

Plant based nano delivery systems for potential food applications: A review

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ABSTRACT

Plant-based nano delivery systems are a distinctive category of drug delivery systems that employ nanoparticles derived from plant-based materials to deliver bioactive food components, nutritional supplements, or other functional ingredients to the intended sites of action within the body. Improved bioavailability, decreased toxicity, and better target specificity are the main benefits that these nano delivery systems provide compared to conventional drug delivery techniques. In terms of surface area to volume, these nanoparticles are practically suitable for use in drug delivery. They are safe for usage within the system since they are biocompatible, biodegradable, and non-toxic. The chitosan nanoparticles, cellulose nanoparticles, and lipid-based nanoparticles are used to create nanoparticles for drug delivery applications. The review addressed plant-based components for matrix encapsulation, such as the use of proteins, polysaccharides, phospholipids, and lipids. The various encapsulation processes are addressed, including spray drying, freeze drying, spray cooling, complex coacervation, and co-extrusion. The structure, production, and characteristics of nano emulsions, nanoliposomes, and nanophytosomes are studied in the delivery system. Research into plant-based nano delivery systems has great promise for the creation of novel, more efficient, and less hazardous means of delivering functional ingredients in food and nutraceutical industries.

1. Introduction

Plant based components, including proteins, lipids, fats, phospholipids, and polysaccharides, have been utilized for targeting nano delivery of foods and have gained increasing attention recently. These nanosized delivery systems enhance the quality and improve the safety, availability, and effectiveness of food materials that promote human health (Sahani & Sharma, 2021). The food manufactured through the intervention of nanotechnology during processing, production, safety, or packaging is referred to as nanofood. Nanomaterials in food applications were used since they were not explored, e.g., stabilizing the milk

fats by casein micelles (Kopjar et al., 2021). The use of nanomaterials involves the control of the material at the lowest atomic levels. Apart from food industries, many areas are covered by the utilization of nanotechnology, such as agriculture, health, pharma, fabrics, wastewater, and the automobile industries. Nanoencapsulation is a promising technique employed for protecting food bioactive components, including nutraceuticals. Nanomaterials can be derived from nanospheres, nanocapsules, nanofibers, and thin films exhibiting unique characteristics, and the use of different nanoencapsulating methods, such as freeze drying, spray drying, spray cooling, extrusion, homogenization, Complex coacervation, etc. The most significant benefit of

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plant-origin nanomaterials is that they are recyclable and are commonly recognized as safe GRAS as compared to other nanomaterials (Batarseh, 2025). Many reports have explored the use of nanomaterials derived from natural biopolymers, including proteins (e.g., prolamines such as zein, kafirin, hordein, gliadin, and soy protein), polysaccharides (e.g., cellulose, starch, and gums), as well as lignin, a complex aromatic polymer. The application of nanomaterials enhances the shelf stability of foodstuffs by encapsulating antioxidant and antimicrobial components. The sensory properties of food materials have been improved by the encapsulation of different pigments and flavor components (Gottardo et al., 2021). Several studies have suggested the use of nanomaterials in ensuring food quality concerning packaging and safety of food stuff with substantial improvement in desirable quality attributes (Pinto et al., 2025). Additionally, nanocapsulation ensures the sustainability of food products during the design of nutritious food regimens for geographic populations. Development of new fortified foods delivers regulated nutrition through nano-therapy intelligent systems (Sahoo et al., 2021). There are two different approaches by which nanotechnology can be applied in food industries, either from “bottom up or top down”. The outlook of utilizing nanofoods has sparked the utmost debate. There are several concerns regarding the reduction of different properties, including size reduction, the effect of the nanomaterial used on its toxicity, etc. Nano foods require proper testing and quality checks for consumption as they are categorized as novel foods (Gottardo et al., 2021). Such safety concerns should be addressed for the commercial application of products.

Over the past years, nanostructured delivery systems based on plants have become a disruptive innovation in the functional food market due to the growing demand of consumers for clean-label, sustainable, and vegan-friendly foods. Although the early developments in the field of plant-based colloidal carriers were summarised in foundational reviews, the swift developments that have occurred since 2023, including precision nanoemulsions, hybrid biopolymer nanoparticles, microfluidic-assisted encapsulation, AI-optimised nanoformulations, and green nanomanufacturing, remain to be synthesised. The nano-delivery systems are currently being facilitated by new plant-derived materials such as pea protein, chia phospholipids, nanocellulose, citrus pectin, and modified starches, which have much better bioavailability, oxidative stability, sensory masking, and targeted gastrointestinal release. Besides, innovations, including the use of CRISPR to design biopolymers and ultrasound to nanoencapsulate, have enhanced the versatility of plant-based carriers, which have become a formidable alternative to synthetic or animal-based nanomaterials. The fact that there is no updated framework that characterizes next-generation plant-based systems vis-à-vis traditional delivery technologies only supports the point that there is a high requirement of a new and application-based analysis. This review seeks to place plant-based nano delivery systems in the context of the emerging trends in research and identification of future challenges and opportunities so that they may determine how the next generation of functional food, nutraceutical and sustainable food processing technology can be shaped in the future.

2. Plant-based ingredients for encapsulating matrix

2.1. Proteins

An ample proportion of vital amino acids used for the growth and repair of the human body are present in plant protein sources. In the last several years, the formation of plant-based nanocarriers to food bioactives has come a long way, not just in formulation approaches but in the increase in the number of plant-based biopolymers and safe delivery substances. Some authors have pointed out that legumes, oilseeds, cereals, tubers, and other plant proteins have the potential to be good emulsifiers or encapsulating matrices of lipophilic bioactives, including carotenoids, polyphenols, vitamins, and polyunsaturated fatty acids. There are several sources from which these proteins can be obtained,

such as cereals, dairy, algae, and microalgae. Sensory and textural characteristics depend on the functional and structural properties of the origin of the plant protein. Generally, proteins exist in globular structures with multimeric elements linked with each other by chemical and physical bonds (Domínguez et al., 2021). The multifaceted graded orientation with bundles of muscle fibers embedded with connective tissue has been responsible for the textural and sensory properties of meat (De Angelis et al., 2024). Thus, imitating this complex fibrous structure in meat with plant globular proteins has shown promising results (Kopjar et al., 2021). Casein protein consists of a supple coil structure having hydrophilic-phobic interactions with phosphate groups, which play a significant role in the manufacturing of dairy products like yogurt and cheese (Soni et al., 2022). As an example, a study shows that plant-protein-based delivery systems (hydrogels, emulsions, self-assembled nanoparticles, films) provide a sustainable, GRAS-compliant alternative to synthetic or animal-derived delivery systems, but technological advances are required to enhance the encapsulation efficiency and the release profile (Gomes & Sobral, 2021). An emulsion-based delivery system is reported to have better encapsulation stability, release kinetics, and increased bioavailability of bioactives when physical and chemical processing conditions are optimized, and bioactives are delivered by plant-protein stabilizers. The 3D structural network of casein protein is responsible for the texture of cheese and yogurt, and is different from the globular proteins derived from plant sources. Properties like gel formation, thickening, emulsifying, and foaming are the desirable functional properties of plant origin proteins with potential water-holding capacity, resulting in their application in the food industry dealing with the production of plant-based foods. Due to the occurrence of anti-nutritional factors in various cereal-originated sources of protein, it is very complex to mimic the structural as well as functional properties of animal-based food products (Boostani et al., 2022). Fig. 1(A) depicts the role of essential oils being nanoencapsulated as natural food antimicrobial agents. Different techniques could be used to reduce these anti-nutritional factors. The anabolic capacity of proteins derived from plants may be due to the lack of essential amino acids in comparison to animal-originated proteins. Their design prevents the bioactive compounds from deficiency inside the food material and enhances bioavailability in the human body (Guan et al., 2022). The antioxidant property and chemical strength of quercetin can be improved by trapping it within zein (a protein found in maize). Various examples of bio-based delivery systems prepared for food applications have been given in detail in Table 2. Moreover, the interactions of plant-protein-based nano delivery systems with biological membranes have been reported to significantly influence the absorption and pharmacokinetics of encapsulated bioactive compounds (Shanmugam et al., 2022; Guan et al., 2022). In addition to proteins, other, more complicated biopolymers and lipid-based nanostructures of plant origin have been studied. Indicatively, more recent studies have shown the encapsulation of antioxidant-enriched extracts (*Hibiscus sabdariffa*) in nanostructured lipid carriers that can then be used to fortify milks, which suggests the potential to use plant-based nanocarriers in actual food systems. The use of nanofibers made of plant-based proteins (pea protein, gluten, zein) in food packaging and carrier matrices is also of increasing interest, which also indicates a tendency towards multifunctional systems of delivery and packaging (Venkidasamy et al., 2025). Optimizing the size, surface charge, and hydrophobicity of plant-protein nanoparticles can enhance their cellular uptake and improve systemic bioavailability, making them highly promising for functional food and nutraceutical applications.

2.2. Polysaccharides

Polysaccharides are formed by different units of monosaccharide connected with glycosidic bonds (alpha and beta (1→4, 1→6, 1→3, etc.) and linear or branched macromolecules. There are two types of polysaccharides, depending upon their function, and they can be categorized

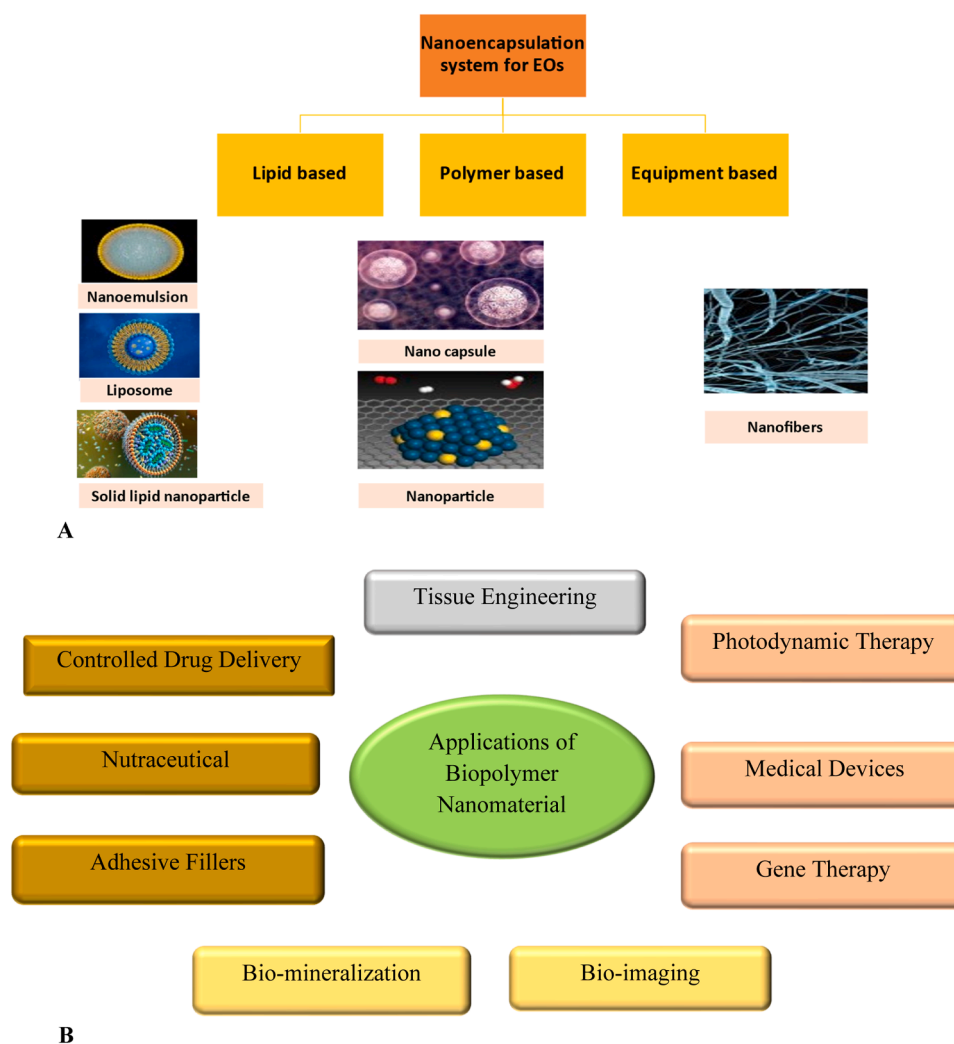


Fig. 1. Encapsulation process (A) Essential oils being nanoencapsulated as natural food antimicrobial agents and applications of biopolymer nanomaterials (B) Nanoencapsulation by Spray drying techniques.

as storage polysaccharides and structural. Starch, inulin, and glycogen are in the category of storage polysaccharides, while cellulose and chitin belong to structural polysaccharides (Zhang et al., 2022). Starch is made up of linear and branched α -D-glucopyranose units containing amylose and amylopectin and is arranged in amorphous lamellae (9 nm) and crystalline form in the 2–100 μ m starch granules (Yan et al., 2025). Due to the crystalline structural presence of starch, it is used as a nanomaterial for encapsulation. Starch is recyclable, cost-effective and safe as compared to other plant-based nanomaterials (Domínguez et al., 2021). Other polysaccharides like gum arabic, pectin, dextran, chitin, chitosan, and cellulose can be utilized as thickeners, emulsifiers, and gel formers. This recent research has demonstrated that starch nanoparticles are a potent enhancer of antioxidant lipophilic compounds in beverage analogues and dairy analogues in terms of oxidative stability and dispersibility (Paul et al., 2025). Recent studies show that pectin-based and alginate based nanogels have a significant effect of increasing gastrointestinal stability and sustained release of polyphenols when the polyphenol is exposed to simulated digestion conditions (Pan et al., 2025).

Dextran nanomaterials are used for the stability of bioactive proteins as well as can also be used for the encapsulation of protein to *Leuconostoc mesenteroides* dextran and polyethylene glycol in water, preceded by different processes such as phase separation, freezing, and freeze drying. Dichloromethane is used for washing, and desired nanomaterials of dextran loaded with the required protein can be obtained

(Buljeta et al., 2022). Polysaccharides exhibit a wide range of functional, physical, and chemical characteristics, e.g. water solubility, foam and gel formation, binding and thickening, capacity of water retention, etc., that make them suitable ingredients for the desired nutritional value and structure. Polysaccharide based nano materials for nanoencapsulation are gaining importance nowadays in order to gain stability and controlled release of the flavors (Prasher et al., 2021). Chitosan, being soluble in organic acids (diluted) with a pH <6.5 is reported by several scientists as an active nano material carrier for bioactive components. Vitamin C was encapsulated in chitosan nanomaterials to develop the ionotropic gel. α -lipoic acid is an essential cofactor unstable to light or heat exposure, but its stability could be enhanced by encapsulation of chitosan (Waghmar et al., 2022). It has been established that the mucilaginous sources of chitosan analogues (i.e., okra and chia seeds) provide plant-derived chitosan analogues with similar encapsulation with reduced biocompatibility in comparison to traditional chitosan (Shiam et al., 2025). Several cellulose derivatives have been used for the preparation of nanoparticles, such as calcium chloride for the fabrication of spherical carboxymethyl cellulose nanoparticles (Waghmar et al., 2022). Encapsulation of curcumin in hydroxypropyl methylcellulose (HPMC) nanoparticles showed a positive effect on cancer and reversed the changes induced by cellular apoptosis in prostate cancer cells (Shiam et al., 2025).

Compared to surfactant-based emulsions, nanocellulose-based Pickering emulsions are more advantageous in thermal and oxidative

stability, which is why they can be applied to functional beverages and packaging (Yang et al., 2025). Several polysaccharide-originated nanomaterials have been encapsulated for controlled delivery, such as the sweet taste of chewing gum, and other confectioners can be increased by encapsulation of several sweeteners. The bitter taste of the stevia plant could also be masked by encapsulation using polysaccharide-based nanomaterial (Edris, 2021). Even with these advancements, there still exist very important areas of ignorance within the issues of scale-up feasibility, interactions between matrices, and the standardized protocols of toxicological evaluation that are vital in the process of industrial translation of polysaccharide nanocarriers.

2.3. Phospholipids

Phospholipids are the main bio membranes among lipids with amphiphilic molecules linked with hydrophilic heads and hydrophobic tails (Tan & McClements, 2021). Phospholipids are predominantly reported to be used as stabilizers of oil in water interfaces. They are considered to have been used for the making of several foams and particles. Solid lipid nanoparticles have been developed by using lecithin to stabilize emulsions that are formed of pure triglycerides.

Recent studies show that solid lipid nanoparticles composed of curcumin-lecithin improve the oxidative stability and storage capability of nutraceuticals encapsulated (Mankan et al., 2025). Formation of gel and aggregation of solid nanoparticles have been shown to be prevented by adding cosurfactants that can tolerate the basic lipid surface, preventing aggregation. Phospholipids have shown the ability to stabilize both types of emulsion used to stabilize vesicles of water in aqueous media (Edris, 2021). A thin layer of phospholipids has been developed with a water-oil-water system combined in oil as a volatile solvent that allows the solvent to evaporate and then forms a monolayer at the two side interfacial surfaces (De Angelis et al., 2024). More complex systems of phospholipid vesicles demonstrate better GI stability and increased control of the release of encapsulated polyphenols and vitamins that are soluble in lipids (Batarseh, 2025). The melting point of phospholipids varies and affects the melting property of other homologous lipids in a bilayer manner, and different bilayer phases exist at a specific temperature and pressure for a mixed profile of bilayer phospholipids (Edris, 2021). Tuning phospholipid composition (chain length and degree of unsaturation) directly alters bilayer rigidity, permeability, and encapsulation efficiency, enabling customized release profiles for food and nutraceutical formulations (Yu et al., 2025). Recent studies emphasize that phospholipid-based vesicles not only stabilize encapsulated compounds but also actively participate in modulating their bio-distribution and cellular uptake through specific nano-bio interactions (Shanmugam et al., 2022). This underlines the emerging role of phospholipids in next-generation functional foods and targeted therapeutics.

2.4. Lipids

The naturally occurring fats derived from different plant and animal origins are known as lipids, including waxes, sterols, and some fat-soluble vitamins (Tan & McClements, 2021). Seeds are the key sources in which lipids are present, e.g., cottonseed, rapeseed, soybean, sunflower, etc. Among fruits and nuts, the presence of lipids belongs to olive, avocado, palm fruit, and walnut, respectively (Zhang et al., 2022). Triglycerides contain three fatty acids connected with one molecule of glycerol through an ester linkage from the lipids. The molecular structure of lipids is responsible for their chemical and physical properties. Most plant-originated lipids exist in liquid form at normal temperatures because of the occurrence of Monounsaturated Fatty Acids (MUFA) and Polyunsaturated Fatty Acids (PUFA) (Comunian et al., 2022). The stability of oils like olive and peanut has been considered to be higher compared to oils like soybean and corn, due to their increased unsaturation. Therefore, these physicochemical properties of lipids deliver the desired properties of food products like cake aeration for fluffiness,

buttery and cheesy look, and transfer of heat in deep fried foods, used for glazing (Chaudhari et al., 2021). These effects can be managed by a reduction in the degree of unsaturation, including processes like hydrogenation. Nanoencapsulation can be useful in decreasing issues linked with the stability of lipids. Accordingly, the solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) made of food-grade lipids are especially useful in stabilizing lipophilic antioxidants and polyunsaturated fatty acids against oxidation, and at the same time increasing their bioaccessibility and controlled release when used in functional food systems (Jacob et al., 2025). Vitamin A has been used to encapsulate solid lipid nanoparticles by employing the hydrogenation process. After the hydrogenation process, plant-based lipids exhibit similar properties to those of animal-based lipids. The fatty oils contain more solid fats; therefore, they imbibe the properties of animal-based fats (De Angelis et al., 2024). The rearrangement of fatty acids could serve as an alternative method for the hydrogenation process that does not produce trans fats. Fatty acids present in plant-based lipids affect the quality of nutrients and are more prone to oxidation. Therefore, nano-encapsulation could serve best for the controlled delivery of micro-nutrients with their bioavailability, particularly in the gastrointestinal tract. Oxidative stability of lipids is increased by encapsulating oils with spray drying technology.

A number of recent reports indicate that microcapsules of fish oil and other PUFA-rich vegetable oils dried by it result in significantly better oxidative stability and a longer shelf-life than the corresponding non-encapsulated oils, which demonstrates the effectiveness of spray drying as a powerful tool to safeguard sensitive edible lipids (Pinto et al., 2025; Culina et al., 2025). Furthermore, lipid-based nano delivery systems are increasingly being designed with precise control over particle characteristics to enhance their pharmacokinetic behavior, including extended circulation times and improved target tissue accumulation (Shanmugam et al., 2022). Even though most formulations are based on pharmaceutical research, the recent research on lipid-based nanocarriers of natural bioactives shows significant improvements in oral bioavailability and targeted delivery, which can be directly applied to nutraceutical and functional food products (Yu et al., 2025). Such advanced formulations contribute significantly to the efficacy of lipid-encapsulated functional ingredients. It has been investigated that oils such as walnut, palm, and sativa have been encapsulated by several plant-based lipid matrices, resulting in improving their oxidative stability and enhancing their health profile (Pinto et al., 2025).

3. Encapsulation techniques

3.1. Spray drying

Spray drying is considered one of the oldest and most cost-effective methods employed for encapsulation of food products such as flavors, oils, and fragrances. The encapsulation by spray drying includes 4 stages (i) dispersion preparation, (ii) homogenization of the dispersion by an atomizer, (iii) drying of the dispersion by a hot gas carrier to achieve the evaporation of the solvent, (iv) collection of dry particles by cyclones (Dantas et al., 2024). The dispersion is fed into the drying vessel using a nozzle or an atomizer to create tiny droplets, followed by the solvent evaporating. The dried particles are then removed from the drying gas into a collector with the application of a cyclone or filter. The detailed process of preparation of nanoencapsulation by spray drying techniques is shown in Fig. 1(B). The features of spray-dried powders are influenced by a number of spray drying processing variables, including feed flow rate, drying air flow rate, drying temperature, atomizer speed, sort, and carrier agent concentration, among others (Molaveisi et al., 2025). An aerosol is produced in this procedure by atomizing a mixture of core and shell materials that have been dissolved and distributed in a solvent. Then, with the help of heat, the solvent is eliminated, forming tiny, coagulated droplets that entrap the compounds of interest (Pinto et al., 2025). Due to the decreased water activity in the spray drying process, it

delays microbial growth, reduces transport and storage costs, avoids degradation processes, and improves the rapid solubility of the final product.

However, for food products and nutraceuticals encapsulation, spray drying technology is commonly used. It has been observed that this technique has certain limitations for drying sugar-rich products. This process cannot be used directly with juices, honey, and polyphenol extracts from fruits, as the low glass transition temperatures (T_g) of low molecular sugars in these products can cause a gluey problem, which leads to low powder recovery (Zhao et al., 2025). Research showed that agri-food by-products (lupin hull and camelina press-cake) as oil-in-water Pickering emulsions have a higher ability to retain and stabilize volatile flavors (D-limonene) during spray drying and storage than traditional emulsions (Burgos-Diaz et al., 2024). Recent comparative research on the application of spray drying versus freeze-drying to encapsulate bioactive-laden plant extracts indicated that spray drying was more advantageous because it formed more homogeneous micro-particles that had improved accessibility of the core material and improved powder reconstitution, which is more suitable in the scale-up context (Zhao et al., 2025). Recently, the review of the innovations in spray-drying technologies (including pulsed-combustion spray drying, electrostatic spray drying) has been considered as a potential way of minimizing thermal stress and improving the preservation of heat- and oxidation-sensitive compounds, improving encapsulation efficiency, and stability (Dantas et al., 2024). In another review, it is noted that spray drying is among the least costly and most generalized encapsulation methods of food ingredients and nutraceuticals, particularly when wall material and process parameters are optimized to enhance yield, flowability, and retention of bioactive substances (Pudziuvelyte et al., 2025). However, some process-related issues are still outlined in the recent work: Continuous spray drying yield is reduced due to wall-deposition and powder loss on a batch-to-batch basis, especially in the case of high-solid or high-viscosity feeds (Nik Abd Rahman et al.,

2024). It has been demonstrated that high inlet temperatures and poor parameter optimization can have a detrimental effect on powder morphology, encapsulation efficiency, and volatile compound or sensitive oils retention (Gonçalves et al., 2023). In general, as spray drying is an economical, scalable and versatile method to nano/micro-encapsulate food oils, flavours and nutraceuticals, recent developments in Pickering emulsions, new drying technologies, and optimisation of process parameters, retention and stability are being enhanced. However, the problems of scale-up, loss of yields, and volatility or heat-sensitive compounds retention are also relevant limitations to consider that require cautious formulation and optimization of the process. A comparative overview of major encapsulation techniques, including advantages, limitations, scalability, and practical application, is presented in Table 1 to highlight methodological differences and industrial relevance. Also, for certain flavors containing very volatile aromas, this process may not be suitable for encapsulation, as it may change the balance of molecular composition during processing.

3.2. Freeze drying

Freeze-drying is a drying method based on sublimation and has been used to yield powders with distinct properties. During sublimation, H_2O is directly transferred to steam without going through the liquid state in a vacuum, which allows the maximum preservation of oxidation-prone and heat-sensitive compounds and also other bioactive compounds. In order to freeze the feed emulsion, minus temperature is employed under a vacuum that undergoes very low pressure, and the created ice crystals are sublimated (Pinto et al., 2025). Freeze-drying has been effectively used for the encapsulation process. This process helps in the formulation of products that are resilient to oxidation and gives protection to heat-sensitive core materials in case of encapsulated freeze-dried products. However, there are some drawbacks associated with this method, such as high energy, long processing times, and elevated production

Table 1
Comparative evaluation of major encapsulation techniques in agri-food applications.

Sl No	Technique	Suitable bioactives / core materials	Main advantage	Key limitation	Scalability / Industrial relevance	Typical application	References
1	Spray drying / Nanospray drying	Oils, flavors, polyphenols, volatile bioactives	Low cost, scalable, widely used, fast drying	Heat/oxidation-sensitive actives, loss of volatiles, limited retention of unstable oils	High — widely used in food industry	Nutraceutical powders, flavor encapsulation, oils, beverage powders	Mohammadi et al. (2021)
2	Freeze drying (lyophilization)	Heat-sensitive compounds, polyphenols, certain oils, probiotics	Gentle drying — minimal heat damage, good retention of actives, good for thermo-labile substances	High energy, long time, expensive, low throughput	Low to moderate — more niche/ high-value products	Nutraceuticals, probiotics powders, high-end functional foods	Kandasamy and Naveen (2022)
3	Fluid-bed coating	Vitamins, antioxidants, oils, microcapsules needing coating	Controlled coating layer, uniform particles, continuous / semi-continuous process	Thermal exposure risk, possible degradation of sensitive actives	Moderate — established in food/ pharma coatings	Fortified foods, controlled-release powders	Xu et al. (2024)
4	Spray chilling / Spray cooling	Oils, fat-soluble vitamins, flavor oils needing protection from oxidation	Solvent-free, avoids high temperatures (compared to spray drying), good oxidative protection	Poor water-dispersibility, may not suit aqueous systems well	High — simple process, scalable for food oils	Bakery fats, fat-based components, oil-fortified foods	N'GUESSAN-GNAMAN et al. (2024)
5	Complex coacervation (plus drying)	Flavors, hydrophilic and moderately hydrophobic bioactives, sensitive actives	High encapsulation efficiency, gentle conditions, good core loading, controlled release	pH/ionic strength sensitivity, need for compatible polymers, drying challenges	Moderate — used in research and some industrial flavor/ fragrance encapsulation	Flavor encapsulation, nutraceuticals, controlled-release food ingredients	Szpicer et al. (2025)
6	Solid Lipid Nanoparticles (SLNs) / Lipid-based carriers	Lipophilic bioactives, vitamins, omega-3 oils, antioxidants	Controlled release, protection of labile lipophilic compounds, improved bioavailability and stability	Polymorphic transitions, stability challenges, lipid crystallization, loading capacity limits	Emerging — scalable with advances in production	Nutraceutical oils, omega-3 delivery, functional food lipids	Bukke et al. (2024)

Table 2

Naturally derived polymers and the production of Bio-based delivery systems in the agri-food sector.

A: Naturally derived polymers			
Application/ Functional property	Key Mechanism	Natural polymers used	References
Thickening agent	Absorb water, increase in viscosity, provide a thicker texture	Xanthan gum (0.1 - 0.2%) Carrageenan (0.1–1%) Starch (2–8%) Alginate (0.2–1%)	Kopjar et al., 2021
Gelling agent	Formation of a three- dimensional network, causing trapping of water and a gel-like structure	Carrageenan (0.01–1.0%) Alginate (0.1–1.0%) Gelatin (0.5 – 10%)	Molaveisi et al., 2025
Packaging material	Regulate moisture and gas permeation, maintaining stability and controlled release	Alginate (1–4%) Starch (3–10%) Carrageenan (1–3%) Chitosan (1–2%) Cellulose (1–5%)	Zhou et al., 2021
Controlled- release fertilizers (CRF)	A nano-enabled fertilizer system that regulates the release of nutrients as per the plant requirements.	Carrageenan (2–8%) Chitosan (1–5%) Gelatin (3–10%) Cellulose (2–6%) Starch (5–30%)	De Angelis et al., 2024
Water Retention	Absorption of water by the natural polymers forming hydrogels and controlled release of stored water to plant roots.	Alginate (1–8%) Cellulose (0.2–5%) Carrageenan (1–8%) Guar gum (0.1–2%)	Molaveisi et al., 2025
Pesticides	Natural polymers as a biodegradable carrier for the delivery of pesticides and the controlled release of pesticides	Alginate (0.1 –15%) Cellulose (0.1–5%) Carrageenan (1–4%) Pectin (0.1–5%)	Batarseh, 2025
B. Production of Bio-based delivery systems			
Bioactive compounds	Encapsulation technique used	Bio-based material/ Encapsulating material used	References
Lycopene (1–10%)	Spray drying	Polysaccharide based: Starch	Cheng et al., 2024
Curcumin (0.01–0.2%)	Anti-solvent precipitation	Polysaccharide based: Zein	Molaveisi et al., 2025
β- lactoglobulin (0.5–5%)	Freeze drying	Protein-based: Thiosulfinate allicin	Guan et al., 2022
Whey protein (0.5- 5%)	Spray drying	Protein-based: Astaxanthin	Domínguez et al., 2021
Liquid oil (2–15%) and solid lipid (1–10%)	Homogenization	Lipid-based: Vitamin A	Yan et al., 2025
Lipid mixture of low trans hydrogenated vegetable fat (1–10%)	Spray drying	Lipid-based: Phytosterols	Shanmugam et al., 2022

costs (Kumbhar et al., 2025).

The process of freeze drying can be divided into three stages: i) freezing, ii) primary drying (main drying, sublimation drying), and iii) secondary drying (desorption drying). (Zhao et al., 2025). In the first step, the development and size of ice crystals are resolved by freezing rate. The low rate of freezing makes larger ice crystals, which can sublimate and raise the primary drying rate. In primary drying, to start the sublimation, using a vacuum, the shelf temperature will rise. The endpoint of the primary drying phase is an important constraint to determine because the increase in temperature (in the secondary drying) before the sublimation of all ice could collapse the end product quality (Buljeta et al., 2022). According to research, pheophytin and trans-fucoanthin, two dominant seaweed pigments that function as bioactive compounds, were successfully encapsulated and rapidly extracted into Tween-80 matrices and malt dextrin using the freeze-drying method. Fig. 2 shows examples of micro- and nano-delivery devices for bioactive substances intended for the food industry. More recent studies have indicated that freeze-drying in olive seed extracts better preserves phenolics and antioxidant activity of the extract compared to spray drying when encapsulating polyphenol-rich plant extracts (Aydar et al., 2025). When freeze drying was compared with oven drying in a low moisture food of *Averrhoa bilimbi*, an improvement in color stability, flavonoid stability, and rehydration behaviour of freeze-dried fruit-based bioactives was reported (Yusoff et al., 2024). It was shown that freeze-dried lipid nanoparticles with carotenoids showed greater oxidative stability and longer shelf life of carotenoid-rich pumpkin extract at accelerated storage conditions (Pinna et al., 2025). Although freeze drying has shown a great preservation potential, it is still limited by scalability and energy consumption, which promotes the hybrid process, including vacuum-microwave assisted freeze drying to shorten the process time and reduce the production cost (Al Faruq et al., 2025).

3.3. Spray cooling

Another encapsulation method is called spray cooling/chilling, where the reverse process of spray drying is employed. In this process, instead of evaporation of the carrier mixture, such as in spray drying, the mixture is subjected to cooling (Rai et al., 2025). Spray-cooling is divided into two steps. In the first step, the matrix material has to be introduced together with the substance to be encapsulated; this material is often an oil-in-water emulsion or, in the case of hydrophilic material, a melted lipid. The lipid phase is atomized by a heated atomizer nozzle in the second stage in order to maintain an appropriate temperature and prevent the lipid molecules from recrystallization (Favaro-Trindade et al., 2021). When this nebulized material enters a chamber containing liquid nitrogen or cold injection at a temperature below the lipid's melting point, heat transfer between the lipid and the cold air occurs, solidifying the matrix and producing the particles, and is then collected in a container beneath the cooling chamber. The resting phase of the sprayed droplet is quite brief in the cooling chamber. Compared to other techniques, such as spray drying, this method is said to be more ecologically friendly. Microencapsulation methods of functional foods identified spray chilling as a potential low-cost, solvent-free, continuous method of encapsulating vitamins, flavors, oils and other bioactives, which makes it an attractive choice in improving stability, reducing hygroscopicity, and hiding unattractive flavours or odours. Also, it was found that spray chilled microparticles exhibited enhanced storage stability in accelerated oxidation environments, and maintained bioactive activity in food more effectively than non-encapsulated controls - highlighting their use in food products that need shelf stability (Mardani et al., 2024). Nevertheless, some limitations are also known. Spray chilled lipid-coated microparticles are generally not soluble in water, and that could be a drawback in using these lipid-coated microparticles in an aqueous food structure or beverage (Rai et al., 2025). Besides, process parameters (melting point of lipid matrix, chamber cooling rate

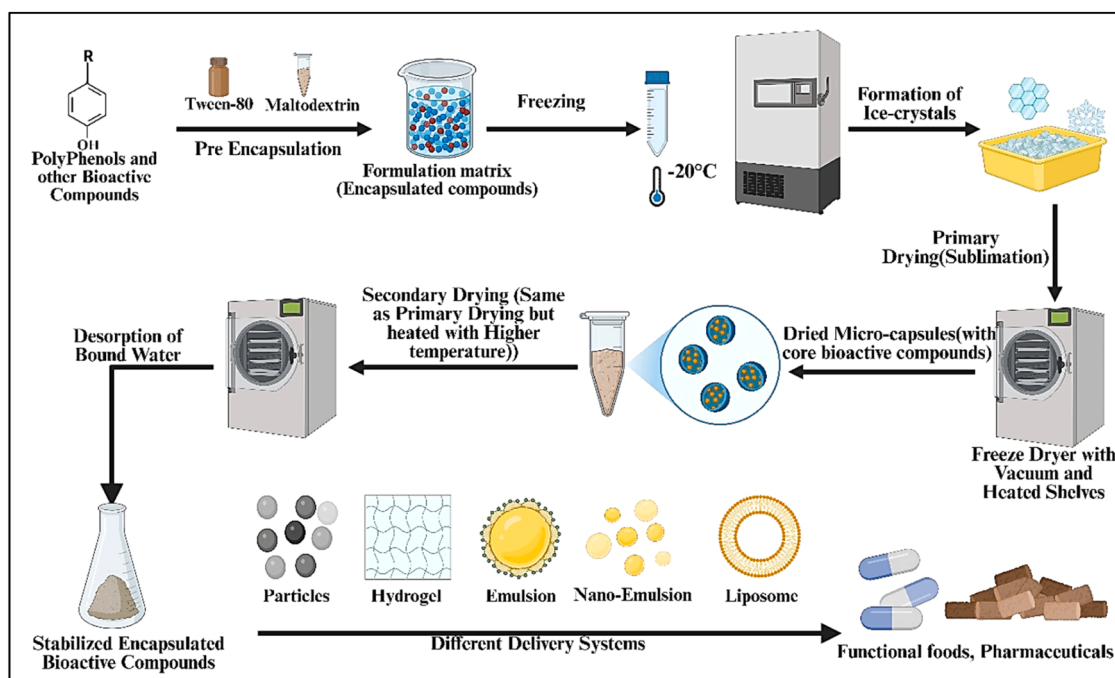


Fig. 2. Micro and nano-delivery technologies for encapsulating bioactive ingredients employed in the food industry.

and atomization settings) can have a substantial effect on particle size distribution and encapsulation efficiency, and loading capacity can be quite low when it comes to high-dose applications. The other advantage attributed to this method is that it can be used in continuous mode, which can pave the way for scaling up the output.

3.4. Complex coacervation

Complex coacervation is an electrostatically induced liquid-liquid phase division phenomenon involving biopolymers with opposing charges (Batarseh, 2025). The interest in complex coacervation of food systems has highlighted the capacity to develop dense polymer-rich phases that have a high loading capacity and a modifiable release behaviour, which is especially desirable in the encapsulation of delicate food bioactives (Alrosan et al., 2025). In the food industry, complex coacervation is favored for the encapsulation of sensitive bioactives because it can provide improved protection and controlled release over simple coacervation or spray drying. It has been effectively applied to compounds such as lutein, lycopene, antioxidants, flavors and vitamins. Its principal benefits are mild processing conditions, high encapsulation efficiency, high core loading, and the formation of water-immiscible capsules for sustained release (Yan et al., 2025). In this process, originally water-soluble associative electrostatic interactions between two oppositely charged polyelectrolytes undergo reciprocal and reversible complexation, generating an insoluble hydrophilic macromolecule complex containing significant amounts of water. More recent studies on plant protein-polysaccharide pairs have demonstrated that complex coacervation can achieve encapsulation efficiencies of greater than 90 percent and can effectively stabilize carotenoids, essential oils and probiotics during in vitro gastrointestinal digestion and put it in a central position as a technology to create next-generation functional foods (Muhoza et al., 2022; Alrosan et al., 2025).

Proteins and polysaccharides are the source of production of coacervates, thus having a wide range of functionality in a variety of food products. Different properties like polymer concentration, pH, thermal treatments, polymer mixing ratio, and ionic strength have a substantial influence on the fabrication of complex coacervates. The viscoelastic properties determine the practical application of coacervates. Recent

studies have progressively focused on a more sustainable use of protein-polysaccharide systems containing plant-based sources of proteins (e.g., soy, pea, lentil proteins with pectin, gum arabic or carrageenan) as an alternative to gelatin-gum arabic coacervates, which involves protein modification (enzymatic, Maillard, deamidation) to enhance solubility and coacervation behaviour (Cao et al., 2025). Alongside rheological and interfacial analyses, it has been established that storage, loss and gel strength of protein-polysaccharide coacervates remain extremely pH and ionic strength sensitive directly influencing capsule mechanical stability and release kinetics under food-like conditions (Wan et al., 2023). The complicated coacervation of gum arabic-gelatin, a polysaccharide-protein system, was first thoroughly explored (Yan et al., 2025). In the intricate process of coacervation encapsulation, the coacervates are distributed evenly along the edge, generating a covering that solidifies upon cooling and produces capsules when colloidal dispersions are present.

Different experimental conditions such as pH, type of polymer and core material, stirring rate, concentration, and ratio of core and shell materials directly affect the structure and morphology of coacervates forming mono or multinuclear capsules highly dispersed nanosphere and continuous polymer network (González-Monje et al., 2021). This process performs as a technique intended to separate and entrap suspended fine nanomaterials from aqueous suspensions, for their removal, recycling and recovery. This principle has been demonstrated to scale up to encapsulate and sediment engineered nanomaterials of larger aqueous sludges; complex coacervation proved to be a low-cost and environmentally friendly platform to concentrate and recover nanomaterials (Yan et al., 2025). Simultaneously, coacervation of complexes has been used to produce active packaging films, such as gelatin-tragacanth gum coacervate films containing curcumin, which had a high antioxidant activity and released in the simulated fatty food (Amani et al., 2022).

3.5. Co-extrusion

The technique of co-extrusion produces core and shell particles by using a concentric feed nozzle, which pumps core and wall materials independently via several nozzles located on the extruder's external

surface to create various forms of microcapsules. The nozzle allows the pumping of a dual fluid stream, which may be vibrating, rotating, and stationary in a moving carrier and fluid (Bamidele & Emmambux, 2021). In this process, a dual fluid stream (core and shell material) is pumped through the nozzle. Vibrations used near the outlet of the concentric tubes cause droplets to form, which eventually solidify as a result of chemical cross-linking and solvent evaporation (Madybekova et al., 2024). Recent reports affirm that nozzle vibration frequency, flow rate ratio, and polymer concentration are the most important parameters that control the uniformity of capsule diameter and encapsulation efficiency in co-extrusion systems (Rani & Kamble, 2024). Interfacial polymerization is the method of encapsulation adopted by coextrusion. This method involves the application of a water-immiscible organic solvent in order to emulsify an aqueous mixture. During the coextrusion process, the wall stuff and the core material, which are soluble in their respective miscible phases, interact at the interface with the aid of centrifugal force acting on the extruder's surface. This produces a microcapsule, which is made up of a liquid droplet encased in a polymeric membrane and can be gathered in a moving chamber. Recent studies also show that co-extruded capsules made of alginate-protein and chitosan are better at protecting the oxidative conditions of encapsulated oils and enhancing gastrointestinal survival of probiotics in co-extruded capsules, versus spray-dried formulations (Madybekova et al., 2024).

Co-extrusion technology is applied in the encapsulation of oil and probiotic bacteria since it requires less heat for encapsulation. The stability of the encapsulated oil towards oxidation is one of the significant accomplishments of co-extrusion. In contrast to the spray drying encapsulation approach, it also extends the shelf stability of the encapsulated ligands by limiting the interaction of O₂ during storage. (Madybekova et al., 2024) has reported the possibility of encapsulating almond essential oil using chitosan as the wall material and found that the cross-linker 8.0 g/L at a concentration of 1% (w/v) of chitosan was a key factor for producing stable and irreversible capsules. Co-extruded and encapsulated fish oil and probiotics in dual-core microcapsules in co-extrusion, and proved the stability of oil and high survival of probiotics on storage (Bazzaz et al., 2025). The non-uniformity of the wall material is considered a limitation of this method that results in the core materials' interfacial instability and inadequate encapsulation. The role of encapsulation of probiotics in milk protein microcapsules is depicted in Fig. 3.

3.6. Fluid bed coating

Fluid bed coating is a microencapsulation process where bioactive compounds are suspended in a stream of ascending air, and a coating material is atomized and sprayed over them to create a protective layer directly on the particles (Choudhury et al., 2021). This method offers several benefits, including low energy requirements, high process reproducibility, particle morphology control, and reduced operational time and cost, particularly when contrasted with traditional techniques such as freeze drying. This technique has been found useful for encapsulating sensitive materials such as probiotics, vitamin C, and antioxidants. Nevertheless, its biggest flaw is the protracted heat exposure, which is likely to degenerate or oxidize these chemicals, diminishing their potency (Multisona et al., 2024). The recent research shows that fluid-bed encapsulated *Lactobacillus acidophilus* have a much higher survival rate under simulated gastric and intestinal conditions than uncoated cells, thereby supporting their usefulness in providing functional foods with a live culture (Mirzamani et al., 2021). Vitamin C and polyphenols coated by fluid-bed technologies exhibited better oxidative stability and reduced the kinetics of degradation of these nutrients during accelerated storage tests, and this method proved to be suitable in terms of applications with thermally sensitive nutrients (Li et al., 2023). Recent variants of the process, like Wurster bottom-spray coating, are reported to decrease coating defects and thermal stress, which leads to the enhancement of coating homogeneity and extended antioxidant activity retention (Multisona et al., 2024). In spite of these developments, scale-up has continued to be problematic because of the thermal gradients in the interior of large-volume chambers, leading to recent studies on the use of hybrid fluid-bed systems coupled with cooling or pulsed-spray approaches.

3.7. Homogenisation

Several homogenization methods have been devised to create colloidal dispersions with particular properties and constraints depending on the use. Frequently used methods are high-shear mixing, high-pressure homogenization, microfluidization, and, more recently, membrane and microchannel homogenizers. High-shear mixers are typically applied to generate coarse emulsions with large droplets or complicated colloidal systems such as water-in-water (W/W) and oil-in-water-in-water (O/W/W) emulsions formed from phase-separated biopolymers (Zhou et al., 2021). The mixers, which are suitable for low to medium-viscosity fluids, incorporate a high-speed rotating head to

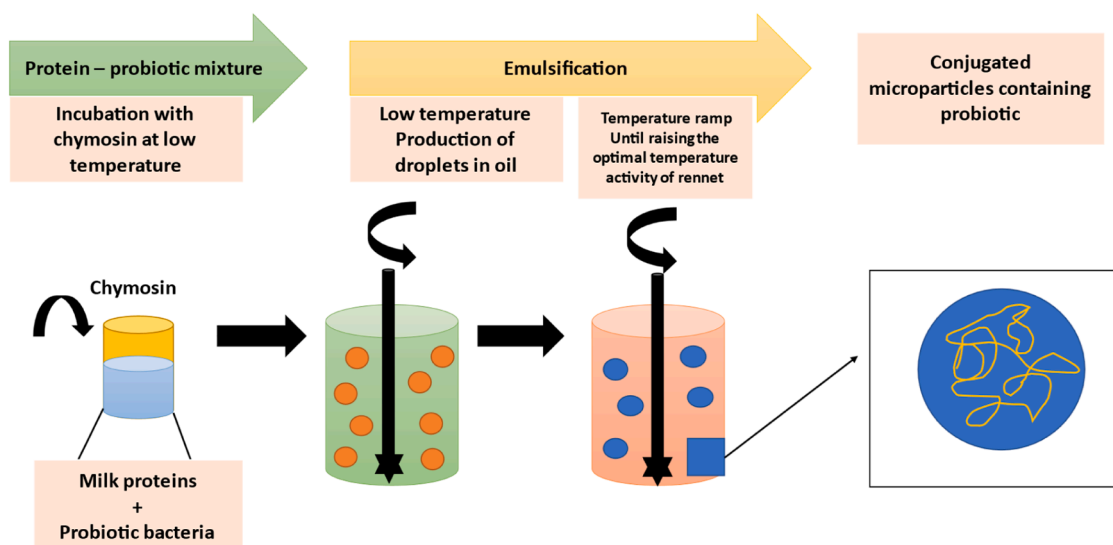


Fig. 3. Encapsulation of probiotics in milk protein microcapsules.

create strong shear forces that fragment oil into droplets suspended in water (Mardani et al., 2024).

According to recent research, the optimization of rotor-stator geometry and mixing speed profiles has a strong positive impact on the droplet size uniformity in plant-protein-stabilized emulsions, positively influencing physical stability and sensory consistency of functional beverages (Ranjan et al., 2024). High-pressure homogenization is a common technique used to produce emulsions with smaller, more consistent droplets. It does this by passing a pre-mixed oil-water mixture through a small valve, where high shear and turbulence disintegrate droplet size (Zhou et al., 2021). Microfluidization, a related process, passes the fluid through specially constructed microchannels at high pressure. It has benefits such as wide particle size control, high reproducibility, and solvent-free processing. Both high-pressure homogenization and microfluidization are used extensively in the mass production of nanoemulsions. Both techniques are energy-driven, however, and precise control over droplet size is still challenging due to the complicated flow conditions. Both technologies consume approximately 90–99% of energy for the formation of droplets (Multisona et al., 2025). Recent focus is that microfluidizers are better in making ultra-fine emulsions with enhanced kinetic stability, particularly used in encapsulation of lipophilic nutraceuticals and essential oils (Abbasi et al., 2025). To overcome these challenges, low-energy options in the form of membrane and microchannel homogenizers have been developed. These methods allow the creation of consistent, well-defined emulsions with less energy input. In membrane homogenization, the disperse phase is forced under pressure through a porous membrane into the continuous phase and creates droplets. Droplet size is affected by membrane pore size, type of emulsifier, interfacial tension, pressure applied, and flow rate (Gonçalves et al., 2023). Microchannel homogenizers work in a similar way but utilize carefully shaped channels to create uniform droplets. This technique is particularly useful for generating emulsions with narrow size distributions and predetermined internal structures, e.g., core-shell morphologies (Rummel et al., 2025).

4. Delivery systems: structure, formation, and properties

4.1. Nano emulsions

Fabrication of nanoscale dispersions of droplets of one liquid in another immiscible liquid, intense emulsification methods can be applied (Molaveisi et al., 2025). Non-equilibrium systems of structured liquids are created by advanced practical microfluidic and ultrasonic techniques for rupturing larger microscale droplets into nanoscale droplets. Despite their metastability, nanoemulsions can persist for several months or even years due to the presence of surfactant, which prevents the droplets from coalescing (Kumar et al., 2021).

A large category of multiphase colloidal dispersions includes nanoemulsions, like "micellar phases," "mesophases," and "microemulsions," some lyotropic liquid crystalline phases that are in fact significantly distinct from nanoemulsions in terms of content and nanoscale structure. Lyotropic liquid crystals are equilibrium structures made of liquids and surfactants and include lamellar sheets, hexagonally packed columns, and worm-like micellar phases (Rummel et al., 2025). Thermodynamic self-assembly causes them to come together naturally. In contrast, the creation of nanoemulsions necessitates the use of an external shear to separate larger droplets into tiny ones. The dispersion of polymers, solid particles, and droplets in a thick liquid formulates a wide variety of essential flexible materials. Most multiphase dispersions consist of two phases: a continuous phase that is a viscous liquid made of very small molecules, up to a few nanometers in size, and a dispersed phase that is a collection of larger, more numerous molecules, but not discrete, macroscopic structures made of a different material. The structures, ranging from a few nanometres to a few microns in size, have been referred to as "colloids." Because the size of the dispersed structures in most colloidal dispersions is quite small and the continuous and

dispersed phases are compactly different, heat energy can keep the colloids from sedimenting under gravity for an extended period of time (Rana et al., 2024). Moreover, dispersions have been shown to go through a number of pronounced structural changes, and at high volumes of the dispersed phase, have been observed to transform into viscoelastic materials. To improve the stability of colloidal systems such as nanoemulsions, it is essential to prevent the aggregation of dispersed particles (Xiong et al., 2025). Two critical mechanisms that contribute to this stabilization are excluded volume effects and steric interactions. Excluded volume refers to the space around each particle that cannot be occupied by others due to physical constraints. When particles approach one another, the overlap of these excluded zones leads to increased system entropy, resulting in a repulsive force that keeps the particles apart. Steric stabilization occurs when polymers or surfactants are anchored onto particle surfaces (Azani & Hassanpour, 2024). These surface-bound chains act as physical barriers; when two particles draw near, the overlapping of polymer layers restricts their movement and generates repulsive forces due to entropic and osmotic effects, effectively preventing aggregation. On the other side, aggregation and fast sedimentation may take place if the interactions between the distributed phase structures are appealing (Wu et al., 2025). Aggregation structures can be very tenuous fractal gels, which are out of equilibrium for strong attractions, or extremely tight flocs, which maintain equilibrium exchange with a gas-like phase of single scattered particles. Emulsions are mechanically produced immiscible liquid phase dispersions of one liquid phase. A detailed description of the biocompatibility of biomaterials for nanoencapsulation is shown in Fig. 4.

4.2. Formation of nanoemulsions

The various parameters are to be controlled in order to produce a stable emulsion continuously, and these include selecting the ideal mixture, controlling the order in which the components are supplied, and applying suitable shear to rupture droplets. For nanoemulsions, there are other factors that need to be taken into consideration. Ostwald ripening should be largely impenetrable in the continuous phase for the very high Laplace pressures to prevent it from happening quickly. Ostwald ripening can be prevented in several ways (Guo et al., 2024), but the simplest way is to use an extremely insoluble liquid as the dispersion phase. The second prerequisite calls for choosing ingredients, particularly surfactants, that don't produce lyotropic liquid crystalline "microemulsion" phases (Naim et al., 2022). These phases are known to occur in systems including short-chain alkanes, water, alcohols, and surfactants. The continuous phase must have a considerable surplus of surfactant, which is the third condition. This surplus makes it possible for the nanoscale droplets' rapidly expanding surface area to be layered during emulsification, preventing shear-induced coalescence. In the continuous phase, this surplus typically takes the form of surfactant micelles. These micelles break down into monomers, which quickly bind to the surfaces of freshly formed droplets. The application of some kind of severe shear to split microscale droplets into nanodroplets is the fourth prerequisite. The stress level must typically be at or above the Laplace pressure of droplets of the appropriate size, which is often between 10 and 100 atm (Tanuku et al., 2024).

4.3. Solid lipid nanoparticles

Solid lipid, one of the physical configurations of lipid, is employed to articulate nanoparticles, often known as solid lipid nanoparticles, as a supplementary transport mechanism for emulsions, liposomes, and polymeric micro- and nano-particles (SLNs). Although avoiding some of the key disadvantages of conventional systems, SLNs incorporate their benefits. Solid lipid (matrix material), emulsifier, and water are crucial SLN excipients (Fathi et al., 2024). The word lipid used here includes saturated monoacid triglycerides, partial glycerides such as glyceryl behenate, glyceryl monostearate, and glyceryl palmitostearate, steroids,

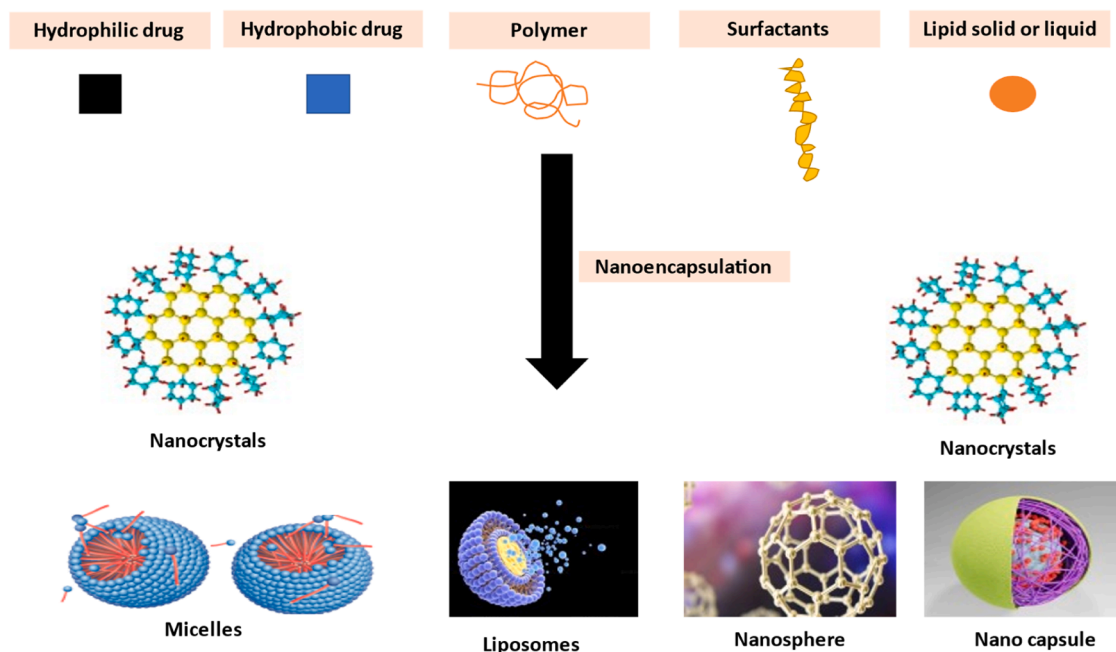


Fig. 4. Biocompatibility of biomaterials for nanoencapsulation.

fatty acids, like cholesterol, and waxes such as cetyl palmitate. The most challenging aspect of SLNs is related to their stability. Stability investigation should be the first and primary phase in the development of SLN. Emodin (EMO, 3-methyl-1,6,8-trihydroxyanthraquinone), a Chinese herbal anthraquinone derivative, can be extracted from many medicinal herbs such as Rhubarb, Aloe, and the leaf of Senna (Zhang et al., 2022). It has gained much attention in recent times because of its numerous biological activities, such as vasorelaxant, immunosuppressive, hepatoprotective, and anti-tumor properties. Particle size analysis, zeta potential measurement, drug entrapment efficiency (EE), stability, and in vitro drug release behavior have been used to examine the physico-chemical properties of the emodin-loaded solid lipid nanoparticles (E-SLNs). After being kept for four months in storage, the E-SLNs demonstrated constant particle size at 28.63.1 nm, excellent drug EE, and comparatively long-term physical stability. E-SLNs are considered as potential vehicles for oral drug administration since their sustained profile of drug release might continue for up to 72 h. Therefore, the E-SLNs have shown a promising drug delivery strategy (Das et al., 2025).

A unique nanocolloidal system for drug administration has been developed in the shape of solid lipid nanoparticles (SLNs) (Sethuraman et al., 2024). SLNs have been applied for treating cancer, infectious diseases, diabetes, ailments of the central nervous system, cardiovascular diseases, and pharmaceuticals, among other illnesses. The pharmacokinetics are enhanced, and the drug releases are modified by SLNs. Different techniques have been applied for the preparation of SLNs, including High-pressure homogenization (HPH), Ultrasonication, Solvent emulsification–evaporation, Supercritical fluid (SCF), etc. (Das et al., 2025). High shear stress and cavitation compulsion are required to produce particles in the submicron range. High pressures (100–2000 bar) of HPH force the liquid through a small opening (range of a few microns). Across a little distance, the fluid travels more quickly and with great velocity. Even high lipid concentrations might be turned into nano dispersions by the homogenization process. One of the main promising technologies for producing solid nanoparticles is supercritical fluid extraction, which operates on the mechanism that lipid nanoparticles are generated from oil-water emulsions (SCF) (Munir et al., 2024). This technology has an advantage over other processes in that it produces nanoparticles at low temperatures (35 °C) and is considered solvent-free processing, as there is no requirement for organic solvents. The

advantage of this technology is that the particles produced by this process have smooth surfaces, smaller particle sizes and distributions, and are free flowing. SLNs will be produced by the supercritical CO₂ solutions, attributed to their quick expansion. When the saturated solution is sprayed using an atomizer or nozzle, it soon expands and releases SCF, leaving behind tiny dry lipid particles (Khairnar et al., 2022). In general, for a dispersion to stay physically stable, the zeta potential must be higher than 60 mV. This fact is then achieved by lyophilization, a method that plays a promising role in enhancing the chemical and physical strength of SLN throughout time. The SLNs are divided into three types depending on the chemical structure of the lipid and active compounds, the solubility of the drug in the melted lipid, the nature and concentration of surfactants, the type of production, and production temperature (Queiroz & Muehlmann, 2024). Type I SLNs have a homogeneous matrix, Type II SLNs have a drug-enriched shell, and Type III SLNs have a drug-enriched core model (Molaveisi et al., 2025). The application of SLNs as drug carriers has been studied for a number of purposes; among them, improving oral bioavailability, encapsulating cytotoxic drugs that are lipid soluble for anticancer effects, and applying bioactive substances topically to drugs and cosmetics have received the majority of attention and research for the past 20 years. Current scientific efforts have concentrated on the regulated delivery of biopharmaceuticals, including genetic materials, peptides, and proteins. (Rai et al., 2025).

4.4. Nanoliposomes

Nanoliposomes are termed liposomes in their smallest form. A greater quantum of energy is required to formulate nanoliposomes since it gives rise to greater surface areas. Most of the applications of nanoliposomes are attributed to their mean diameter, which ranges between 50 and 150 nm. Liposomes or nanoliposomes are considered thermodynamically unstable. Using natural and economically feasible ingredients, including crude lecithin, nanoliposomes could be used for potential industrial applications (Rahim et al., 2025). It includes phosphatidylcholine (PC), a significant source of phospholipids, and is responsible for encapsulation and release of hydrophobic and hydrophilic compounds separately or in combination. The advantages of nanoliposomes include their higher bioavailability of constituents, their

solubility, and dispersibility in food systems, improving their stability in hostile environments (Madybekova et al., 2024). Nanoliposomes are considered versatile due to their application in the food and pharmaceutical industries. The lipid nanostructures are applied in the food industry primarily for improving the texture of food, flavor, and facilitating food preservation (Wang et al., 2025). Nanoliposomes have been considered as potential carriers for bioactive compounds due to their natural lipid organization and capacity to encapsulate both hydrophilic and hydrophobic substances. Instead of oil-in-water nanoemulsions, phospholipids are frequently applied in the lipid phase during various studies of nanoliposomes used in food applications (Molaveisi et al., 2025). It has been observed that no surfactants are required to stabilize the emulsions or nanoliposomes since Brownian motion is responsible for their stability. Mostly phospholipids, cholesterol, and other constituents to be encapsulated have been added to chloroform or methanol for the fabrication of nanoliposomes (John et al., 2024). Sonication and microfluidization processes are applied to get the desirable liposome size. Nanoliposomes exhibit a diverse range of applications, including tocosomes, that provide a unique and viable environment for encapsulation and nutraceutical administration. Indeed, the mRNA COVID-19 vaccine was developed using nanoliposome technology, demonstrating the viability of industrial-scale application of nanoliposomes (Bondu & Yen, 2022). The various methods of lipid thin film hydration, elimination of detergent, injection of solvent, reverse phase evaporation, emulsion, and microfluidic techniques are used in the formulation of micro and nanoliposomes. Several studies have been conducted on traditional liposomal production techniques such as solvent injection, detergent dialysis, thin-film hydration, and ultrasonication. However, these methods have a number of limitations, including uneven size distribution, high temperature requirements during liposomal formation, and the instability of the phospholipids as a result of insufficient organic phase clearance (Alavi et al., 2022). Saffron extract (SE) was more protected during its release when it was encapsulated using nanoliposomes as compared to free SE, which rapidly deteriorated under the identical circumstances in PBS solution. The pullulan films are considered impermeable to oxygen, and the incorporation of nanoliposomes further decreased their permeability to oxygen. The pullulan-based films have shown remarkable results as functional edible packaging due to their excellent oxygen barrier qualities and substantial antioxidative potential due to pullulan-loaded saffron nanoliposome (SENL). The encapsulation of the bioactive components of saffron extract in nanoliposomes and polymer matrix provides protection to them from degradation during release in the gastrointestinal system, resulting in imparting the health-promoting properties of saffron extract bioactive components. It is essential to apply an edible polymer as a covering to the films to increase their water vapor permeability (WVP) (Najafi et al., 2021). Lecithin-based nanoliposomes' vesicle size is affected by both the preparation method, such as the sonication parameters (time, amplitude), and the liposome configuration, such as the type and concentration of phospholipids. Because of the increased surface contact in the vesicle core, those liposomes showed a higher binding affinity with citrus extract (CE), a hydrophilic extract, according to isothermal titration calorimetry (ITC) studies. Hence, it can be claimed that nanoliposomes are a promising technique for nanoencapsulation of potential bioactive extracts. The commercial application of encapsulated natural preservatives using such nanoliposomes in the food industry may play a vital role in increasing the shelf-life of food products (Ben-Fadhel et al., 2022). The novel capsaicin (CAP)-loaded nanoliposomes have been developed to have better activity than CAP alone against cancer cells, including excellent stability, selectivity, and safety. As compared to CAP, CAP-loaded nanoliposomes significantly improved anticancer efficacy against human cancer cell lines and selectively caused apoptosis in cancer cell lines. The use of CAP-loaded nanoliposomes has been found to be a possible therapeutic approach for the treatment of tumors and different types of cancers. Capsaicin-loaded nanoliposomes showed the

most desirable properties, including particle size, shape, zeta potential, and stability, and this was authenticated by using the thin-film technique. Therefore, these nanoliposomes could be used for the prevention and cure of cancer (Al-Samydai et al., 2021). Chia oil and phospholipid-rich sources could be applied using the technique that involves spontaneous emulsification during lipid hydration to create stable nanoliposomes (NL) or nanoemulsions (NE), which may be useful in cosmetics, medicine, and other healthcare applications. A single sonication stage is all that is necessary for this low-cost, low-energy approach of NL and NE synthesis, which can be useful for production at an industrial scale. As per microstructural analysis, NE and NL are mostly spherical as revealed from transmission electron microscopy, with a size of around 120 nm in hydrated conditions and remained stable for five days. It can be observed that chia lipids are considered an excellent source of phospholipids and omega-3 PUFA that may be exploited to fabricate NL and NE as nanocarriers for diverse applications in the healthcare sector, such as cosmetics and pharmaceuticals (Rai et al., 2025). HOPO is a crucial part of the food processing sector because it contains unsaturated fatty acids like oleic acid (>50%), which provides numerous health benefits like reduction in total cholesterol, prevention of cardiac ailments, facilitates the production of antioxidants, enhances cell wall integrity, and aids in the repair of tissues and prevents cell damage. However, in comparison to those prepared by microfluidization (MF), the US-prepared NLs HOPO triglycerides have been shown to be less absorbed, showing higher stability and, consequently, providing improved stability of the encapsulated constituents in the gastrointestinal medium. The rate at which solubilized bioactive compounds degrade in the gastrointestinal tract and the gastric hydrolysis of HOPO have been shown to be decreased by the NL encapsulation (Kapoor et al., 2021). Laurel, *Artemisia annua*, and *Satureja khuzestanica* essential oils have been successfully encapsulated into nanoliposomes for application in pork, cherry tomatoes, and lamb meat preservation, respectively (Lopez-Polo et al., 2021). These nanoliposome-encapsulated essential oils contributed significantly to microbial inhibition and prolonged shelf-life. Furthermore, encapsulation of garlic essential oil in nanoliposomes added to chitosan-based coatings showed a more effective reduction of spoilage bacteria in vacuum-packed sausage samples than the freely added oils, attributed to increased surface-volume ratio and enhanced membrane interaction. Similar outcomes were observed with cinnamon essential oil, where nanoliposome-encapsulated forms retained higher antimicrobial stability during storage due to the protective and controlled-release nature of the lipid bilayer (Jacob et al., 2025). These real-world examples validate the significant role of nanoliposomes in improving preservation, texture, and flavor through enhanced stability and bioactivity of encapsulated compounds.

4.5. Nanophytosomes

The term "phyto" refers to the bioactive component of the phytosome compound that originates from plants. Certain phytosome complexes exhibit a structure which is the same as that of cell membranes. The compatibility of phytosome complexes with hydrophilic and lipophilic media has already been established (Jacob et al., 2025). Phospholipids and polyphenols interact suitably in non-polar solvents, which are employed in the synthesis of phytosomes. The major interaction of phytosomal structures with hydrogen bonds (H-bonds) plays a key role in the formulation of phytosomes. Phytosome preparation is a simple process that could be scaled up for its commercial application. Nanocarrier such as nanophytosomes (NP) have proven their role in the development of nutraceuticals (Kumbhar et al., 2025). Furthermore, these types of nanocarriers could be used in food designs since they are incorporated with components that are safe for consumption. The thin-layer hydration approach has been used to manufacture the NP of cumin essential oil (CEO), which demonstrated good storage stability, small size (100 nm), high encapsulation efficiency (>90%), and the

ability to overcome the instability of cumin essential oil. It has been observed that CEO—NP possesses more antioxidant potential than native cumin essential oil. The CEO has been incorporated with a controlled-release profile in the simulated digestive fluids by the encapsulation of NP. Furthermore, this mechanism could be used as a natural antioxidant in the fabrication of pharmaceutical industries and functional food.

The stability and bioavailability of phytochemicals in encapsulated form have been influenced by the particle size of nano-phytosomes. Fine particles exhibit a greater surface area, swifter rate of release, and enhanced stability. Recently, phytosomes have been added to develop plant-based formulations and drug delivery systems to form lipophilic molecular complexes that increase the bioavailability and absorption of phytochemicals (Singh et al., 2023). A well-known flavonoid quercetin, with diverse biological functions, plays a vital role in food preservation by scavenging free radicals. However, quercetin has one limiting factor that affects its antioxidant potential is its bioavailability. However, to overcome this disadvantage, phosphatidylcholine (PC) and cholesterol can be used to fabricate a nanophytosome loaded with quercetin (CH). The study revealed that the formulation has a reduced particle size (80 nm) and a greater encapsulation efficiency up to (98%) when quercetin: PC: CH was used. Moreover, the incorporation of cholesterol increased the physical stability of nano phytosomes for a period of more than three weeks. It was reported through differential scanning calorimetry (DSC) that quercetin addition to the phospholipid bilayer decreased the phase transition temperature of the bilayer in the nano phytosome structure while increasing the release and bioavailability of the components (Kumbhar et al., 2025). Garlic essential oil physicochemical composition has been reported using three distinct techniques. Dynamic light scattering (DLS), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) have been used to investigate the physicochemical composition of nanophytosomes. The physical stability, antioxidant activity, and antibacterial effects against food-borne pathogens like *Escherichia coli* and *Staphylococcus aureus* were investigated. The standard GEO nanophytosomes with a 115 nm size and a 40% loading capacity revealed promising results. The FT-IR data showed that the GEO was loaded into the nanophytosomes' structure. The antimicrobial activity of GEO nanophytosomes also increased. It was shown that GEO-nanophytosomes could effectively impart desirable physicochemical characteristics specifically in acidic food products and may be considered as a potential natural food preservative (Batarseh, 2025). The formulation of nanostructures rich in rutin opens new vistas for the fortification of foods and beverages with lipophilic herbal supplements. Rutin-loaded nanophytosomes resulted in small particle sizes, desirable encapsulation activity, and greater stability through their physicochemical characteristics. Furthermore, it is ascertained that phytosomes have better bioavailability than conventional herbal extracts due to their potential absorption capacity (improved ability to pass the lipoidal biomembrane), higher bioavailability, and ability to pass into systemic circulation (Jacob et al., 2025).

4.6. Biopolymer nanoparticles

Several techniques have been employed for the formulation of biopolymeric nanoparticles, which are biodegradable polymer-based colloidal systems with diameters ranging from 1 to 1000 nm. These methods have emerged as a practical and environmentally friendly alternative to enhance the stability, bioavailability, and biological effects of phenolic compounds (Nishimoto-Sauceda et al., 2022). Biopolymer particles are colloidal in nature and are fabricated from one or more types of biopolymeric molecules and find various types of potential applications in the food industry (Ahmad et al., 2025). According to the type of phase separation mechanism involved in particle formation, there are typically two strategies for producing biopolymer particles: associative and segregative. The primary driving force for phase separation in associative processes is a relatively high attraction

between different types of biopolymers, whereas, in segregative processes, the primary driving force is a relatively strong repulsion between various types of biopolymers in solution (Kumbhar et al., 2025). Furthermore, nanoparticles have been formulated using various techniques. Furthermore, many conventional protocols could not be executed practically because they require a lot of energy, time, and materials and involve numerous phases. Biopolymer nanoparticles are best produced practically using microemulsion droplets. Furthermore, it can be in either amorphous or crystalline forms, depending on its nature and method of fabrication and can be nanospheres (homogeneous spheres) or nanocapsules. The four methods, including microemulsification, solidification, isolation, and drying, may be applied to condense the whole process of producing biopolymer nanoparticles in nanoreactors (De Angelis et al., 2024). Depending on the method of formulation, these biopolymer nanoparticles comprise variable sizes and charges, influencing their capacity for the encapsulation of drugs and targeted delivery (Stevanović & Filipović, 2024). It has been clearly indicated that nanoparticles produced by utilizing biodegradable and/or biocompatible building blocks as key constituents for use in therapeutic and clinical assessment plans. Biopolymer nanoparticles exhibit significant potential as a tool for cancer therapy and diagnosis due to their tumor-inhibiting potential specifically (Kumbhar et al., 2025). Anti-solvent precipitation has been used for the preparation of zein alginate core/shell nanoparticles, and electrostatic deposition has been used to produce an alginate shell. Due to their high electrostatic and steric interaction with each other, these composite biopolymer nanoparticles have proven to be stable over a wider pH range (3–8). The nanoparticles showed excellent resistance to strong ions at pH 4, although their resistance, however, increased after being maintained at 90 °C. The nanoparticles were resilient to heating (90 °C for 120 min) at pH 7. However, nanoparticles at ambient and refrigeration temperatures showed excellent storage stabilities. The resulting biopolymeric nanoparticles could be applied to encapsulate and release bioactive compounds in food and pharmaceutical formulations in a controlled manner (Ahmad et al., 2025). Curcumin can be loaded in self-assembled nanoparticles of GRAS status lipid and biopolymer, as revealed from different studies, and their preparation does not require advanced expertise in nanoformulation or energy expenditure. It can be revealed that nano-encapsulation of nutraceutical ingredients has given rise to new technological innovations for the food industry to solve numerous problems, including ingredient stability, bioavailability, and solubility (Kapoor et al., 2021). In recent years, many researchers have demonstrated the practical use of biopolymer nanoparticles encapsulating essential oils (EOs) to enhance functional performance in food systems. For example, chitosan nanoparticles loaded with clove essential oil were used to extend the shelf life of pomegranate arils during cold storage, while maintaining their microbial safety and sensory quality (Ahmad et al., 2025). Similarly, nanoparticles formulated with alginate and cashew gum successfully encapsulated *Lippia sidoides* EO, achieving high encapsulation efficiency and controlled release. In another study, zein nanoparticles incorporating thymol and stabilized with chitosan hydrochloride and sodium caseinate exhibited antibacterial activity, particularly against Gram-positive bacteria. These practical examples emphasize the functional versatility of biopolymeric nanoparticles in delivering bioactive compounds and improving the safety and quality of food products (Kumbhar et al., 2025).

5. Designing particle properties for enhanced functionality

5.1. Nanoparticle characteristics

The biological distribution and suitability of a delivery method depend on physical characteristics like the nanoparticle size. In addition to nanoparticle size, undesirable constituents released during their distribution and disintegration also affect the toxicity of delivery systems (Havelikar et al., 2024). Therefore, biodegradability is highly

significant. Better biocompatibility and regulated response are produced by multifunctional transition optimization of nanoparticle delivery systems, and such innovative designs will hasten in vivo applications (Zhang et al., 2024). As a nano carrier system for several medications, solid lipid nanoparticles (SLNs) are widely employed. Further, lipid-based particles ranging in size from 50 to 1000 nm are stable at ambient temperatures. Lipid acids, mono-, di-, or triglycerides, glyceride mixes, or waxes stabilized with biocompatible surfactants are some of the lipids used in the production of SLNs (Lüdtke et al., 2025). The SLNs have potential benefits over conventional drug delivery systems, including physical stability, controlled release, protection against heat-labile degradation, and ease of manufacture. Large-scale production of SLNs is viable and cost-effective. The most suitable example of resveratrol delivery methods is an endurance drink for sports nutrition. It has been reported that resveratrol-loaded solid lipid nanoparticles play a key role in enhancing antioxidant properties (Khishvand et al., 2024). Whey protein nanoparticles serve as a vehicle for the encapsulation, transit, and gradual gastrointestinal release of polyphenolic compounds like curcumin due to their stability at pH 7. For spherically shaped particles, the role of size has been profoundly examined, and certain broad trends have been identified (Liu et al., 2025). The liver, spleen, and bone marrow are the primary sites of aggregation for particles that vary in size from the nanometer range to around 15 μ m (Zhang et al., 2024). Extravasation or renal clearance swiftly removes particles smaller than 5 nm from the bloodstream. The biological distribution of nanoparticles in the size range of 10 nm to 15 μ m typically varies, and cellular absorption of these particles is highly dependent on the type of cell. The methodology behind the synthetic nanoparticle formulation faces significant hurdles in achieving customized, activated, controlled release. The most common approaches currently include bioactive compounds which are enzymatically degradable, pH-sensitive, or reductively labile, allowing for the bond breaking of the drug and carrier or the destabilization of the carrier upon arrival at the target site of action (Zhao et al., 2025a). Several types of nanoparticles placed in a bulk hydrogel framework have led to the fabrication of a wide range of nanoparticle-hydrogel composites. There are five major ways to obtain a uniform distribution, including gelation, the nanoparticles are physically embedded into a hydrogel matrix, reactive nanoparticle production inside a preformed gel, cross-linking with nanoparticles to create hydrogels, and gel formation with nanoparticles, polymers, and unique gelator molecules (Zhang et al., 2024).

5.2. Physicochemical and functional attributes

Food proteins' complex structures are controlled by a variety of factors, such as electrostatic interaction, hydrophobic activities, disulfide bond interaction, etc., resulting in a profound influence on their operation (Zhao et al., 2025b). Several studies have shown that the deviation in the pH may significantly affect the functional properties of dietary proteins, including their capacity to emulsify, form solids, be soluble in liquids, and absorb water and oil. It has been investigated that the variation in pH has a considerable influence on the functional and physicochemical properties of protein isolates (Tang et al., 2021). Furthermore, food and non-food applications and their biodegradable nature, plant-derived proteins have gained profound interest in recent years. Also, by adopting specific extraction and processing techniques, plant-based protein isolates, flours, and concentrates could be used for their sensory and functional properties (De Angelis et al., 2024). These plant-based proteins are employed as stabilizers, emulsifiers, structural agents, and food texture modifiers for creating vegan and vegetarian dishes, according to the property profile. By physical, thermal, fermentation, and enzymatic techniques, these proteins' technological-functional and sensory characteristics may be changed (Kumar et al., 2021). Among other essential functional characteristics like viscosity, color, appearance, turbidity, etc., the sedimentation feature of plant milk is regarded as an essential functional characteristic

that exposes the overall sensory acceptance of non-dairy plant milk on the market. New physical approaches, including ultrasonography, high-pressure homogenizers, and ultra-high-pressure homogenizers, are used to address the instability issue. As sonicated samples have a high proportion of sedimentation, their particle stability will rise as a result. Hence, ultrasonography can be considered a useful method for reducing sedimentation (Vallath & Shanmugam, 2022).

6. Food applications of plant-based delivery systems

6.1. Vitamins

They are classified as a class of micronutrients that the human body is unable to manufacture. Vitamins are chemically reactive substances that play important roles in human existence by regulating metabolic and cellular processes, enhancing well-being, promoting reproduction and development, and lowering the risk of disease (Alam et al., 2025). Serious illnesses, including scurvy, beriberi, and night blindness, can be brought on by their scarcity. Nevertheless, during food processing and storage, chemical and physical elements like light, temperature, pH, and oxygen levels have an impact on the stability of the food, which causes considerable nutritional losses in the finished goods, such as canned goods. The food industry is looking for methods to safeguard vitamins throughout manufacturing and storage in order to stop these losses. A contemporary technique called microencapsulation embeds biologically active materials (vitamins, enzymes, phenols, polymers, and organisms) in a specific covering to shield them from the environment (De Angelis et al., 2024). The waste materials can be used to make organic antioxidants. Press cake was found to include procyanidins, chlorogenic acid, phloridzin, and vitamin C compounds, which might be exploited to produce lipid oxidation inhibitors and agents with an antibacterial effect as medications and food additives. It was discovered that a dual-channel microfluidizer may be used to create plant-based, vitamin E-fortified nanoemulsions. As a result, when the amount of vitamin E in the oil phase grew, so did its bioaccessibility. Once the nanoemulsions were kept at frigid temperatures for a period of 12 weeks, vitamin bioaccessibility did not decline, suggesting that this kind of delivery mechanism would be an effective way to give vitamin E. The emulsions so produced suggest that natural component emulsions are useful for many culinary and nutraceutical applications (Molaveisi et al., 2025). The primary micronutrients present in milk from cows, such as calcium and vitamin D, are lacking in a variety of plant-based milks. The effect of different calcium amounts and forms (CaCO_3 vs. CaCl_2) on the physicochemical properties, lipid digestibility, and vitamin D bioaccessibility was examined in the almond milk supplemented with these two micronutrients, which did so by reducing electrostatic repulsion; particle aggregation was not induced. High calcium (soluble or insoluble) levels reduced vitamin D's bioaccessibility because they caused the formation of insoluble calcium soap in the small intestine. The creation of nutritionally enhanced plant-based milk with enhanced physicochemical and nutritional qualities can benefit from these findings (Zhou et al., 2021). To encapsulate vitamin D3, a phase inversion-based nanoemulsion production technology was created. The stability investigations showed that the phase inversion-based encapsulation technology may be utilized to create a rather stable nano delivery system for encapsulating, protecting, and guaranteeing high bioavailability of vitamin D. On the basis of several sensory features, the appropriateness of the encapsulated vitamin D for the purpose of fortifying buttermilk was assessed, and it was proposed that the created nano emulsion may be employed for the effective administration of vitamin D through milk-based drinks (Batarseh, 2025). Table 1 lists some of the naturally derived polymers utilized in the agri-food industry.

6.2. Omega-3 oils

Docosahexaenoic acid (DHA), which has a variety of health

advantages, including boosting nervous system, heart, and brain functioning as well as preventing cardiovascular disease, immunological disorders, and inflammation, is a viable replacement for fish oil in microalgae oil (Kapoor et al., 2021). Algal oil is said to be more environmentally friendly and sustainable than fish oil since it contains three to ten times as much DHA. Omega-3 fatty acids may be added to vegetarian and vegan diets by creating plant-based delivery methods (Sun et al., 2022). Foods can be supplemented with omega-3 rich oils to increase the consumption of omega-3 fatty acids. Omega-3 oils may be used in a stable, manageable form by being microencapsulated, which slows down oxidative breakdown. There are several methods for microencapsulating omega-3 fatty acids, with complicated coacervation and spray-dried emulsions being the two most used in the commercial world (Szpicier et al., 2025). Further techniques, including spray freezing, extrusion coating, and liposome entrapment, are being developed. The choice of wall material is the most important factor in all of these procedures (Buniowska-Olejnik et al., 2024). Vegetable sources, such as vegetable oils, can provide omega-3 PUFAs (Alpha-Linolenic Acid). Linseed oil, sometimes referred to as flaxseed oil, is a strong source of omega-3 s from vegetables since it contains >50% ALA (Jacob et al., 2025). The oil from flaxseed (a plant-based source of omega-3 fatty acids). integrated into four delivery systems: hydrogel beads (HB), caseinate-containing hydrogel beads (HB+C), nanoemulsions (NE+C), and nanoemulsions plus caseinate (NE+C). Inside the simulated small intestine, the flaxseed oil in the nanoemulsions (NE and NE+C) hydrolyzed fast, with approximately 76% and 65% of the free fatty acids (FFAs) being released in the first 5 min, respectively. Contrarily, only around 37% and 22% of the flaxseed oil in the hydrogel beads (HB and HB+C) was released during the same time period due to the slow digestion of the oil. Designing delivery strategies to protect omega-3 fatty acids from oxidation in functional meals while enabling their release in the GIT may benefit from this understanding. This kind of delivery method might be utilized to regulate the release rate of hydrophobic bioactive substances, maintain blood triglyceride levels, or cause satiety (Yan et al., 2025). A new and exclusive nutritional oil known as "Ahiflower oil" is cultivated in colder temperate zones or at higher altitudes in temperate regions in either hemisphere. Although mechanical irrigation is not necessary, it enjoys wet, well-drained soils that are neutral to slightly alkaline. In essence, it is a better dietary oil for those seeking more effective omega-3 plant nutrition. It also provides valuable anti-inflammatory GLA that is not present in fish or algal oils. The naturally occurring omega-6 linolenic acid (LA) and omega-6 gamma linolenic acid (GLA) in sunflower oil combine to provide a 15–18% total omega-6 content. The total omega-3–6–9 content of sunflower oil is above 90%, making it the new standard for plant-derived, omega-rich oils that are supported by human clinical studies (Jacob et al., 2025). Omega-3 fatty acids' poor chemical stability, limited bioavailability, and low water solubility are some of the difficulties associated with putting them into functional foods and beverages. Again, colloidal delivery techniques can be used to circumvent these difficulties (Tan & McClements, 2021).

6.3. Nutraceuticals

Plant polyphenols have drawn a lot of interest because of their role in the prevention of several illnesses, including cancer, diabetes, and high cholesterol. Plant polyphenols have been created as the primary active ingredients in a number of functional foods. The employment of biomolecule-based nanoparticles as polyphenol chemical delivery vehicles in dietary meals is advantageous due to their abundance, biocompatibility, and other features (Zhang et al., 2022). Many functional food items, including drinks, bread, dairy products, sauces, dressings, frozen dinners, and meat products, can be made with curcumin (Buniowska-Olejnik et al., 2024). Each food has unique physical and chemical characteristics, such as color, flavor, texture, and shelf life, which should fit within a defined range for a particular food product. For

instance, it would be advantageous to have a delivery method that was in a fluid or powder form that could be easily diffused within the product if curcumin were to be added to a nutritious beverage (Gonçalves et al., 2023). It is essential to find the rheological qualities of the delivery system since they will influence how it is handled and processed, and how the finished product feels. It's crucial for a nutritional beverage that the distribution method does not add at the expense of the product being either too runny or too thick. For instance, curcumin-enriched powders can be added to drinks, dressings, sauces, and baked products. In simulated gastrointestinal circumstances, it was shown that beta-carotene enclosed in biopolymer nanoparticles made from conjugated beta-lactoglobulin and dextran showed better stability of nanoparticles. In a pharmaceutical trial, encapsulating a hydrophobic medication (doxorubicin) in nanoparticles made of chitosan coupled with carbohydrates and fatty acids increased the drug's distribution. The chemical deterioration of encapsulated carotene may be successfully avoided because of the ternary conjugates' potent emulsifier properties. Hence, these ternary complexes may be useful for preventing the chemical lability of nutraceuticals in functional meals and drinks (Baydin et al., 2022). Cannabinoids (such as THC and CBD) found in commercial edible items have recently been encapsulated, and their release is controlled using food-grade nanoemulsions (Assadpour et al., 2023). They have also been utilized to encapsulate nutraceuticals and increase their bioavailability in commercially available functional meals and supplements. Pre-emulsified chewable gels made of gelatin provide benefits over conventional tablets, bulk oils, and hard and soft capsules for oral administration (Baydin et al., 2022). The desire for plant-based gelling ingredients that may be articulated into digestible emulsion gels has increased due to ethical, ecological, and religious issues. According to textural assessments, pectin emulsion gel had a softer texture than gelatin emulsion gel, but agar emulsion gel had a firmer and more brittle texture. The polysaccharide emulsion gels' industrial potential and problems showed that plant-based pre-emulsified chewable gels might be made for the oral administration of nutraceuticals (Baydin et al., 2022). The meat business may employ a variety of components, such as roots, berries/fruits, leaves, seeds, or agro-food by-products, as natural and potentially effective additions. These bioactive substances can be utilized in meats as powders, water-soluble extracts (such as oleo-resins and essential oils), and water-insoluble extracts. As a result, phytochemical-based preservatives have drawn a lot of interest in the meat business since customers consider them to be safe, and they are GRAS (Generally Recognized as Safe). The sensory qualities of meat products should not be adversely affected by these natural extracts, and they should be effective at low concentrations, accessible, and stable throughout the production process for industrial uses (Domínguez et al., 2021).

6.4. Antimicrobials and antioxidants

The likelihood of numerous degenerative illnesses may be decreased by adding plant derivatives with antioxidant components, such as vitamins A, C, and E, minerals, polyphenols, flavonoids, and terpenoids, to meat products. The meat industry is undergoing significant changes to meet consumer preferences by using non-meat ingredients, which are primarily derived from plant sources to improve the nutritional quality and shelf stability of meat products (Li et al., 2025). Using plant-based antimicrobials to guard against microbial deterioration improves food quality, safety, and shelf life. Meat with thyme and oregano oil nano emulsions added significantly reduces the growth of *S. aureus* and *E. coli*, extending the product's shelf life (Hussain et al., 2025). In a simulated meat environment, *E. coli* K12, *Listeria innocua*, and *Pseudomonas lundensis* growth were found to be suppressed by geraniol and linalool-loaded nanoemulsions. As well as chitosan, *Zataria Boiss* (ZEO) and *Bunium persicum Boiss* (BEO) essential oil nanoemulsions have been shown to prevent microbial development in refrigerated turkey breast fillets (Keykhosravi et al., 2022). Casein-stabilized thymol oil

nanoemulsions are effective antibacterial agents in dairy products against *Bacillus cereus* and improve the bactericidal activity of carvacrol (Li et al., 2025). Moreover, mandarin oil nanoemulsion-based edible coatings on chitosan showed antibacterial efficacy against *L. innocua* in green beans. Similarly to this, thymol nanoemulsions stopped *B. cinerea* mold from growing on chilled tomatoes (McClements et al., 2021). Although nanoencapsulation is one of the potential methods for delivering essential oils (EOs) to food, the toxicological properties of various nanocarriers and their molecular targets have not been well studied. Thus, before their commercial implementation, it is necessary to explore the physicochemical connections of nanoencapsulated EOs with the food system and their toxicological effects. Nowadays, a range of nanotechnology-based products are being employed in several food sectors, including food processing, quality control, dietary supplements, antimicrobials, and smart packaging systems (Mohapatra, 2025). The creation of programmable food, a futuristic idea offering customers food of chosen color, flavor, and nutrition, can play a significant part in the usage of nanotechnology due to promising findings and applications. Thus, in the near future, nanotechnology may provide creative and profitable development pathways for food safety (Molaveisi et al., 2025). The hunt for natural food preservatives is becoming more and more popular in the meat sector. Plants high in polyphenols that are utilized as natural food preservatives offer the finest replacement for their synthetic equivalents, whether it be a partial or whole replacement. The by-product made from chestnuts has a high content of phenols and hydrolyzable tannins. It has been noted that the chestnut inner shell extracts (CISE) have an antibacterial impact on meat products (Rodrigues et al., 2023). Also, it was discovered that adding Amla extracts to a raw chicken flesh batter can stop lipid oxidation without affecting the batter's sensory qualities (Beya et al., 2021). With the potential to generate active packaging that extends the shelf life of food items, EOs can be employed as a vigorous and efficient constituent for biodegradable food packaging. In order to add a natural preservative to the chilled pork packaging, Jacob et al. (2025) added cinnamon-loaded chitosan nanoparticles (NPs) to the active wrapping low-density polyethylene films. These NPs improved the antibacterial and antioxidant properties of pork. Another essential oil used to flavor flounder fillets was clove oil, which was contained in an agar-based film.

7. Future prospects

The rapid development of plant-based nano-delivery systems has demonstrated strong potential for enhancing the stability, bioavailability, and controlled release of food bioactives and nutraceuticals. However, despite promising laboratory-scale achievements, several scientific and translational challenges remain unresolved, presenting important directions for future research. One of the most critical research gaps is the limited understanding of nano-matrix interactions in real food systems. Most studies are conducted under model conditions, whereas complex food matrices can significantly alter nanoparticle behavior, release kinetics, and sensory attributes. Greater emphasis is needed on evaluating nanoencapsulation systems under commercial processing conditions, such as thermal treatment, freezing, dehydration, and storage, to improve industrial relevance. Safety evaluation and regulatory validation represent major challenges in advancing plant-based nanocarriers toward commercialization. Although many carrier materials are classified as GRAS when used in bulk form, their nano-scale behavior may differ in terms of absorption, bio-distribution, and metabolic fate. Long-term toxicity, accumulation potential, and interactions with the gut microbiota are not yet fully understood. Comprehensive in vivo and chronic exposure studies are therefore essential to establish regulatory frameworks and consumer confidence. Another major limitation is the lack of standardized characterization protocols for assessing nanoparticle size, stability, release behavior, and bioaccessibility. The absence of harmonized testing methods complicates comparison across studies and delays regulatory

approval. Future research should focus on developing validated analytical methodologies that reflect real consumption conditions. From a commercialization standpoint, scalability and manufacturing consistency remain key barriers. Many promising encapsulation methods rely on energy-intensive processing or complex fabrication processes that are difficult to scale economically. In addition, maintaining batch-to-batch uniformity, shelf-life stability, and cost effectiveness are ongoing challenges. Research into low-energy, solvent-free, and continuous production technologies is therefore essential. Finally, future innovation is expected to focus on hybrid nanocarriers, stimuli-responsive delivery systems, and AI-assisted formulation design. These approaches offer opportunities to tailor delivery behavior based on food matrix conditions, digestive environment, and targeted release profiles. Overall, future research should shift from laboratory optimization to industrial translation, safety validation, and regulatory acceptance. Addressing these gaps will be essential for transforming plant-based nano-delivery systems from emerging laboratory technologies into commercially viable, consumer-trusted solutions for functional foods and nutraceuticals.

8. Conclusion

Plant-based nano delivery systems have demonstrated significant potential for enhancing the delivery of bioactive compounds, functional ingredients, and nutraceuticals in the food industry. Natural polymers such as cellulose, chitosan, and plant-derived lipids serve as excellent biocompatible, biodegradable, and non-toxic carriers. Lipid-based and polysaccharide-based nanoparticles have been employed to encapsulate sensitive components like vitamins, omega-3 fatty acids, and antioxidants, improving their bioavailability, stability, and controlled release. Techniques such as complex coacervation, spray drying, and freeze drying have been successfully utilized to design these delivery systems for functional foods. Continued research and innovation in plant-based nano delivery systems can contribute to the development of safer, more efficient, and sustainable strategies for fortifying foods, extending shelf life, and improving overall human health.

Ethics approval consent

Not applicable.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

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CRediT authorship contribution statement

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Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Irtiqa Shabir:** Writing – review & editing, Visualization, Validation, Software, Resources, Methodology. **Shivangi Srivastava:** Writing – review & editing, Visualization, Validation, Software, Resources, Methodology. **Vinay Kumar Pandey:** Writing – review & editing, Visualization, Validation, Software, Resources, Formal analysis. **Rafeeya Shams:** Writing – review & editing, Visualization, Software, Resources, Methodology, Formal analysis. **Vikanksha:** Writing – review & editing, Visualization, Software, Resources, Methodology, Formal analysis. **Bhawana Jha:** Writing – review & editing, Visualization, Software, Resources, Methodology, Data curation. **Parmjit S. Panesar:** Writing – review & editing, Visualization, Software, Resources, Formal analysis, Data curation. **Ufaq Fayaz:** Writing – review & editing, Visualization, Software, Resources. **Ayaz Mukarram Shaikh:** Writing – review & editing, Validation, Software, Resources, Methodology, Data curation. **Kovács Béla:** Writing – review & editing, Visualization, Validation, Software, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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