beneficial metabolite production, pathogen exclusion, and mucosal immunity, whereas dysbiosis can impair nutrient utilization and increase disease susceptibility (Aruwa et al., 2021; Oni & Oke, 2025). Encapsulation enhances the delivery of probiotics, prebiotics, synbiotics, organic acids, and phytogenic compounds by protecting them during feed processing and gastrointestinal transit. Improved survival and targeted release in the ileum and ceca increase their potential to modulate microbial communities, promote beneficial bacteria, suppress pathogens, and improve microbial stability (Gyawali et al., 2022; Qi et al., 2025; Yue et al., 2025). Encapsulated essential oils and organic acids provide localized antimicrobial effects, while protected prebiotics and synbiotics support fermentation and short-chain fatty acid production. Although these strategies can improve microbiota balance, intestinal health, and performance, their effectiveness depends on factors such as bird age, diet composition, environmental conditions, pathogen pressure, and formulation characteristics (Bindari & Gerber, 2022; Hu et al., 2015).

8.3 Immune Competence and Oral Vaccine Delivery

The gastrointestinal tract is a major immune organ in poultry, where gut-associated lymphoid tissue (GALT) contributes to mucosal immune surveillance and defense against enteric pathogens. Maintaining intestinal integrity and microbial balance through nutritional strategies can enhance immune competence and reduce pathogen pressure (Emami & Dalloul, 2021). Encapsulation technologies based on biodegradable polymers, lipid matrices, and nano-carriers provide promising platforms for delivering immunostimulants, vaccine antigens, probiotics, phytogenics, and other functional additives. By protecting sensitive compounds during feed processing and gastrointestinal transit, these systems can improve stability and promote targeted release at intestinal immune sites (Bhusal et al., 2026; Flores et al., 2026). In oral vaccine delivery, encapsulation may enhance antigen protection, intestinal uptake, and mucosal immune responses. Although promising results have been reported for encapsulated vaccines against diseases such as coccidiosis, Newcastle disease, and infectious bronchitis, commercial implementation remains limited (El-Saadony et al., 2022). Beyond vaccination, encapsulated organic acids, phytogenics, probiotics, and trace minerals may support immunity by reducing inflammation, modulating immune responses, and enhancing antioxidant defense. Thus, encapsulation can contribute to integrated gut health management and precision nutrition strategies in poultry production (Buonaiuto et al., 2025; Sokol et al., 2025).

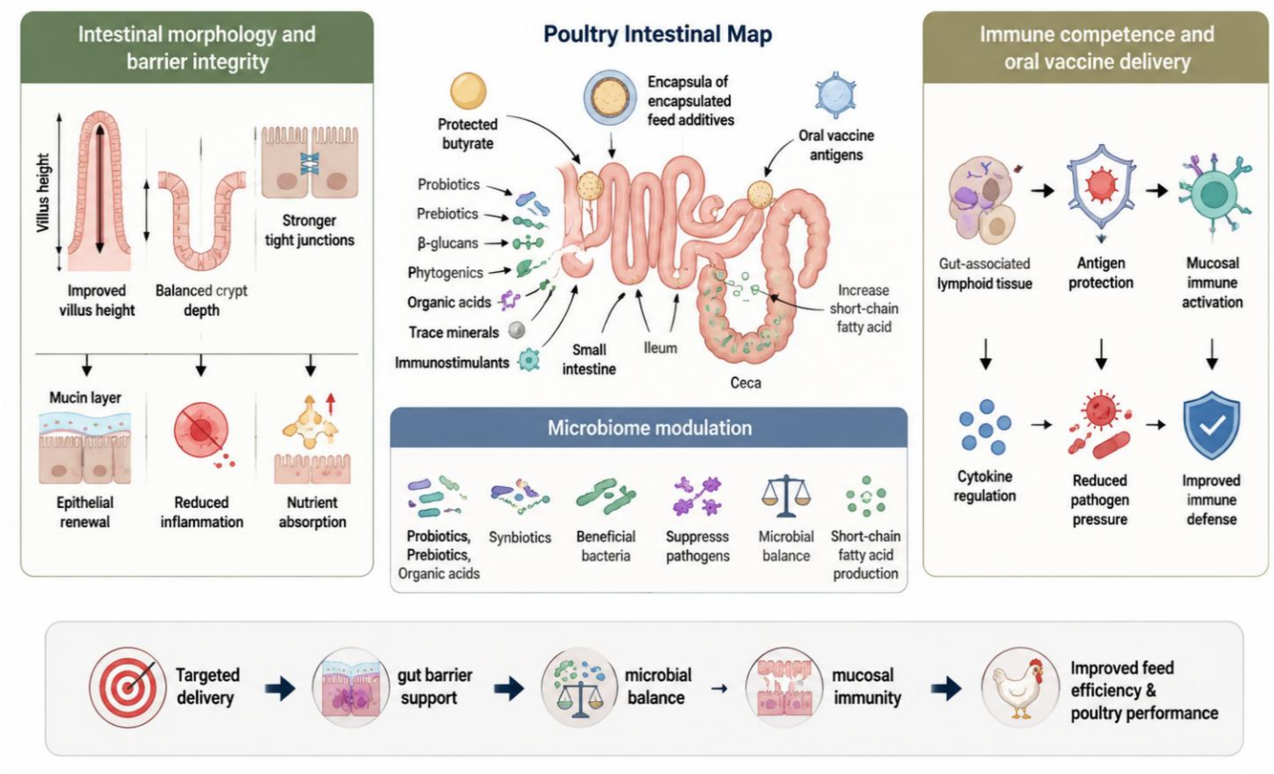


Figure 8. Overview of targeted delivery systems for gut health management in poultry, illustrating the controlled intestinal release of functional feed additives and their roles in enhancing gut integrity, microbial balance, immune function, nutrient absorption, and production performance.

Overall, targeted delivery of functional feed additives can support intestinal morphology, barrier integrity, microbiome stability, and immune competence in poultry (Oni & Oke, 2025). Although encapsulated formulations have shown promising effects on gut health and productive performance, their efficacy remains highly dependent on additive type, formulation, bird age, diet, and production conditions (Abdelli et al., 2020; Pham et al., 2020). Further commercial-scale studies integrating intestinal morphology, microbiome, immune, and performance data are needed to better define the contribution of targeted delivery systems to poultry gut health. Table S7 summarizes the main gut-health-related outcomes of targeted encapsulated feed additives discussed in this section.

9 Challenges, Limitations, and Safety Considerations

9.1 Regulatory and Commercialization Considerations

The commercialization of encapsulated feed additives is largely determined by regional regulatory frameworks. In the European Union, feed additives are regulated under Regulation (EC) No. 1831/2003, while novel encapsulation materials, controlled-release systems, and nano-formulations may require additional safety and efficacy evaluations by EFSA (Additives et al., 2021). Similar regulatory approaches exist in other regions, although requirements vary depending on the active compound, carrier material, formulation, and application (Sokol et al., 2025). Advanced nano-formulated and controlled-release systems face additional regulatory challenges, requiring comprehensive evaluation of particle characteristics, encapsulation efficiency, release profile, stability, bioavailability, and safety. The lack of harmonized international guidelines increases regulatory complexity and may delay commercialization (Committee et al., 2018; Movahedi et al., 2024). Commercial success further depends on scalability, consistency, quality control, feed compatibility, and cost-effectiveness. While spray drying and fluidized-bed coating are established industrial approaches, more advanced systems such as nanoemulsions, multilayer coatings, and stimuli-responsive carriers still require further optimization for large-scale application (Jin & Wang, 2026; Moosavi et al., 2025).

9.2 Safety, Standardization, and Environmental Considerations

Although encapsulation technologies improve nutrient delivery, their safety requires careful evaluation. Nano-scale systems are of particular concern because particle size may affect absorption, biodistribution, cellular interactions, and biological responses. While many food-grade and biodegradable materials appear safe, further studies are needed to assess long-term exposure, tissue accumulation, residues, gut microbiota effects, and interactions with dietary components under commercial conditions (Vilas-Boas et al., 2021; Zhou et al., 2026). Standardization remains a major challenge due to variations among studies in encapsulation methods, carrier materials, particle characteristics, release behavior, inclusion levels, diets, animal age, and evaluation criteria. Consistent reporting of key parameters, including particle size, zeta potential, active compound loading, encapsulation efficiency, stability, release profile, and bioavailability, is essential to improve reproducibility and facilitate comparison among delivery systems (Fontana et al., 2025; Nantapo & Marume, 2025; Oni & Oke, 2025). Environmental sustainability is another important consideration. Although some synthetic carriers may persist in agricultural environments, biodegradable materials such as starch, alginate, chitosan, pectin, proteins, and lipid-based matrices offer more environmentally compatible alternatives. Future development should focus on delivery systems that combine efficiency, safety, feed compatibility, biodegradability, and minimal environmental impact (Herdiana, 2025; Puglia et al., 2021). Overall, successful commercialization of encapsulated feed additives requires balancing efficacy, safety, scalability, cost, regulatory compliance, and environmental sustainability. Wider adoption will depend on long-term safety assessments, commercial-scale feeding trials, dose-response studies, and harmonized quality standards (Movahedi et al., 2024).

10 Future Perspectives and Emerging Technologies

Encapsulation technologies are expected to become key tools in precision poultry nutrition by improving the stability, targeted delivery, and efficacy of functional feed additives. Future systems will move toward multifunctional platforms capable of protecting bioactive compounds, controlling gastrointestinal release, and enhancing absorption, particularly for unstable or poorly bioavailable additives (Obianwuna et al., 2024; Stevanović et al., 2018). Emerging approaches, including pH-responsive, enzyme-triggered, lipid-based, and microbiota-responsive delivery systems, may enhance the effectiveness of probiotics, phytogenic compounds, enzymes, organic acids, vitamins, and minerals. Multilayer and composite carriers may further enable sequential release and synergistic delivery of multiple bioactive compounds (Guo et al., 2025; Hashem et al., 2023). Future development will increasingly focus on sustainable biodegradable carriers and improved industrial feasibility through lower production costs, consistent quality, and stability during feed processing and storage. Integration with precision livestock farming may enable adaptive use of encapsulated additives according to animal performance, health status, and environmental challenges (Mackenzie, 2023; Sokol et al., 2025; Vlaicu et al., 2024). Despite rapid advances, widespread adoption requires further validation through commercial-scale trials, standardized characterization, safety assessments, environmental evaluations, and techno-economic analyses. Collaboration among researchers, industry, and regulatory authorities will be essential for translating encapsulation technologies into practical feed solutions (Buonaiuto et al., 2025; Flores et al., 2026). Overall, encapsulated feed additives represent a promising strategy to improve poultry health, productivity, and sustainability while supporting reduced reliance on antibiotic growth promoters (Azizi et al., 2026; Movahedi et al., 2024).

11 Conclusions

Encapsulation technologies provide a promising approach for enhancing the stability, bioavailability, and targeted delivery of functional feed additives in poultry nutrition. Advances in microencapsulation, nanoemulsions, spray drying, fluidized-bed coating, and controlled-release systems have improved the effectiveness of vitamins, phytogenic compounds, organic acids, probiotics, enzymes, and minerals by protecting them during processing, storage, and gastrointestinal transit.Current evidence indicates that encapsulated additives can support nutrient utilization, gut health, microbiota balance, immune function, and productive performance, making them particularly valuable for antibiotic reduction and antibiotic-free poultry production systems. However, large-scale implementation remains limited by challenges related to cost, scalability, formulation stability, regulatory requirements, and the need for long-term safety and efficacy validation. Future research should focus on optimized carrier materials, standardized characterization, controlled release strategies, commercial-scale trials, and techno-economic evaluation. Integrating encapsulation with precision nutrition and sustainable feed technologies may facilitate the development of next-generation delivery systems for more efficient, resilient, and sustainable poultry production.

Supporting Information

Tables S1–S7 are available in the Supporting Information file associated with this article.

Acknowledgements

The authors gratefully acknowledge the support provided by the Shahid Beheshti University Research Council.

Use of Artificial Intelligence

Artificial intelligence (AI) tools were solely used for language editing and improvement of the visual presentation of Figure 1. The AI tools were not used for study design, data collection, data analysis, interpretation of results, or generation of scientific conclusions. All scientific content, analyses, interpretations, and final manuscript revisions were reviewed and approved by the authors.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

B.S.A: Methodology, Investigation, Data curation, Visualization, Writing– original draft preparation. E.S.D: Investigation, Writing– review & editing. S.N.E: Conceptualization, Supervision, Project administration, Funding acquisition, Writing– review & editing.

Data Availability Statement

Data are available from the corresponding author upon request.

Ethical Considerations

As this study is a literature review and did not involve human participants, animals, or the collection of primary data, ethical approval was not required.

Funding

The authors declare that they received no external financial support for this study.

References

Abbaszadeh, S., Gandomi, H., Misaghi, A., Bokaei, S., & Noori, N. (2014). The Effect Of Alginate And Chitosan Concentrations On Some Properties Of Chitosan-Coated Alginate Beads And Survivability Of Encapsulated Lactobacillus Rhamnosus In Simulated Gastrointestinal Conditions And During Heat Processing. *Journal of the Science of Food and Agriculture*, *94*(11), 2210-2216. [PMID: 24343670] [DOI]

Abdelli, N., Pérez, J. F., Vilarrasa, E., Cabeza Luna, I., Melo-Duran, D., & D'Angelo, M. (2020). Targeted-Release Organic Acids And Essential Oils Improve Performance And Digestive Function In Broilers Under A Necrotic Enteritis Challenge. *Animals*, *10*(2), 259. [PMID: 32041160] [PMCID: PMC7070292] [DOI]

Abdelli, N., Solà-Oriol, D., & Pérez, J. F. (2021). Phytogenic Feed Additives In Poultry: Achievements, Prospective And Challenges. *Animals*, *11*(12), 3471. [PMID: 34944248] [PMCID: PMC8698016] [DOI]

Abdullah, S. H. (2025). Emerging Technologies In Animal Nutrition And Their Impacts On Sustainability And Productivity: Article Review. *American Journal of Biology and Natural Sciences*, *2*(8), 232-243. [DOI]

Aboalnaja, K. O., Yaghmoor, S., Kumosani, T. A., & Mcclements, D. J. (2016). Utilization Of Nanoemulsions To Enhance Bioactivity Of Pharmaceuticals, Supplements, And Nutraceuticals: Nanoemulsion Delivery Systems And Nanoemulsion Excipient Systems. *Expert Opinion on Drug Delivery*, *13*(9), 1327-1336. [PMID: 26984045] [DOI]

Additives, E. P. O., Products OR Substances Used In Animal, F., Bampidis, V., Azimonti, G., Bastos, M. D. L., Christensen, H., Dusemund, B., & Revez, J. (2021). Safety And Efficacy Of A Feed Additive Consisting Of Lactiplantibacillus Plantarum (Formerly Lactobacillus Plantarum) Imi 507027 For All Animal Species (All-Technology (Ireland) Limited [Alltech Ireland]). *EFSA Journal*, *19*(7), e06704. [PMID: PMID: 34335920] [DOI]

Adedokun, S. A., & Olojede, O. C. (2019). Optimizing Gastrointestinal Integrity In Poultry: The Role Of Nutrients And Feed Additives. *Frontiers in Veterinary Science*, *5*, 348. [PMID: 30766877] [PMCID: PMC6366008] [DOI]

Alagawany, M., Elnesr, S. S., Farag, M. R., Tiwari, R., Yatoo, M. I., & Karthik, K. (2021). Nutritional Significance Of Amino Acids, Vitamins And Minerals As Nutraceuticals In Poultry Production And Health- A Comprehensive Review. *Veterinary Quarterly*, *41*(1), 1-29. [PMID: 33250002] [PMCID: PMC7755404] [DOI]

Alam, M. S., Akhtar, A., Ahmad, J., & Nollet, L. M. L. (2021). Stability Perspectives Of Nanoemulsions. In J. Ahmad & L. M. L. Nollet (Eds.), *Nanoemulsions in food technology: Development, characterization, and applications* (pp. 89-110). CRC Press. [DOI]

Almassri, N., Trujillo, F. J., & Terefe, N. S. (2024). Microencapsulation Technology For Delivery Of Enzymes In Ruminant Feed. *Frontiers in Veterinary Science*, *11*, 1352375. [PMID: 39071783] [PMCID: PMC11273329] [DOI]

Alrosan, M., Al-Rabadi, N., Alu'Datt, M. H., Al-Qaisi, A., Al-Shunnaq, E. E., & Abu-Khalaf, N. (2025). Complex Coacervation Of Plant-Based Proteins And Polysaccharides:

Sustainable Encapsulation Techniques For Bioactive Compounds. *Food Engineering Reviews*, *17*(4), 1059-1082. [DOI]

Aruwa, C. E., Pillay, C., Nyaga, M. M., & Sabiu, S. (2021). Poultry Gut Health- Microbiome Functions, Environmental Impacts, Microbiome Engineering And Advancements In Characterization Technologies. *Journal of Animal Science and Biotechnology*, *12*(1), 119. [PMID: 34857055] [PMCID: PMC8638651] [DOI]

Asri-Rezaei, S., Nourian, A., Shalizar-Jalali, A., Najafi, G., Nazarizadeh, A., & Koohestani, M. (2018). Selenium Supplementation In The Form Of Selenium Nanoparticles And Selenite Sodium Improves Mature Male Mice Reproductive Performances. *Iranian Journal of Basic Medical Sciences*, *21*(6), 577-585. [PMID: PMID: 29942447]

Ayalew, H., Zhang, H., Wang, J., Wu, S., Qiu, K., & Qi, G. (2022). Potential Feed Additives As Antibiotic Alternatives In Broiler Production. *Frontiers in Veterinary Science*, *9*, 916473. [PMID: 35782570] [PMCID: PMC9247512] [DOI]

Azizi, M. N., Aminullah, N., Alam, S., & Faisal, D. (2026). Poultry Gut Health: Industry Drivers, Management Determinants, And Emerging Research Directions. *Veterinary and Animal Science*, *31*, 100566. [PMID: 41551216] [PMCID: PMC12807808] [DOI]

Banasaz, S., Morozova, K., Ferrentino, G., & Scampicchio, M. (2020). Encapsulation Of Lipid-Soluble Bioactives By Nanoemulsions. *Molecules*, *25*(17), 3966. [PMID: 32878137] [PMCID: PMC7504786] [DOI]

Bao, H., Xue, Y., Zhang, Y., Tu, F., Wang, R., & Cao, Y. (2023). Encapsulated Essential Oils Improve The Growth Performance Of Meat Ducks By Enhancing Intestinal Morphology, Barrier Function, Antioxidant Capacity And The Cecal Microbiota. *Antioxidants*, *12*(2), 253. [PMID: 36829812] [PMCID: PMC9952412] [DOI]

Bedford, A., & Gong, J. (2018). Implications Of Butyrate And Its Derivatives For Gut Health And Animal Production. *Animal Nutrition*, *4*(2), 151-159. [PMID: 30140754] [PMCID: PMC6104520] [DOI]

Bendary, M. M., Ibrahim, D., Mosbah, R. A., Mosallam, F., Hegazy, W. A. H., & Awad, N. F. S. (2020). Thymol Nanoemulsion: A New Therapeutic Option For Extensively Drug Resistant Foodborne Pathogens. *Antibiotics*, *10*(1), 25. [PMID: 33396722] [PMCID: PMC7823989] [DOI]

Bergek, J., Trojer, M. A., Uhr, H., & Nordstierna, L. (2016). Controlled Release Of A Microencapsulated Arduous Semi-Hydrophobic Active From Coatings: Superhydrophilic Polyelectrolyte Shells As Globally Rate-Determining Barriers. *Journal of Controlled Release*, *225*, 31-39. [PMID: 26774222] [DOI]

Bhatt, P., Bhatt, T., Jain, V., Jain, R., & Bigoniya, P. (2024). Nanoemulsion Through Cold Emulsification: An Advanced Cold Manufacturing Process For A Stable And Advanced Drug Delivery System. *Journal of Applied Pharmaceutical Science*, *14*(5), 12-21. [DOI]

Bhusal, P., Sajid, G. A., & Paudel, S. (2026). Addressing Therapeutic Challenges In Poultry Production, With Particular Emphasis On Free-Range And Organic Systems: The Potential Of Controlled-Release Delivery Systems (Crds). *Poultry Science*, *105*(4), 106503. [PMID: 41619492] [PMCID: PMC12887392] [DOI]

Bialkowski, S., Toschi, A., Yu, L. E., Schlitzkus, L., Mann, P., & Grilli, E. (2023). Effects Of Microencapsulated Blend Of Organic Acids And Botanicals On Growth Performance, Intestinal Barrier Function, Inflammatory Cytokines, And Endocannabinoid System Gene Expression In Broiler Chickens. *Poultry Science*, *102*(3), 102460. [PMID: 36680863] [PMCID: PMC10014334] [DOI]

Bindari, Y. R., & Gerber, P. F. (2022). Centennial Review: Factors Affecting The Chicken Gastrointestinal Microbial Composition And Their Association With Gut Health And Productive Performance. *Poultry Science*, *101*(1), 101612. [PMID: 34872745] [PMCID: PMC8713025] [DOI]

Bist, R. B., Bist, K., Poudel, S., Subedi, D., Yang, X., & Paneru. (2024). Sustainable Poultry Farming Practices: A Critical Review Of Current Strategies And Future Prospects. *Poultry Science*, *103*(12), 104295. [PMID: 39312848] [PMCID: PMC11447413] [DOI]

Buonaiuto, G., Danese, T., El-Sabrout, K., & Yıldırım, A. (2025). Bioactive Feed Additives In Animal Nutrition: Bridging Innovation, Health, And Sustainability. *Frontiers in Veterinary Science*, *12*, 1727126. [PMID: 41487484] [PMCID: PMC12756971] [DOI]

Burgain, J., Gaiani, C., Linder, M., & Scher, J. (2011). Encapsulation Of Probiotic Living Cells: From Laboratory Scale To Industrial Applications. *Journal of Food Engineering*, *104*(4), 467-483. [DOI]

Butani, N., Bhatt, M. D., Parmar, P., Jobanputra, J., Dobriyal, A. K., & Bhatt, D. (2020). Nanoemulsions Of Plant-Based Bioactive Compounds: Synthesis, Properties, And Applications. In *Nanotechnological Approaches in Food Microbiology* (pp. 187-226). CRC Press. [DOI]

Byrne, L., & Murphy, R. A. (2022). Relative Bioavailability Of Trace Minerals In Production Animal Nutrition: A Review. *Animals*, *12*(15), 1981. [PMID: 35953970] [PMCID: PMC9367456] [DOI]

Chakravarthy, P. S. A., Popli, P., Challa, R. R., Vallamkonda, B., Singh, I., & Swami, R. (2024). Bile Salts: Unlocking The Potential As Bio-Surfactant For Enhanced Drug Absorption. *Journal of Nanoparticle Research*, *26*(4), 76. [DOI]

Chen, Y., Li, S., Zhang, Z., Chen, Y., Dong, S., & Chen, G. (2020). Complex Coacervation Of Zein-Chitosan Via Atmospheric Cold Plasma Treatment: Improvement Of Encapsulation Efficiency And Dispersion Stability. *Food Hydrocolloids*, *107*, 105943. [DOI]

Committee, E. S. (2021). Guidance on risk assessment of nanomaterials to be applied in the food and feed chain: human and animal health. *EFSA Journal*, *19*(8), e06768. [PMID: PMID: 34377190] [DOI]

Committee, E. S., Hardy, A., Benford, D., Halldorsson, T., Jeger, M. J., Knutsen, H. K., & Mortensen, A. (2018). Guidance on risk assessment of the application of nanoscience and nanotechnologies in the food and feed chain: Part 1, human and animal health. *EFSA Journal*, *16*(7), e05327. [PMID: PMID: 32625968] [DOI]

Contreras-López, G., Carrillo-López, L. M., Vargas-Bello-Pérez, E., & García-Galicia, I. A. (2024). Microencapsulation Of Feed Additives With Potential In Livestock And Poultry Production: A Systematic Review. *Chilean Journal of Agricultural & Animal Sciences*, *40*(1), 229-249. [DOI]

Corrêa-Filho, L. C., Santos, D. I., Brito, L., Moldão-Martins, M., & Alves, V. D. (2022). Storage Stability And In Vitro Bioaccessibility Of Microencapsulated Tomato (Solanum Lycopersicum L.) Pomace Extract. *Bioengineering*, *9*(7), 311. [PMID: 35877362] [PMCID: PMC9312032] [DOI]

Corrêa, J. H. M., De Laurentiz, A. C., De Souza Furiozo Rondis, C. C., Da Silva Filardi, R., De Oliveira, E. S., & Da Silva De Laurentiz, R. (2025). Inclusion Of A Microencapsulated Pepper, Cashew Nut, And Copaiba Essential Oils Blend In Broiler Feed: Evaluation Of Performance And Nutrient Metabolizability. *Tropical Animal Health and Production*, *57*(6), 288. [PMID: 40569351] [DOI]

D'Amico, V., Cavaliere, M., Ivone, M., Lacassia, C., Celano, G., & Vacca, M. (2025). Microencapsulation Of Probiotics For

Enhanced Stability And Health Benefits In Dairy Functional Foods: A Focus On Pasta Filata Cheese. *Pharmaceutics*, *17*(2), 185. [PMID: 40006552] [PMCID: PMC11859715] [DOI]

Dahiya, D., Terpou, A., Dasenaki, M., & Nigam, P. S. (2023). Current Status And Future Prospects Of Bioactive Molecules Delivered Through Sustainable Encapsulation Techniques For Food Fortification. *Sustainable Food Technology*, *1*(4), 500-510. [DOI]

Dashtestani, F., Ma'Mani, L., Jokar, F., Maleki, M., Eskandari Fard, M., & Hosseini Salekdeh, G. (2021). Zeolite-Based Nanocomposite As A SMART Ph-Sensitive Nanovehicle For Release Of Xylanase As Poultry Feed Supplement. *Scientific Reports*, *11*(1), 21386. [PMID: 34725388] [PMCID: PMC8560943] [DOI]

De Oliveira, T. T. B., Ferreira, T. C. S., Tavares, P. P. L. G., Correia, P. R. C., Ribeiro, C. V. D. M., & De Souza, C. O. (2025). Innovative Lipid Delivery Systems In Ruminant Diets: The Role Of Spray Drying. *Frontiers in Veterinary Science*, *12*, 1619263. [PMID: 41321573] [PMCID: PMC12662176] [DOI]

De Souza Iacia, M. V. M., Mendes, M. E. F., De Oliveira Vieira, K. C., Ruiz, G. C. M., Constantino, C. J. L., & Da Silva Martin, C. (2024). Evaluation Of Curcumin Nanoemulsion Effect To Prevent Intestinal Damage. *International Journal of Pharmaceutics*, *650*, 123683. [PMID: 38092264] [DOI]

Deng, F., Tang, S., Zhao, H., Zhong, R., Liu, L., & Meng, Q. (2023). Anti-Inflammatory And Antioxidant Capacity, Intestinal Morphology And Microbiota Of Broilers At Early Stage. *Poultry Science*, *102*(5), 102585. [PMID: 36913758] [PMCID: PMC10023969] [DOI]

Desai, K. G. H., & Park, H. J. (2005). Recent Developments In Microencapsulation Of Food Ingredients. *Drying Technology*, *23*(7), 1361-1394. [DOI]

Dos Santos, A., Indrati, R., & Sjofjan, O. (2024). Implementation Of Curcuma Xanthorrhiza Roxb Encapsulation As A Feed Additive On Production Performance Of Broiler. *Animal Production*, *26*(1), 15-22. [DOI]

El-Din, M. N., Mishrif, M. R., & El-Tabey, A. (2018). A Study On The Effect Of Dynamic Interfacial Tension On The Stability Of Nano-Emulsified Diesel. *Journal of Molecular Liquids*, *254*, 39-46. [DOI]

El-Saadony, M. T., Salem, H. M., El-Tahan, A. M., Abd El-Mageed, T. A., Soliman, S. M., & Khafaga, A. F. (2022). The Control Of Poultry Salmonellosis Using Organic Agents: An Updated Overview. *Poultry Science*, *101*(4), 101716. [PMID: 35176704] [PMCID: PMC8857471] [DOI]

Emami, N. K., & Dalloul, R. A. (2021). Centennial Review: Recent Developments In Host-Pathogen Interactions During Necrotic Enteritis In Poultry. *Poultry Science*, *100*(9), 101330. [PMID: 34280643] [PMCID: PMC8318987] [DOI]

Ewais, O., Abdel-Tawab, H., El-Fayoumi, H., Aboelhadid, S. M., Al-Quraishy, S., & Falkowski, P. (2024). Antioxidant Properties Of D-Limonene And Its Nanoemulsion Form Enhance Its Anticoccidial Efficiency In Experimentally Infected Broilers With Eimeria Tenella: An In Vitro And In Vivo Study. *Veterinary research communications*, *48*(6), 3711-3725. [PMID: 39235470] [DOI]

Falsafi, S. R., Wang, Y., Ashaolu, T. J., Sharma, M., Rawal, S., & Patel, K. (2023). Biopolymer Nanovehicles For Oral Delivery Of Natural Anticancer Agents. *Advanced Functional Materials*, *33*(4), 2209419. [DOI]

Fath El-Bab, A. F., El-Ratel, I. T., Abdel-Warith, A. W. A., Younis, E. M., Davies, S. J., & El-Raghi, A. A. (2024). Investigating The Impact Of Nanoemulsion Of Curcumin-Loaded Olive Oil On Growth Performance, Feed Utilization, Immunological Responses, And Redox Status Of Litopenaeus Vannamei Shrimp With Emphasis On Economic Efficiency Of Supplementation. *Journal of Animal Physiology and Animal Nutrition*, *108*(6), 1877-1889. [PMID: 39041332] [DOI]

Fathi, M., Saeedian, S., & Darvishi, F. (2025). Impact Of Curcumin Nanoparticles Supplementation On Antioxidant Status, Growth Performance, Immune Function, Gut Microbiota, And Hematobiochemical Parameters In Heat-Stressed Broiler Chickens. *Italian Journal of Animal Science*, *24*(1), 2109-2118. [DOI]

Ferroudj, A., El-Ramady, H., & Prokisch, J. (2026). Applications Of Nano-Selenium In The Poultry Industry: An Overview. *Nanomaterials*, *16*(2), 142. [PMID: 41591058] [PMCID: PMC12844274] [DOI]

Fisinin, V. I., Egorov, I. A., Vertiprakhov, V. G., Grozina, A. A., Lenkova, T. N., & Manukyan, V. A. (2017). Activity Of Digestive Enzymes In Duodenal Chymus And Blood In Broilers Of Parental Lines And The Meat Cross Depending On Dietary Bioactive Additives. *Sel'skokhozyaistvennaya Biologiya [Agricultural Biology]*, *52*(6), 1226-1233. [DOI]

Flores, F. P., & Kong, F. (2017). In Vitro Release Kinetics Of Microencapsulated Materials And The Effect Of The Food Matrix. *Annual Review of Food Science and Technology*, *8*, 237-259. [PMID: 28125351] [DOI]

Flores, R. A., Fletcher, P. L. C., Son, K. Y., & Min, W. (2026). Insights Into Non-Antibiotic Alternative And Emerging Control Strategies For Chicken Coccidiosis. *Animals*, *16*(2), 348. [PMID: 41594536] [PMCID: PMC12838395] [DOI]

Fontana, L. B., Henn, G. S., Dos Santos, C. H., Specht, L., Schmitz, C., & Volken De Souza, C. F. (2025). Encapsulation Of Zootechnical Additives For Poultry And Swine Feeding: A Systematic Review. *ACS Omega*, *10*(7), 6294-6305. [PMID: 40028069] [PMCID: PMC11865961] [DOI]

Friedman, M. (2014). Chemistry And Multibeneficial Bioactivities Of Carvacrol (4-Isopropyl-2-Methylphenol), A Component Of Essential Oils Produced By Aromatic Plants And Spices. *Journal of Agricultural and Food Chemistry*, *62*(31), 7652-7670. [PMID: 25058878] [DOI]

Gali, L., Pirozzi, A., & Donsì, F. (2023). Biopolymer-And Lipid-Based Carriers For The Delivery Of Plant-Based Ingredients. *Pharmaceutics*, *15*(3), 927. [PMID: 36986788] [PMCID: PMC10051097] [DOI]

Ganesan, P., Karthivashan, G., Park, S. Y., Kim, J., & Choi, D. K. (2018). Microfluidization Trends In The Development Of Nanodelivery Systems And Applications In Chronic Disease Treatments. *International Journal of Nanomedicine*, *13*, 6109-6121. [PMID: 30349240] [PMCID: PMC6188155] [DOI]

Gao, R., Zhao, D., Zhou, X., Wan, Z., Wang, X., & Rao, H. (2025). Advances In Polysaccharide-Based Biopolymers For Probiotic Encapsulation: From Single Polysaccharides To Composite Systems. *Current Research in Food Science*, *11*, 101186. [PMID: 40955295] [PMCID: PMC12433487] [DOI]

Ghasemi, H. A., Hajkhodadadi, I., Hafizi, M., Taherpour, K., & Nazaran, M. H. (2020). Effect Of Advanced Chelate Technology Based Trace Minerals On Growth Performance, Mineral Digestibility, Tibia Characteristics, And Antioxidant Status In Broiler Chickens. *Nutrition & Metabolism*, *17*(1), 94. [PMID: 33292310] [PMCID: PMC7596981] [DOI]

Gohtani, S., & Prasert, W. (2014). Nano-Emulsions; Emulsification Using Low Energy Methods. *Japan Journal of Food Engineering*, *15*(3), 119-130. [DOI]

Gomes, A., & Sobral, P. J. A. (2022). Plant Protein-Based Delivery Systems: An Emerging Approach For Increasing The Efficacy Of Lipophilic Bioactive Compounds. *Molecules*, *27*(1), 60. [PMID: 35011292] [PMCID: PMC8746547] [DOI]

Guo, Y., Ma, C., Du, L., Xu, Y., & Yang, X. (2025). Research Progress On The Application Of Food Colloids In Precise

Targeted Delivery Of Drugs And Bioactive Compounds. *Gels*, *11*(9), 746. [PMID: 41002520] [PMCID: PMC12469821] [DOI]

Gyawali, I., Zeng, Y., Zhou, J., Li, J., Wu, T., & Shu, G. (2022). Effect Of Novel Lactobacillus Paracasei Microcapsule On Growth Performance, Gut Health And Microbiome Community Of Broiler Chickens. *Poultry Science*, *101*(8), 101912. [PMID: 35689995] [PMCID: PMC9190013] [DOI]

Hamid, H., Shi, H. Q., Ma, G. Y., Fan, Y., Li, W. X., & Zhao, L. H. (2018). Influence Of Acidified Drinking Water On Growth Performance And Gastrointestinal Function Of Broilers. *Poultry Science*, *97*(10), 3601-3609. [PMID: 29860532] [DOI]

Han, X., Kong, J., Zheng, C., Yan, X., Qiu, T., & Chen, Z. (2024). The Effects Of A Mixture Of Small Peptide Chelating Minerals And Inorganic Minerals On The Production Performance And Tissue Deposition Of Broiler Chickens. *Frontiers in Veterinary Science*, *11*, 1380911. [PMID: 38706756] [PMCID: PMC11066274] [DOI]

Hashem, N. M., Hosny, N. S., El-Desoky, N., Soltan, Y. A., Elolimy, A. A., & Sallam, S. M. (2023). Alginate Nanoencapsulated Synbiotic Composite Of Pomegranate Peel Phytogenics And Multi-Probiotic Species As A Potential Feed Additive: Physicochemical, Antioxidant, And Antimicrobial Activities. *Animals*, *13*(15), 2432. [PMID: 37570241] [PMCID: PMC10417444] [DOI]

Hassan, S., Hassan, F. U., & Rehman, M. S. U. (2020). Nanoparticles Of Trace Minerals In Poultry Nutrition: Potential Applications And Future Prospects. *Biological trace Element Research*, *195*(2), 591-612. [PMID: 31473896] [DOI]

He, W., Li, P., & Wu, G. (2021). Amino Acid Nutrition And Metabolism In Chickens. In G. Wu (Ed.), *Amino acids in nutrition and health: Amino acids in the nutrition of companion, zoo and farm animals* (pp. 109-131). Springer International Publishing. [PMID: 33770405] [DOI]

Herdiana, Y. (2025). Polymeric Rumen-Stable Delivery Systems For Delivering Nutricines. *Open Veterinary Journal*, *15*(2), 565-593. [PMID: 40201846] [PMCID: PMC11974284] [DOI]

Homroy, S., Chand, M., Talwar, B., Dhiman, A., Singh, P. K., & Wahid, A. (2024). Long-Term Enhancement Of Food Stability Using Encapsulation-Based Coating. In *Food coatings and preservation technologies* (pp. 367-401). Wiley. [DOI]

Hsu, H. J., Huang, R. F., Kao, T. H., Inbaraj, B. S., & Chen, B. H. (2017). Preparation Of Carotenoid Extracts And Nanoemulsions From Lycium Barbarum L. And Their Effects On Growth Of Ht-29 Colon Cancer Cells. *Nanotechnology*, *28*(13), 135103. [PMID: 28266352] [DOI]

Hu, B., Zhang, L., Liang, R., Chen, F., He, L., & Hu, B. (2015). Cross-Linking Of Interfacial Casein Layer With Genipin Prevented Ph-Induced Structural Instability And Lipase Digestibility Of The Fat Droplets. *Journal of Agricultural and Food Chemistry*, *63*(7), 2033-2040. [PMID: 25647169] [DOI]

Huyben, D., Chiasson, M., Lumsden, J. S., Pham, P. H., & Chowdhury, M. A. K. (2021). Dietary Microencapsulated Blend Of Organic Acids And Plant Essential Oils Affects Intestinal Morphology And Microbiome Of Rainbow Trout (Oncorhynchus Mykiss). *Microorganisms*, *9*(10), 2063. [PMID: 34683384] [PMCID: PMC8537560] [DOI]

Islam, Z., Sultan, A., Khan, S., Khan, K., Jan, A. U., & Aziz, T. (2024). Effects Of An Organic Acids Blend And Coated Essential Oils On Broiler Growth Performance, Blood Biochemical Profile, Gut Health, And Nutrient Digestibility. *Italian Journal of Animal Science*, *23*(1), 152-163. [DOI]

Jaroensaensuai, J., Wongsasulak, S., Yoovidhya, T., Devahastin, S., & Rungrassamee, W. (2022). Improvement Of Moist Heat Resistance Of Ascorbic Acid Through Encapsulation In Egg Yolk-Chitosan Composite: Application For Production Of Highly Nutritious Shrimp Feed Pellets. *Animals*, *12*(18), 2384. [PMID: 36139244] [PMCID: PMC9495111] [DOI]

Jayari, A., Donsì, F., Ferrari, G., & Maaroufi, A. (2022). Nanoencapsulation Of Thyme Essential Oils: Formulation, Characterization, Storage Stability, And Biological Activity. *Foods*, *11*(13), 1858. [PMID: 35804672] [PMCID: PMC9265609] [DOI]

Jha, R., Das, R., Oak, S., & Mishra, P. (2020). Probiotics (Direct-Fed Microbials) In Poultry Nutrition And Their Effects On Nutrient Utilization, Growth And Laying Performance, And Gut Health: A Systematic Review. *Animals*, *10*(10), 1863. [PMID: 33066185] [PMCID: PMC7602066] [DOI]

Ji, J., Shankar, S., Royon, F., Salmieri, S., & Lacroix, M. (2023). Essential Oils As Natural Antimicrobials Applied In Meat And Meat Products-A Review. *Critical reviews in food science and nutrition*, *63*(8), 993-1009. [PMID: 34309444] [DOI]

Jin, Z., & Wang, Y. (2026). Recent Progress In Probiotic Encapsulation: Techniques, Characterization And Food Industry Prospects. *Foods*, *15*(3), 431. [PMID: 41683018] [PMCID: PMC12897067] [DOI]

Jyothi, N. V. N., Prasanna, P. M., Sakarkar, S. N., Prabha, K. S., Ramaiah, P. S., & Srawan, G. Y. (2010). Microencapsulation Techniques, Factors Influencing Encapsulation Efficiency. *Journal of Microencapsulation*, *27*(3), 187-197. [PMID: 20406093] [DOI]

Kamwa, R., Khurajog, B., Muangsin, N., Pupa, P., Hampson, D. J., & Prapasarakul, N. (2024). Water-Soluble Microencapsulation Using Gum Arabic And Skim Milk Enhances Viability And Efficacy Of Pediococcus Acidilactici Probiotic Strains For Application In Broiler Chickens. *Animal Bioscience*, *37*(8), 1440-1451. [PMID: 38575120] [PMCID: PMC11222858] [DOI]

Khezerlou, A., Tavassoli, M., Alizadeh Sani, M., Mohammadi, K., Ehsani, A., & Mcclements, D. J. (2021). Application Of Nanotechnology To Improve The Performance Of Biodegradable Biopolymer-Based Packaging Materials. *Polymers*, *13*(24), 4399. [PMID: 34960949] [PMCID: PMC8707388] [DOI]

Kleyn, R., & Roosendaal, B. (2024). The Use Of New-Era Feed Additives To Enhance Gut Health, Immune Status, Nutrient Absorption And Broiler Performance. Poultry Beyond 2030 Broiler Nutrition Conference, Queenstown, New Zealand.

Klymchenko, A. S., Liu, F., Collot, M., & Anton, N. (2021). Dye-Loaded Nanoemulsions: Biomimetic Fluorescent Nanocarriers For Bioimaging And Nanomedicine. *Advanced Healthcare Materials*, *10*(1), 2001289. [PMID: 33052037] [DOI]

Kolar, S., Jurić, S., Vlahoviček-Kahlina, K., & Vinceković, M. (2020). Potential For Application Of Feed Additives Encapsulation Technology In Animal Nutrition. *Krmiva: Časopis O Hranidbi Životinja, Proizvodnji I Tehnologiji Krme*, *62*(1), 57-66. [DOI]

Lee, S., Jo, K., Jeong, S. K. C., Choi, Y. S., & Jung, S. (2024). Strategies For Modulating The Lipid Digestion Of Emulsions In The Gastrointestinal Tract. *Critical reviews in food science and nutrition*, *64*(27), 9740-9755. [PMID: 37267158] [DOI]

Lee, S. J., Choi, S. J., Li, Y., Decker, E. A., & Mcclements, D. J. (2011). Protein-Stabilized Nanoemulsions And Emulsions: Comparison Of Physicochemical Stability, Lipid Oxidation, And Lipase Digestibility. *Journal of Agricultural and Food Chemistry*, *59*(1), 415-427. [PMID: 21133433] [DOI]

Lei, K., Wang, X., Li, X., & Wang, L. (2019). The Innovative Fabrication And Applications Of Carvacrol Nanoemulsions, Carboxymethyl Chitosan Microgels And Their Composite Films. *Colloids and Surfaces B: Biointerfaces*, *175*, 688-696. [PMID: 30590330] [DOI]

Leonídio, A. R. A., Minafra, C., Andrade, M. A., Nascente, E. P., Nascimento, G. M., & Santos, J. B. (2024). Effects Of

Encapsulated Butyric Acid On General Performance, Intestinal Health, And Colonization In Organs Of Poultry Infected With Salmonella Enteritidis. *Revista Brasileira De Zootecnia*, *53*, e20220150. [DOI]

Lepaus, B. M., Leal, R. M. P., Uliana, D. S., Bonna, L. D., Guimarães, A. P., & De São José, J. F. B. (2026). Nanotechnology To Improve The Quality And Nutritional Value Of Foods. In *Nanotechnology in food safety and sustainability* (pp. 271-292). Springer Nature Switzerland. [PMID: 28118817] [DOI]

Li, J., Gao, J., Zhu, H., Cao, L., Du, J., & Gao, J. (2026). Exploring The Potential Of Food Encapsulation Technologies In Aquaculture: Applications, Innovations, And Future Perspectives. *Aquaculture Reports*, *47*, 103448. [DOI]

Li, Y., Li, X. M., Duan, H. Y., Yang, K. D., & Ye, J. F. (2024). Advances And Optimization Strategies In Bacteriophage Therapy For Treating Inflammatory Bowel Disease. *Frontiers in Immunology*, *15*, 1398652. [PMID: 38779682] [PMCID: PMC11109441] [DOI]

Liu, A., Li, Z., Jin, X., Wu, Q., Hu, H., & Zhang, C. (2022). An Encapsulated Organic Acid And Essential Oil Mixture Improves The Intestinal Health Of Weaned Piglets By Altering Intestinal Inflammation And Antioxidative Capacity. *Animals*, *12*(18), 2426. [PMID: 36139286] [PMCID: PMC9495186] [DOI]

Liu, X., Bi, J., Xiao, H., & Mcclements, D. J. (2016). Enhancement Of Nutraceutical Bioavailability Using Excipient Nanoemulsions: Role Of Lipid Digestion Products On Bioaccessibility Of Carotenoids And Phenolics From Mangoes. *Journal of Food Science*, *81*(3), N754-N761. [DOI]

Longo, J. P. F., & De Moraes, J. (2025). Recent Advances In Nanoformulations For Helminthiasis Treatment. *Expert Opinion on Drug Delivery*, *22*(12), 1861-1876. [PMID: 40974615] [DOI]

Lorenzo-Rebenaque, L., Malik, D. J., Catalá-Gregori, P., Marin, C., & Sevilla-Navarro, S. (2021). In Vitro And In Vivo Gastrointestinal Survival Of Non-Encapsulated And Microencapsulated Salmonella Bacteriophages: Implications For Bacteriophage Therapy In Poultry. *Pharmaceuticals*, *14*(5), 434. [PMID: 34066346] [PMCID: PMC8148174] [DOI]

Lu, J., Zeng, Y., Zhong, H., Guo, W., Zhang, Y., & Mai, W. (2024). Dual-Stimuli-Responsive Gut Microbiota-Targeting Nitidine Chloride-Cs/Pt-Nps Improved Metabolic Status In Nafld. *International Journal of Nanomedicine*, *19*, 2409-2428. [PMID: 38476281] [PMCID: PMC10929648] [DOI]

Lupo, N., Steinbring, C., Friedl, J. D., Le-Vinh, B., & Bernkop-Schnürch, A. (2021). Impact Of Bile Salts And A Medium Chain Fatty Acid On The Physical Properties Of Self-Emulsifying Drug Delivery Systems. *Drug Development and Industrial Pharmacy*, *47*(1), 22-35. [PMID: 33185140] [DOI]

Ma, S. W., & Faciola, A. P. (2024). Impacts Of Slow-Release Urea In Ruminant Diets: A Review. *Fermentation*, *10*(10), 527. [DOI]

Mackenzie, S. G. (2023). The Potential Contribution Of SMART Animal Nutrition In Reducing The Environmental Impacts Of Livestock Systems. In *Smart Livestock Nutrition* (pp. 311-336). Springer International Publishing. [PMID: 28118817] [DOI]

Maghsoudi, S., Taghavi Shahraki, B., Rabiee, N., Fatahi, Y., Bagherzadeh, M., & Dinarvand, R. (2022). The Colorful World Of Carotenoids: A Profound Insight On Therapeutics And Recent Trends In Nano Delivery Systems. *Critical reviews in food science and nutrition*, *62*(13), 3658-3697. [PMID: 33399020] [DOI]

Mahdi, A. A., Mohammed, J. K., Al-Ansi, W., Ghaleb, A. D., Al-Maqtari, Q. A., & Ma, M. (2020). Microencapsulation Of Fingered Citron Extract With Gum Arabic, Modified Starch, Whey Protein, And Maltodextrin Using Spray Drying. *International Journal of Biological Macromolecules*, *152*, 1125-1134. [PMID: 31751737] [DOI]

Mahmoud, R., Salama, B., Safhi, F. A., PET, I., PET, E., & Ateya, A. (2024). Assessing The Impacts Of Different Levels Of Nano-Selenium On Growth Performance, Serum Metabolites, And Gene Expression In Heat-Stressed Growing Quails. *Veterinary Sciences*, *11*(6), 228. [PMID: 38921975] [PMCID: PMC11209059] [DOI]

Mahotra, M., Yu, H., Xu, Q., Liew, W. C., Kharel, S., & Tan, L. S. E. (2022). Solid Lipid Microparticles As Leaching Free, Slow-Release Encapsulation System For Methionine In Aquaculture. *Aquaculture*, *557*, 738342. [DOI]

Mârza, S. M., Munteanu, C., Papuc, I., Radu, L., & Purdoiu, R. C. (2025). The Role Of Probiotics In Enhancing Animal Health: Mechanisms, Benefits, And Applications In Livestock And Companion Animals. *Animals*, *15*(20), 2986. [PMID: 41153915] [PMCID: PMC12560942] [DOI]

Masiuk, D., Nedzvetsky, V., & Maksymchuk, Y. (2024). The Current State And Prospects For The Use Of Organic Acids And Their Compositions In Poultry Feed: A Literature Review. *Scientific Horizons*, *27*(7), 148-157. [DOI]

Mátis, G., Mackei, M., Boomsma, B., Fébel, H., Nadolna, K., & Szymański, Ł. (2022). Dietary Protected Butyrate Supplementation Of Broilers Modulates Intestinal Tight Junction Proteins And Stimulates Endogenous Production Of Short Chain Fatty Acids In The Caecum. *Animals*, *12*(15), 1940. [PMID: 35953929] [PMCID: PMC9367590] [DOI]

Mccafferty, K. W., & Purswell, J. L. (2024). Effects Of Production Time, Die Condition, And Feed Mill On The Physical Quality Of Commercial Broiler Diets. *Journal of Applied Poultry Research*, *33*(3), 100430. [DOI]

Mcclements, D. J., & Rao, J. (2011). Food-Grade Nanoemulsions: Formulation, Fabrication, Properties, Performance, Biological Fate, And Potential Toxicity. *Critical reviews in food science and nutrition*, *51*(4), 285-330. [PMID: 21432697] [DOI]

Mehran, M., Masoum, S., & Memarzadeh, M. (2020). Microencapsulation Of Mentha Spicata Essential Oil By Spray Drying: Optimization, Characterization, Release Kinetics Of Essential Oil From Microcapsules In Food Models. *Industrial Crops and Products*, *154*, 112694. [DOI]

Mehta, N., Kumar, P., Verma, A. K., Umaraw, P., Kumar, Y., & Malav, O. P. (2022). Microencapsulation As A Noble Technique For The Application Of Bioactive Compounds In The Food Industry: A Comprehensive Review. *Applied Sciences*, *12*(3), 1424. [DOI]

Melaku, M., Zhong, R., Han, H., Wan, F., Yi, B., & Zhang, H. (2021). Butyric And Citric Acids And Their Salts In Poultry Nutrition: Effects On Gut Health And Intestinal Microbiota. *International Journal of Molecular Sciences*, *22*(19), 10392. [PMID: 34638730] [PMCID: PMC8508690] [DOI]

Mirsalami, S. M., & Mirsalami, M. (2024). Leveraging Lactobacillus Plantarum Probiotics To Mitigate Diarrhea And Salmonella Infections In Broiler Chickens. *Amb Express*, *14*(1), 137. [PMID: 39694979] [PMCID: PMC11655822] [DOI]

Mirzaei, H., Ghorbani, M. R., Salari, S., & Mehrnia, M. A. (2023). Antioxidant Properties Of The Fennel Essential Oil Nanoemulsion: Effect On European Production Efficiency Factor, Blood Metabolites, Immune System And Cecal Microbial Population Of Heat Stressed Broiler Chickens. *Journal of Livestock Science and Technologies*, *11*(1), 53-60. [DOI]

Mo, K., Li, J., Liu, F., Xu, Y., Huang, X., & Ni, H. (2022). Superiority Of Microencapsulated Essential Oils Compared With Common Essential Oils And Antibiotics: Effects On The Intestinal Health And Gut Microbiota Of Weaning Piglets. *Frontiers in nutrition*, *8*, 808106. [PMID: 35096948] [PMCID: PMC8790512] [DOI]

Mohammed, N. K., Tan, C. P., Manap, Y. A., Muhialdin, B. J., & Hussin, A. S. M. (2020). Spray Drying For The Encapsulation Of Oils-A Review. *Molecules*, *25*(17), 3873. [PMID: 32858785] [PMCID: PMC7503953] [DOI]

Moharreri, M., Vakili, R., Oskoueian, E., & Rajabzadeh, G. (2021). Phytobiotic Role Of Essential Oil-Loaded Microcapsules In Improving The Health Parameters In Clostridium Perfringens-Infected Broiler Chickens. *Italian Journal of Animal Science*, *20*(1), 2075-2085. [DOI]

Mohite, P., Rajput, T., Pandhare, R., Sangale, A., Singh, S., & Prajapati, B. G. (2023). Nanoemulsion In Management Of Colorectal Cancer: Challenges And Future Prospects. *Nanomanufacturing*, *3*(2), 139-166. [DOI]

Moosavi, M., Rahimi, S., Torshizi, M. A. K., Salehi, T. Z., & Grimes, J. (2025). Egg Yolk Immunoglobulin Y Administration On Salmonella Typhimurium Colonization, Intestinal Health, And Growth Performance In Broiler Chickens. *Poultry Science*, *104*(10), 105487. [PMID: 40651206] [PMCID: PMC12275192] [DOI]

Movahedi, F., Nirmal, N., Wang, P., Jin, H., Grøndahl, L., & Li, L. (2024). Recent Advances In Essential Oils And Their Nanoformulations For Poultry Feed. *Journal of Animal Science and Biotechnology*, *15*(1), 110. [PMID: 39123220] [PMCID: PMC11316336] [DOI]

Mucha, W., & Witkowska, D. (2021). The Applicability Of Essential Oils In Different Stages Of Production Of Animal-Based Foods. *Molecules*, *26*(13), 3798. [PMID: 34206449] [PMCID: PMC8270267] [DOI]

Mustafa, G., Alotaibi, F. O., Aldhafiri, F. K., & Arshad, M. F. (2021). Ingredients And Composition Of Food Grade Nanoemulsions. In *Nanoemulsions in Food Technology* (pp. 27-64). CRC Press. [PMID: 33430286] [PMCID: PMC7825740] [DOI]

Muthusamy, N., Natarajan, A., Kumaresan, G., Raja, A., Karthikeyan, N., & Purushothaman, M. R. (2020). Viability Of Spray-Dried Probiotics In Crumble Feed During Storage. *International Journal of Current Microbiology and Applied Sciences*, *9*(7), 1389-1396. [DOI]

Nantapo, C. W., & Marume, U. (2025). Strategic Technologies To Improve Phytogenic Feed Additive Efficacy In Pigs And Poultry. *Animal Nutrition*, *23*, 286-303. [PMID: 41321516] [PMCID: PMC12664070] [DOI]

Nasser, R., Ibrahim, E., Fouad, H., Ahmad, F., Li, W., & Zhou, Q. (2024). Termiticidal, Biochemical, And Morpho-Histological Effects Of Botanical Based Nanoemulsion Against A Subterranean Termite, Odontotermes Formosanus Shiraki. *Frontiers in Plant Science*, *14*, 1292272. [PMID: 38259939] [PMCID: PMC10800573] [DOI]

Nobrega, D. B., Tang, K. L., Caffrey, N. P., De Buck, J., Cork, S. C., & Ronksley, P. E. (2021). Prevalence Of Antimicrobial Resistance Genes And Its Association With Restricted Antimicrobial Use In Food-Producing Animals: A Systematic Review And Meta-Analysis. *Journal of antimicrobial chemotherapy*, *76*(3), 561-575. [PMID: 33146719] [DOI]

Obianwuna, U. E., Chang, X., Oleforuh-Okoleh, V. U., Onu, P. N., Zhang, H., & Qiu, K. (2024). Phytobiotics In Poultry: Revolutionizing Broiler Chicken Nutrition With Plant-Derived Gut Health Enhancers. *Journal of Animal Science and Biotechnology*, *15*(1), 169. [PMID: 39648201] [PMCID: PMC11626766] [DOI]

Oh, W. Y., Moon, C., & Yeo, J. (2026). Bioavailability Of Bioactive Lipids. In *Bioavailability of nutraceuticals and bioactive compounds* (pp. 194-210). CRC Press. [PMCID: PMC11792660] [DOI]

Omidian, H., Cubeddu, L. X., & Gill, E. J. (2025). Harnessing Nanotechnology To Enhance Essential Oil Applications. *Molecules*, *30*(3), 520. [PMID: 39942625] [PMCID: PMC11821119] [DOI]

Oni, A. I., & Oke, O. E. (2025). Gut Health Modulation Through Phytogenics In Poultry: Mechanisms, Benefits, And Applications. *Frontiers in Veterinary Science*, *12*, 1616734. [PMID: 40909941] [PMCID: PMC12405288] [DOI]

Panagiotou, T., & Fisher, R. (2019). Production Of Nanoemulsions At Relevant Industrial Rates: Innovative Scale-Up Strategies. *TechConnect Briefs*.

Pateiro, M., Gómez, B., Munekata, P. E., Barba, F. J., Putnik, P., & Kovačević, D. B. (2021). Nanoencapsulation Of Promising Bioactive Compounds To Improve Their Absorption, Stability, Functionality And The Appearance Of The Final Food Products. *Molecules*, *26*(6), 1547. [PMID: 33799855] [PMCID: PMC7999092] [DOI]

Patel, A. R., & Bhandari, B. (2014). Nano- And Microencapsulation Of Vitamins. In H. S. Kwak (Ed.), *Nano- and microencapsulation for foods* (pp. 223-248). Wiley. [DOI]

Pearlin, B. V., Muthuvel, S., Govidasamy, P., Villavan, M., Alagawany, M., & Farag, M. R. (2020). Role Of Acidifiers In Livestock Nutrition And Health: A Review. *Journal of Animal Physiology and Animal Nutrition*, *104*(2), 558-569. [PMID: 31912950] [DOI]

Pereira, A. G., Perez-Vazquez, A., Barciela, P., Jorge, A. O., Yuksek, E. N., & Nogueira-Marques, R. (2026). Bioactive Nanoemulsions For Enhancing Sausage And Meat Patty Shelf-Life. *Foods*, *15*(3), 430. [PMID: 41683017] [PMCID: PMC12896650] [DOI]

Pham, V. H., Kan, L., Huang, J., Geng, Y., Zhen, W., & Guo, Y. (2020). Dietary Encapsulated Essential Oils And Organic Acids Mixture Improves Gut Health In Broiler Chickens Challenged With Necrotic Enteritis. *Journal of Animal Science and Biotechnology*, *11*(1), 18. [PMID: 32110391] [PMCID: PMC7033934] [DOI]

Phupaboon, S., Muslykhah, U., Suriyapha, C., Sommai, S., Matra, M., & Dagaew, G. (2025). Encapsulated Phytogenic Oils Enhance In Vitro Rumen Fermentation And Reduce Methane Emissions. *BMC Veterinary Research*, *21*(1), 352. [PMID: 40382599] [PMCID: PMC12085062] [DOI]

Piva, A., Pizzamiglio, V., Morlacchini, M., Tedeschi, M., & Piva, G. (2007). Lipid Microencapsulation Allows Slow Release Of Organic Acids And Natural Identical Flavors Along The Swine Intestine. *Journal of Animal Science*, *85*(2), 486-493. [PMID: 17040943] [DOI]

Puglia, D., Pezzolla, D., Gigliotti, G., Torre, L., Bartucca, M. L., & Del Buono, D. (2021). The Opportunity Of Valorizing Agricultural Waste, Through Its Conversion Into Biostimulants, Biofertilizers, And Biopolymers. *Sustainability*, *13*(5), 2710. [DOI]

Qi, Y., Wang, Y., Wang, X., Zheng, H., & Lu, Y. (2025). Tuning Gut Microbiota By Advanced Nanotechnology. *Materials Futures*, *4*(1), 012302. [DOI]

Qian, C., Decker, E. A., Xiao, H., & Mcclements, D. J. (2012). Nanoemulsion Delivery Systems: Influence Of Carrier Oil On Β-Carotene Bioaccessibility. *Food Chemistry*, *135*(3), 1440-1447. [PMID: 22953878] [DOI]

Rahim, M. A., Zahran, H. A., Jaffar, H. M., Ambreen, S., Ramadan, M. F., & Al-Asmari, F. (2025). Liposomal Encapsulation In Food Systems: A Review Of Formulation, Processing, And Applications. *Food Science & Nutrition*, *13*(8), e70587. [PMID: 40766785] [PMCID: PMC12321603] [DOI]

Rahman, M. R. T., Fliss, I., & Biron, E. (2022). Insights In The Development And Uses Of Alternatives To Antibiotic Growth Promoters In Poultry And Swine Production. *Antibiotics*, *11*(6), 766. [PMID: 35740172] [PMCID: PMC9219610] [DOI]

Ramoeletsi, O. T., Sebolao, O. T., Jobe, M. C., & Mwanza, M. (2026). The Impact Of Environmental Variations (Temperature And Humidity) On Fusarium Graminearum In Broiler And Pig Feed. *Frontiers in Fungal Biology*, *7*, 1810614. [PMID: 42112233] [PMCID: PMC13152736] [DOI]

Rao, M., Jha, B., Jha, A. K., & Prasad, K. (2017). Fungal Nanotechnology: A Pandora To Agricultural Science And Engineering. In R. Prasad (Ed.), *Fungal nanotechnology: Applications in agriculture, industry, and medicine* (pp. 1-33). Springer International Publishing. [DOI]

Renukadevi, J., Ranjani, M., Sneha, P., Hussain, J. S., & Shakthi, H. (2025). Gut-Targeted Nutraceutical Delivery: Engineering Microbiome-Responsive Nutraceutical Interfaces. *Food Bioengineering*, *4*(3), 248-261. [DOI]

Rezvankhah, A., Emam-Djomeh, Z., & Askari, G. (2020). Encapsulation And Delivery Of Bioactive Compounds Using Spray And Freeze-Drying Techniques: A Review. *Drying Technology*, *38*(1-2), 235-258. [DOI]

Richards, K., & Malik, D. J. (2021). Bacteriophage Encapsulation In Ph-Responsive Core-Shell Capsules As An Animal Feed Additive. *Viruses*, *13*(6), 1131. [PMID: 34208387] [PMCID: PMC8231228] [DOI]

Saba, N., Moniruzzaman, M., Chin, S., La Min, L. L., Karthikeyan, A., & Lee, D. I. (2026). Insights Into Nanostructured Lipid Carriers For The Effective Delivery Of Bioactives In Swine And Poultry Health. *Animal Bioscience*, *39*(5), 250901. [PMID: 41679270] [PMCID: PMC13175053] [DOI]

Safeer Abbas, M., Afzaal, M., Saeed, F., Asghar, A., Jianfeng, L., & Ahmad, A. (2023). Probiotic Viability As Affected By Encapsulation Materials: Recent Updates And Perspectives. *International Journal of Food Properties*, *26*(1), 1324-1350. [DOI]

Salvia-Trujillo, L., Mcclements, D. J., & Martín-Belloso, O. (2021). Nanoemulsion Design For The Delivery Of Omega-3 Fatty Acids: Formation, Oxidative Stability, And Digestibility. In *Omega-3 delivery systems* (pp. 295-319). Elsevier. [DOI]

Samad, A., Muazzam, A., Alam, A. N., Kim, S., Kim, C., & An, S. (2026). Impact Of Functional Feed Additives And Lower Antibiotic Use On Poultry Meat Quality And Consumer Perception. *Foods*, *15*(11), 1868. [PMID: 42279655] [PMCID: PMC13256159] [DOI]

Serra, V., Salvatori, G., & Pastorelli, G. (2021). Dietary Polyphenol Supplementation In Food Producing Animals: Effects On The Quality Of Derived Products. *Animals*, *11*(2), 401. [PMID: 33562524] [PMCID: PMC7914517] [DOI]

Sharma, R. P., Jerome, N., Pradeep, S., Yadav, S., & Saravanakumar, R. (2025). Recent Advances In Nanoemulsion-Based Therapeutics For Inflammation And Edema Treatment. *Regenerative Engineering and Translational Medicine*, 1-22. [DOI]

Sokol, M., Gulayev, I., Chirkina, M., Klimenko, M., Kamaeva, O., & Yabbarov, N. (2025). Fully Green Particles Loaded With Essential Oils As Phytobiotics: A Review On Preparation And Application In Animal Feed. *Antibiotics*, *14*(8), 803. [PMID: 40867997] [PMCID: PMC12383102] [DOI]

Sonia Indri, P. M., Sri, H., & Widodo, W. (2019). Feed Supplementation With Encapsulated Indigenous Probiotic Lactic Acid Bacteria Increased Broiler Chicken Performance. *ASEAN Journal on Science and Technology for Development*, *36*(1), 29-34. [DOI]

Stamilla, A., Russo, N., Messina, A., Spadaro, C., Natalello, A., & Caggia, C. (2020). Effects Of Microencapsulated Blend Of Organic Acids And Essential Oils As A Feed Additive On Quality Of Chicken Breast Meat. *Animals*, *10*(4), 640. [PMID: 32272803] [PMCID: PMC7222737] [DOI]

Stevanović, Z. D., Bošnjak-Neumüller, J., Pajić-Lijaković, I., Raj, J., & Vasiljević, M. (2018). Essential Oils As Feed Additives-Future Perspectives. *Molecules*, *23*(7), 1717. [PMID: 30011894] [PMCID: PMC6100314] [DOI]

Sun, C., Zhang, Z., Sun, Y., Sun, X., Jin, Y., & Zhu, J. (2025). Enteric Delivery Of Probiotics: Challenges, Techniques, And Activity Assays. *Foods*, *14*(13), 2318. [PMID: 40647075] [PMCID: PMC12248913] [DOI]

Svihus, B. (2014). Function Of The Digestive System. *Journal of Applied Poultry Research*, *23*(2), 306-314. [DOI]

Swain, P. S., Prusty, S., Rao, S. B. N., Rajendran, D., & Patra, A. K. (2021). Essential Nanominerals And Other Nanomaterials In Poultry Nutrition And Production. In *Advances in poultry nutrition research*. IntechOpen. [DOI]

Ta, L. P., Bujna, E., Kun, S., Charalampopoulos, D., & Khutoryanskiy, V. V. (2021). Electrosprayed Mucoadhesive Alginate-Chitosan Microcapsules For Gastrointestinal Delivery Of Probiotics. *International Journal of Pharmaceutics*, *597*, 120342. [PMID: 33545291] [DOI]

Teo, A., Goh, K. K., Wen, J., Oey, I., KO, S., & Kwak, H. S. (2016). Physicochemical Properties Of Whey Protein, Lactoferrin And Tween 20 Stabilised Nanoemulsions: Effect Of Temperature, Ph And SALT. *Food Chemistry*, *197*, 297-306. [PMID: 26616953] [DOI]

Vilas-Boas, A. A., Pintado, M., & Oliveira, A. L. (2021). Natural Bioactive Compounds From Food Waste: Toxicity And Safety Concerns. *Foods*, *10*(7), 1564. [PMID: 34359434] [PMCID: PMC8304211] [DOI]

Vlaicu, P. A., Gras, M. A., Untea, A. E., Lefter, N. A., & Rotar, M. C. (2024). Advancing Livestock Technology: Intelligent Systemization For Enhanced Productivity, Welfare, And Sustainability. *AgriEngineering*, *6*(2), 1479-1496. [DOI]

Wan, K., Sun, L., Hu, X., Yan, Z., Zhang, Y., & Zhang, X. (2016). Novel Nanoemulsion Based Lipid Nanosystems For Favorable In Vitro And In Vivo Characteristics Of Curcumin. *International Journal of Pharmaceutics*, *504*(1-2), 80-88. [PMID: 27034002] [DOI]

Wang, S., Wang, X., Liu, M., Zhang, L., Ge, Z., & Zhao, G. (2020). Preparation And Characterization Of Eucommia Ulmoides Seed Oil O/W Nanoemulsion By Dynamic High-Pressure Microfluidization. *Lwt*, *121*, 108960. [DOI]

Wang, W., Li, T., Chen, J., & Ye, Y. (2023). Inhibition Of Salmonella Enteritidis By Essential Oil Components And The Effect Of Storage On The Quality Of Chicken. *Foods*, *12*(13), 2560. [PMID: 37444298] [DOI]

Wang, Y., Tan, C., Davachi, S. M., Li, P., Davidowsky, P., & Yan, B. (2021). Development Of Microcapsules Using Chitosan And Alginate Via W/O Emulsion For The Protection Of Hydrophilic Compounds By Comparing With Hydrogel Beads. *International Journal of Biological Macromolecules*, *177*, 92-99. [PMID: 33609579] [DOI]

Wik, J., Bansal, K. K., Assmuth, T., Rosling, A., & Rosenholm, J. M. (2020). Facile Methodology Of Nanoemulsion Preparation Using Oily Polymer For The Delivery Of Poorly Soluble Drugs. *Drug Delivery and Translational Research*, *10*(5), 1228-1240. [PMID: 31858441] [PMCID: PMC7447668] [DOI]

Xiao, C., Zhang, L., Zhang, B., Kong, L., Pan, X., & Goossens, T. (2023). Dietary Sodium Butyrate Improves Female Broiler Breeder Performance And Offspring Immune Function By Enhancing Maternal Intestinal Barrier And Microbiota. *Poultry Science*, *102*(6), 102658. [PMID: 37075488] [PMCID: PMC10127124] [DOI]

Xiong, S., Zhang, Q., Zhang, K., Wang, J., Bai, S., & Zeng, Q. (2024). Effects Of Long-Term Coated Sodium Butyrate Supplementation On The Intestinal Health And Colonization Of Cecal Salmonella Of Laying Hens Infected With Salmonella Enteritidis. *Animals*, *14*(9), 1356. [PMID: 38731359] [PMCID: PMC11083467] [DOI]

Xu, Y., Lahaye, L., He, Z., Zhang, J., Yang, C., & Piao, X. (2020). Micro-Encapsulated Essential Oils And Organic Acids Combination Improves Intestinal Barrier Function, Inflammatory Responses And Microbiota Of Weaned Piglets Challenged With Enterotoxigenic Escherichia Coli F4 (K88+). *Animal Nutrition*, *6*(3), 269-277. [PMID: 33005760] [DOI]

Yan, Y., Song, D., He, L., Zhao, Y., Wang, L., & Wang, X. (2025). Optimizing Stability And Controlled Release Of Co-Encapsulated Probiotics And Vitamin B12 Using Fluidized Bed Coating: Impact Of Plasticizers On Tailored Hpmcas-Coated Granules. *Current Research in Food Science*, *11*, 101191. [PMID: 40978511] [PMCID: PMC12446386] [DOI]

Yang, C., Chowdhury, M. K., Hou, Y., & Gong, J. (2015). Phytogenic Compounds As Alternatives To In-Feed Antibiotics: Potentials And Challenges In Application. *Pathogens*, *4*(1), 137-156. [PMID: 25806623] [PMCID: PMC4384076] [DOI]

Yin, D., Tong, T., Moss, A. F., Zhang, R., Kuang, Y., & Zhang, Y. (2022). Effects Of Coated Trace Minerals And The Fat Source On Growth Performance, Antioxidant Status, And Meat Quality In Broiler Chickens. *The Journal of Poultry Science*, *59*(1), 56-63. [PMID: 35125913] [PMCID: PMC8791779] [DOI]

Yin, D., Zhai, F., Lu, W., Moss, A. F., Kuang, Y., & Li, F. (2022). Comparison Of Coated And Uncoated Trace Minerals On Growth Performance, Tissue Mineral Deposition, And Intestinal Microbiota In Ducks. *Frontiers in Microbiology*, *13*, 831945. [PMID: 35495727] [PMCID: PMC9039745] [DOI]

Yoha, K. S., Nida, S., Dutta, S., Moses, J. A., & Anandharamakrishnan, C. (2022). Targeted Delivery Of Probiotics: Perspectives On Research And Commercialization. *Probiotics and Antimicrobial Proteins*, *14*(1), 15-48. [PMID: 33904011] [PMCID: PMC8075719] [DOI]

Yousefi, M., Khanniri, E., Shadnoush, M., Khorshidian, N., & Mortazavian, A. M. (2020). Development, Characterization And In Vitro Antioxidant Activity Of Chitosan-Coated Alginate Microcapsules Entrapping Viola Odorata Linn. Extract. *International Journal of Biological Macromolecules*, *163*, 44-54. [PMID: 32615224] [DOI]

Yue, T., Lu, Y., Ding, W., Xu, B., Zhang, C., & Li, L. (2025). The Role Of Probiotics, Prebiotics, Synbiotics, And Postbiotics In Livestock And Poultry Gut Health: A Review. *Metabolites*, *15*(7), 478. [PMID: 40710579] [PMCID: PMC12300891] [DOI]

Zafar, S., Arshad, M. F., Khan, H., Menahil, R., Iqbal, L., & Prabhavathi, S. J. (2024). Nanoformulations Of Plant Essential Oils For Managing Mycotoxins Producing Fungi: An Overview. *Biocatalysis and Agricultural Biotechnology*, *60*, 103314. [DOI]

Zhang, Y., Yang, Y., Mao, Y., Zhao, Y., Li, X., & Hu, J. (2022). Effects Of Mono-And Di-Glycerides/Phospholipids (Mdg/Pl) On The Bioaccessibility Of Lipophilic Nutrients In A Protein-Based Emulsion System. *Food & Function*, *13*(15), 8168-8178. [PMID: 35822541] [DOI]

Zheng, H., Li, J., Ning, F., Wijaya, W., Chen, Y., & Xiao, J. (2021). Improving In Vitro Bioaccessibility And Bioactivity Of Carnosic Acid Using A Lecithin-Based Nanoemulsion System. *Food & Function*, *12*(4), 1558-1568. [PMID: 33459742] [DOI]

Zhou, C., Li, C., Cui, H., & Lin, L. (2024). Metabolomics Insights Into The Potential Of Encapsulated Essential Oils As Multifunctional Food Additives. *Critical reviews in food science and nutrition*, *64*(15), 5143-5160. [PMID: 36454059] [DOI]

Zhou, Y., Trush, M. M., Ibbotson, L., Espina, L., Lankapalli, A. K., & Farley, A. J. (2026). In Vitro And In Vivo Evaluation Of Nitroxoline As An Effective Antimicrobial Alternative To Poultry Production. *Antibiotics*, *15*(1), 62. [PMID: 41594099] [PMCID: PMC12838059] [DOI]

Zuccari, G., & Alfei, S. (2023). Development Of Phytochemical Delivery Systems By Nano-Suspension And Nano-Emulsion Techniques. *International Journal of Molecular Sciences*, *24*(12), 9824. [PMID: 37372971] [PMCID: PMC10298078] [DOI]