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MICROENCAPSULATION TECHNIQUES: A COMPREHENSIVE REVIEW

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Abstract: Microencapsulation technology consists of wrapping protective layers around bioactive compounds in the form of microcapsules varying in size ranges between 1-1000 µm. This approach encapsulates heat-sensitive ingredients, shielding them from temperature shifts, pH changes, and light, ensuring their controlled release for a variety of pharmaceutical and food uses. This technology can enhance the bioavailability, stability, and organoleptic characteristics of functional compounds such as flavonoids, carotenoids, vitamins and lipophilic nutrients (e.g., PUFA from fish oil). This review focuses on a complex review of microencapsulation technologies, including coacervation, spray drying, emulsification, fluid bed coating, freeze-drying, complex coacervation and solvent evaporation extrusion-based encapsulation and electrospinning-based encapsulation. All methods differed in the particle size, hydrophobicity and solubility, as well as the porosity of the microcapsules. Selecting a suitable technique depends on the properties of core materials and wall materials. Furthermore, the paper explains the influence of encapsulation methods on product functionality, flavor masking, and the enhancement of physical and thermal properties, emphasizing their significance in the evolving food industry.

Key words: *microencapsulation, ionic gelation, bioactive compounds, controlled release, encapsulation efficiency*

INTRODUCTION

Microencapsulation is one of the emerging technologies that define a physical process where thin films are coated on small solid particles that help in the protection of different bioactive compounds and functional constituents from various environmental and process conditions. It involves enclosing liquid, or gas particles within a secondary material, forming microcapsules. The core, containing the active component, is packaged within an encapsulant or shell as shown in Fig. 1. Microcapsules typically range from 1 to 1000 µm in diameter, which is crucial for targeted delivery. This technology extends edible coatings, adapting film-forming agents to microscopic particles. This process enhances controlled-release applications across various industries (Augustin, Sanguansri, Margetts & Young, 2001). They

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also enhance the sensory attributes of the product by masking the unpleasant flavors and aromas. Bioactive components like flavonoids, carotenoids, phytoestrogens, polyphenols, lycopene, alkaloids, and vitamins are being used to develop a desirable product. These bioactive compounds are unstable under particular temperatures, pH, and light. As a result, microencapsulation of these compounds helps in protecting them from these conditions during food processing (Rokkam & Vadaga, 2024). Encapsulating lipophilic vitamins and lipidic nutrients, such as fish oil, addresses challenges in product formulation. The process shields the active compounds from oxidation, preserving their efficacy. Additionally, converting fats into a free-flowing powder helps mask undesirable flavors. Various food components, including flavorings, antioxidants, colorants, sweeteners, acids, bases, leavening agents, and preservatives, benefit from microencapsulation. This technique proves effective in neutralizing disagreeable odors and flavors, enhancing the overall quality of diverse food products (Abd & Abu, 2020).

Coating materials used in this process include gum Arabic, starch, and corn syrup; cellulose such as methylcellulose, cellulose acetate phthalate, and carboxymethylcellulose; lipids such as beeswax, oil, paraffin, fats, and monoglycerides. There are many techniques for microencapsulation including coacervation, spray drying, emulsification, fluid bed coating, and freeze-drying. Depending upon the core material and the composition of the wall material, a method of microencapsulation is selected. According to the selected microencapsulation method, the properties of the capsules such as hydrophobicity, porosity, solubility and particle size vary. The release of the core material is influenced by the nature of the core component, the nature of wall materials, and the ratio of core and wall material being used.

This review analyzes the concepts associated with the different techniques of microencapsulation that are suitable according to the nature of the materials used. Furthermore, it discusses the enhancement of physical, thermal, and functional properties. Microencapsulation techniques have undergone a significant evolution from their initial stages to the current trend in the food sector. Initially, microencapsulation primarily involved simple methods such as coacervation and spray drying, which aimed to encapsulate active ingredients or flavors within a protective shell to enhance stability and controlled release. However, with advancements in technology and materials science, novel techniques have emerged, offering improved efficiency and versatility. These include complex coacervation, solvent evaporation, extrusion, and electrostatic spinning, among others.

Complex coacervation involves the formation of polyelectrolyte complexes to encapsulate bioactive compounds, providing enhanced encapsulation efficiency and controlled release. Solvent evaporation techniques utilize organic solvents to dissolve the core material and encapsulating polymer, followed by solvent removal to obtain microcapsules.

Extrusion methods involve the formation of emulsions or suspensions, which are then extruded through a nozzle to produce microcapsules. Electrostatic spinning utilizes an electric field to draw polymer solutions or melts into fibers, which solidify into microcapsules upon solvent evaporation.

These advanced techniques provide precise control over microcapsule attributes, including size, structure, and release kinetics, while fulfilling the food industry's diverse demands for flavor masking, nutrient fortification, and controlled delivery of bioactive compounds. Despite its numerous advantages, microencapsulation presents certain limitations. Some techniques involve high processing temperatures or the use of organic solvents, which may degrade heat-sensitive bioactive compounds.

Additionally, scale-up for industrial applications often faces technical challenges, including maintaining uniformity and stability. Moreover, the cost of specialized materials and equipment increases the overall production expense. In some cases, incompatibility between core and wall materials can result in premature leakage or incomplete release of the active ingredient. Growing demand for functional foods is set to propel ongoing advances in microencapsulation technologies across the food industry, underpinned by continued research and development aimed at optimizing product performance and improving consumer satisfaction.

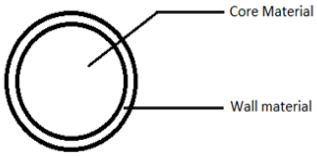

Figure 1. Schematic presentation of the microcapsule with core material and wall material

PROPERTIES OF WALL MATERIALS

An effective wall material for microencapsulation should be tasteless, film-forming, and exhibit low viscosity for efficient processing. It must be non-hygroscopic to ensure moisture stability and water-soluble for controlled release in aqueous systems. Chemical inertness is essential to prevent core interaction, while high stabilizing efficiency is required to protect sensitive bioactives from external factors such as oxidation, heat, and light.

MICROENCAPSULATION METHODS

Fig. 2 illustrates various microencapsulation techniques, including physical (spray drying, freeze drying), physicochemical (coacervation, ionic gelation), and chemical methods (solvent evaporation, co-crystallization). Method selection depends on core material properties, encapsulation efficiency, particle size control, and release kinetics.

Coacervation

Coacervation involves the formation of a coacervate phase, which is a dense liquid phase formed by the association of more polymers or colloids in a solvent (Timilsena, Akanbi, Khalid, Adhikari & Barrow, 2019). This process involves five steps: 1) distribution of active components such as o/w (oil-in-water) droplets in an aqueous solution (hydrocolloids); 2) phase separation of hydrocolloids undergo when pH is lowered below the gelatin's isoelectric point (pH 4.5), causing them to aggregate and form a separate phase; 3) deposition of coacervate particles around the dispersed droplets containing the active component; 4) hardening or forming of microcapsule walls as the suspension is cooled below the gelatin's gelation temperature; 5) chemical cross-linking of the coacervate of the microcapsule walls. This step likely includes the development of chemical bonds between polymer chains to stabilize the microcapsules. It ends with the washing of microcapsules to remove any excess material and possibly drying them to obtain the final product (Ach et al., 2015). This method is applied in the controlled release of pharmaceuticals, improving the bioavailability and stability of active ingredients in food, and providing sustained release of fragrances and active compounds in cosmetics. Various core and wall materials with their respective ratios used in the coacervation method are shown in Table 1.

Spray drying

Spray drying is a process extensively employyyed across various industries, notably in food, pharmaceuticals, and chemicals. In this method, a liquid feed, often an emulsion or suspension, is atomized into fine droplets using a nozzle or rotary atomizer. These droplets are then introduced into a stream of hot air within a drying chamber. The solvent undergoes quick vaporization which results in the formation of microcapsules as shown in Fig. 3. The particle size and morphology can be controlled by adjusting parameters such as feed composition, atomization conditions, and drying temperature. Spray drying offers numerous advantages, including high efficiency, scalability, and the ability to encapsulate heat-sensitive substances while preserving their properties. Spray drying stands out as the most cost-effective encapsulation method due to its continuous, uncomplicated, and rapid nature. It involves atomizing liquid slurry, which quickly forms a glassy polysaccharide or protein matrix upon contact with hot air, effectively trapping the encapsulated compounds. The choice of wall materials impacts the resulting powder's morphology, yield, and the retention of antioxidant activities in the core material. Despite the high drying temperature, the short drying time ensures minimal impact on product quality. This technique is extensively utilized for encapsulating bioactive components such as phenolic compounds found in pomegranate peel, grape pomace, olive leaf, and blackberry pomace, yielding stable, free-flowing products (Tzatsi & Goula, 2021). The standard spray dryer equipment comprises several essential components: a spray drying system, a heating and temperature control system for drying air, a material input system, an air input system, a drying chamber, and an air-powder separation system.

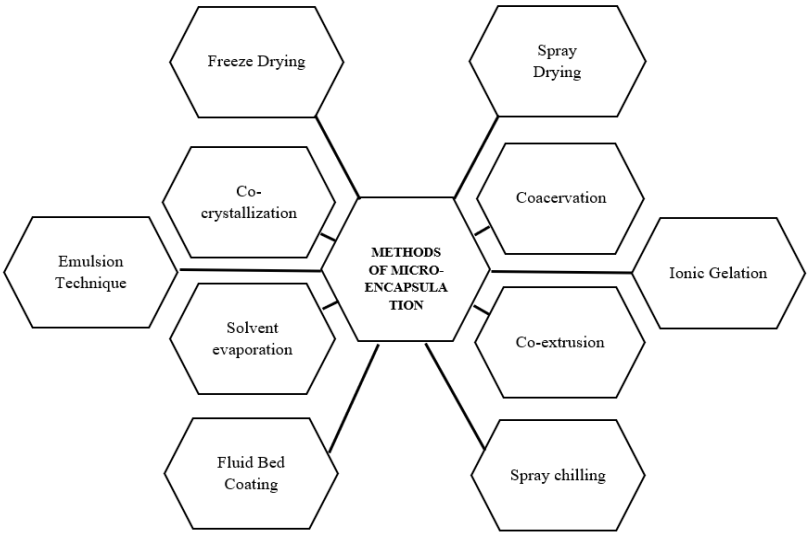

Figure 2. Methods of microencapsulation

Table 1.
Different core materials and wall materials used in the coacervation method

Core material	Wall material	Ratio	Inference	Reference
Angelica sinensis essential oil	Gelatin and chitosan (1.50:1)	10.38:1	Encapsulation efficiency of 82.68 % Rapid release of core material in 120 min under gastrointestinal pH.	He et al., 2025
Turmeric extract	Gelatin and carrageenan	2:1	Encapsulation efficiency of 92.2% Release during gastrointestinal phase of 32.97% after first 30 mins and reach 39.65% after 2 hrs and 48.01% at the end	Bettou, Gali & Oukil, 2025
Citrus limon essential oil	Gelatin and carrageenan	8:3	Encapsulation yield 93 % Release of microcapsules at first 25 mins in gastrointestinal conditions	Dijhad et al., 2024
Juniper berry essential oil and black peppercorn essential oil dissolved in soybean oil or rapeseed oil	Faba bean protein and chia seed polysaccharides	Protein: polysaccharide ratios of 1:1, 1:2, or 2:1	Essential oils were developed using various ratios (1:1, 1:2, or 2:1) and efficiency ranged from 65.64% to 87.85% 1:2 shows higher efficiency and thermal stability.	Napiórkowska, Szpicer, Górska-Horczyczak & Kurek, 2024
Curcumin	Lactoferrin and carboxymethyl Tara gum	4:1	Curcumin microcapsules in gelatin films show 74.78% encapsulation efficiency, 81% intestinal release, and 67% bioaccessibility.	Da Silva Soares, Constantino & Garcia-Rojas, 2024
Ascorbic acid	Bovine gelatin type B and citrus pectin	1:0.5	Ascorbic acid is released faster in gastric fluid than in intestinal fluid. Ascorbic acid releases 68% content of microcapsules in 120 min in the presence of gastric fluid.	Da Cruz, Perusello & Masson, 2018

Table 1. Continued

Pomegranate seed oil	Whey protein isolate and gum Arabic	0.5:5.0	Oil retention of 98.29 (g/100g). Punicic acid content of 63.67 g/100 g fatty acid.	Costa et al., 2020
Fish oil	Gelatin and gum Arabic	2:1.5	Encapsulation efficiency of 76.66%. Oil content of microcapsules of 56.78%.	Habibi, Keramat, Hojjatoleslamy & Tamjidi, 2017
Betacyanin	Pectin	1:1	Betacyanin stability 78% for 80 ºC and 100 ºC 93.2 ± 3.1% encapsulation efficiency.	Rahayuningsih et al., 2021
Ginger essential oil (GO)	Whey protein isolate+gum Arabic and gum Arabic+chitosan	3:1 (w/w) for whey protein isolate +gum Arabic , and 5:1 (w/w) for gum Arabic+chitosan	Gum Arabic+chitosan coacervates - encapsulation efficiency (81.98%) and thermal stability for ginger essential oil. Optimal mass ratios for coacervation were 5:1 gum Arabic+chitosan.	Tavares & Noreña, 2020
Black pepper essential oil	Gelatin and sodium alginate	6:1	Encapsulation performed with 6:1 ratio showed 49.13-82.36% efficiency. GC and NMR identified terpenes. Fourier transform infrared spectroscopy (FT-IR) confirmed gelatin+sodium alginate interaction.	Bastos, 2020
Chili pepper fruit oleoresin	Maltodextrin	2:1	Capsaicinoids from chili pepper oleoresin were encapsulated using complex coacervation with maltodextrin and skim milk powder, and showed 63% recovery.	Juárez-Goiz et al., 2018
Palm oil	Chitosan and xanthan	11:2	Chitosan + xanthan microparticles in yogurt released 50.1% carotenoids over 180 min in gastrointestinal fluid simulation, highlighting food industry applicability.	Rutz et al., 2017

Spray drying process

The process involves pumping the solution/suspension into the atomizer. It forms a mist of droplets, which are then sprayed into the drying chamber for solvent evaporation. Hot-air drying converts liquid droplets into solid particles, which are then trapped in a cyclone separator or equivalent system. The process's efficiency depends on maximizing contact between the feed and the heated air, demanding sufficient energy both to generate the drying medium and to vaporize the liquid. A critical point in the process is spraying the liquid mixture into the drying chamber, as droplet size affects the final product's particle size, dispersion, and velocity of the path of the droplets formed during the spraying of the wet product. The atomizer must produce uniform, low-energy droplets. Within the drying chamber, heat and mass transfer take place concurrently as the solution or suspension interacts with drying air, leading to solvent evaporation. Finally, the dry particles are separated from the drying air (Costa et al., 2015).

The spray drying method of microencapsulation has found its place in food and pharmaceutical/chemical industries in the production of powdered milk, coffee, and food flavors, as well as in the creation of stable formulations of pharmaceuticals such as antibiotics.

Table 2.
Different core materials, wall materials, inlet, and outlet temperatures used in the spray drying method

Core material	Wall material	Temperature		Inference	Reference
		Inlet	Outlet		
Anthocyanin extracted from *Antidesma erostre*	Maltodextrin , Maltodextrin : gum Arabic (3:1) and maltodextrin : Gidyea gum (3:1)	150 °C	90 °C	Gidyea gum–maltodextrin spray-dried method had highest encapsulation efficiency of 88.0 ± 1.1%. Initial total monomeric anthocyanin content was highest in Gidyea gum–maltodextrin spray-dried of 2.94 mg/g d.w.	Hay, Nastasi, Prakash & Fitzgerald, 2025
Red pitaya *Hylocereus polyrhizus)*	Maltodextrin	165 °C	80 °C	Solubility %) 98.47 ± 0.07. Phenolic compounds retention of 9.10 mg/L.	Vieira et al., 2024
Apricot kernel oil	Maltodextrin and Tween 20	170 °C	95-97 °C	Kinetic stability of 90.52 %. Removal of 87 % ergosterol.	Gunel, 2024
Sacha Inchi oil	Cushuro polysaccharide , gum Arabic and maltodextrin	140 °C	70 °C	Higher total phenolic content of 960.11±53.59 µg GAE/g. Maintenance of ω-3 acids, total sterols or tocopherols.	Chasquibol et al., 2024
Gamma- oryzanol	Inulin	160 °C		Encapsulation efficiency of 82.63%.	Rodsuwan et al., 2024
Roselle *(Hibiscus sabdariffa* L.*)* anthocyanins	Maltodextrin and maltodextrin-trehalose	120 °C	85 °C	Antioxidant activity of 3397.55 µg /mL.	Millinia, Mashithah, Nawatila & Kartin, 2024
Oil blends (Flaxseed oil and sesame oil; flaxseed oil and rice bran oil)	Tween 20 and maltodextrin	140 °C	110 °C	Carr's Index of 38.33 ± 0.23, 30.68 ± 0.32, and 33.34 ± 0.46. Moisture content of flax oil emulsion, lax-sesame oil emulsion, and flax-rice bran oil emulsion are 3.72 ± 0.06%, 3.60 ± 0.08%, and 4.00 ± 0.01%.	Areekal, Chakkaravarthi & Debnath, 2024
Camellia seed oil	Pea protein and maltodextrin	180 °C		1:1.5 was the optimized ratio. *Camellia* seed oil microcapsules and *Camellia* seed oil exhibit shelf lives of 64 days and 35 days.	Hu et al., 2024
Citrus latifolia peel essential oil	Maltodextrin	120 °C, 140 °C, 160 °C, and 180 °C		Bacterial inhibition -*S. aureus* showing the highest zones1.27 ± 0.15 cm for *C. latifolia* peel essential oil and 2.57 ± 0.40 cm for encapsulated *C. latifolia* peel essential oil.	Van, Nguyen, Nguyen & Bach, 2024
Tea extracts	Green starch, alginate and carrageenan	115 °C	65±1 °C	Total polyphenolic content after spray drying was observed as 14.02 ± 0.16 g GAE/100 g extract, which was slightly lowered compared to the sample before 14.83 ±0.81 g GAE/100 g extract. High loading efficiencies.	Baltrusch, Torres, Domínguez & Flórez-Fernández 2022
Hempseed oil	Skimmed milk powder, maltodextrin, and whey protein concentrate	180 °C		High consistency coefficient (K) value with skimmed milk powder as wall material. High zeta-potential value 42.7 mV with only whey protein concentrate as wall material.	Cevik, Yalcin & Konca, 2024

Table 2. Continued

Phenolic extracts from cocoa shells	Maltodextrin	120-150 °C	60-80 °C	Ratio of 1:15 spray dried at inlet 150◦C and outlet 73°C had high yield of 80.7%. Ratio of 1:5 had high total phenolic content of 26.2±0.6 (mg GAE/g)	Grassia et al., 2021
Vanilla oleoresin	Chitosan and gum Arabic	100 °C	60 °C	Ratio of 1:2.5 had a retention efficiency of 84.89%	Hernández-Fernández et al., 2020
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Beetroot juice	Low-crystallised maltodextrin, Arabic gum, and their mixture (1:1)	160 °C	76 °C and 71 °C	Highest violet pigment was observed based on Arabic gum. Arabic gum had lower hygroscopicity compared to maltodextrin.	Janiszewska, 2014
Beetroot juice	Low-crystallised maltodextrin, Arabic gum, and their mixture (1:1)	160 °C	76 °C and 71 °C	Highest violet pigment was observed based on Arabic gum. Arabic gum had lower hygroscopicity compared to maltodextrin.	Janiszewska, 2014
Horseradish *(Armoracia rusticana* L.*)*	Maltodextrin, maltodextrin/gum Arabic, soy protein isolate, and starch	120± 4 °C	80 ± 4 °C	80:20 ratio - highest hygroscopicity. 50:50 and 20:80 ratios - low hygroscopicity of 10% and 21%.	Tomsone, Galoburda, Kruma, Durrieu & Cinkmanis,
Horseradish *(Armoracia rusticana* L.*)*	Maltodextrin, maltodextrin/gum Arabic, soy protein isolate, and starch	120± 4 °C	80 ± 4 °C	80:20 ratio - highest hygroscopicity. 50:50 and 20:80 ratios - low hygroscopicity of 10% and 21%.	Tomsone, Galoburda, Kruma, Durrieu & Cinkmanis,
Orange essential oil	Whey protein concentrate and maltodextrin 1:3	190±2 ºC	106±4 ºC	Homogenization pressures higher than 800 bar - emulsions with high rates of coalescence and lower oil retention. Good microcapsules were obtained with a homogenization pressure of 650 bar.	Carmona, Tonon, da Cunha & Hubinger, 2013
Orange essential oil	Whey protein concentrate and maltodextrin 1:3	190±2 ºC	106±4 ºC	Homogenization pressures higher than 800 bar - emulsions with high rates of coalescence and lower oil retention. Good microcapsules were obtained with a homogenization pressure of 650 bar.	Carmona, Tonon, da Cunha & Hubinger, 2013
Amla *(Emblica officinalis)* juice powder	Maltodextrin	125 °C, 150 °C, 175 °C and 200 °C	81 °C, /93.5 °C, 103 °C and 119 °C	Optimized microcapsule can be obtained with inlet temperature at 175°C and 7% maltodextrin concentration. Maltodextrin concentration of 5–9% and inlet temperature of 125–200°C influenced the moisture content, hygroscopicity, TPC, and DPPH radical scavenging activity.	Mishra, Mishra, & Mahanta, 2014

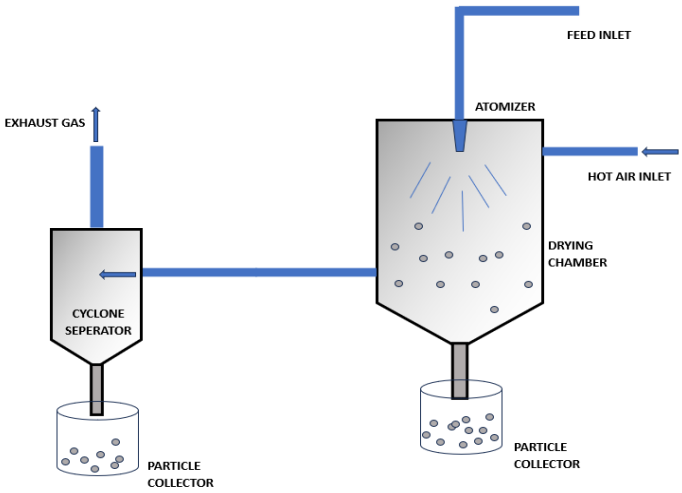


Figure 3. Schematic diagram of a spray dryer

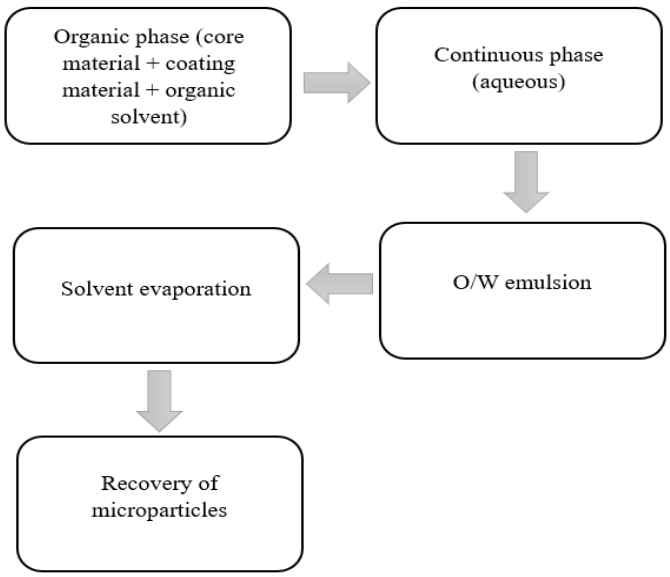


Figure 4. Process of solvent evaporation

Solvent evaporation

Solvent evaporation during microencapsulation involves dispersing a solution containing a core material and a polymer into a solvent. As the solvent evaporates, solid microcapsules form, enclosing the core material within a polymer shell. The complete process is illustrated in Fig. 4. This method is widely employed across industries like pharmaceuticals, food, and cosmetics to regulate the release, safeguard, or target the delivery of active substances. By controlling parameters like microcapsule size, shell thickness, and encapsulation efficiency, solvent evaporation plays an important role in the properties and performance of microcapsules. Applications of the solvent evaporation method in microencapsulation include producing controlled-release drugs in the pharmaceutical industry, encapsulating flavors and nutrients in food products, and stabilizing active ingredients in cosmetics. This method ensures precise delivery and protection of sensitive compounds. Different core, wall materials, and solvents used in the solvent evaporation method are shown in Table 3.

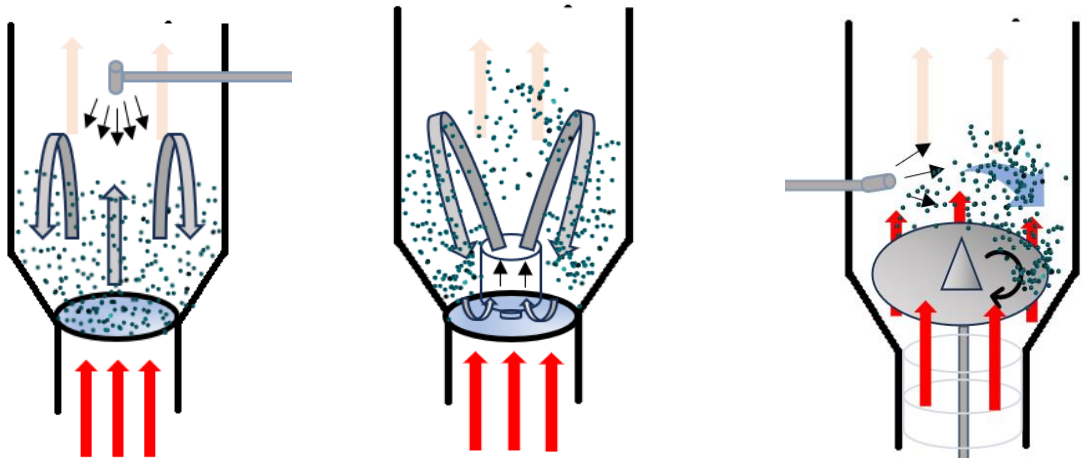
Table 3.
Different core, wall materials, and solvents used in the solvent evaporation method

Core material	Wall material	Solvent	Inference	Reference
Acalypha indica Linn. extracts	Chitosan, poly-(ε-caprolactone)	Ethanol	5 minutes of homogenization had the highest encapsulation efficiency at 74.5%. Chitosan+poly-(ε-caprolactone) blend concentration of 1.0% had an encapsulation efficiency of 92.33%.	Johari et al., 2024
Macaranga gigantea leaf extracts	Ethylcellulose	Dichloromethane	Antioxidant ability - IC50 value of 64.51 ppm. Highest encapsulation efficiency of 88.992%.	Muhaimin, Yusnaidar, Syahri, Latief & Chaerunisaa, 2020
Red propolis	Polymers, Ethylcellulose and polycaprolactone	Dichloromethane	Antioxidant encapsulation of 79.7 ± 7.7%. Polymeric ratio of 1/4, 1/2 and ¾.	Paulo, Paula, Estevinho, & Santos, 2021
Sodium selenite	Arabian to Persian gum, Na-selenite	Ethanol 96%	Highest encapsulation efficiency of 93.74%. Antioxidant activity of 482 ppm.	Jalalizand & Goli, 2020
Iron	Gum Arabic, maltodextrin, and modified starch	Absolute alcohol	Iron microcapsules fortified had a bioavailability of 63.78 ± 0.23 %. Absolute alcohol ratio (1:10) and gum Arabic, maltodextrin, and modified starch (4:1:1) had encapsulation efficiency of 91.58%.	Gupta, Chawla, Arora, Tomar & Singh, 2015
Capsaicin	Polylactic acid	Dichloromethane	Optimized product - concentration of polyvinyl alcohol 2%, concentration of polylactic acid 4%, and oil/water ratio 1:6. Improved thermal behavior from 220 to 300°C. Capsaicin had a weight loss at 200°C and rapidly degraded at 360°C.	Wang, , Dong, Chen & Lou, 2013

pesticides and dyes. Spray drying is a method that ensures the efficient and rapid production of high-quality microencapsulated products, making it indispensable across various industries. Various core and wall materials and inlet and outlet temperatures used in the spray drying method are listed in Table 2.

Fluid bed coating

Fluid bed coating technique involves suspending solid core particles in a stream of air, creating a fluidized state, and then spraying them with a liquid coating material. The coated particles are subsequently moved to an area where their shells are solidified through cooling. This method is extensively used in the pharmaceutical industry for encapsulating active ingredients. For example, ascorbic acid has been successfully microencapsulated in materials such as polymethacrylate and ethyl cellulose utilizing this technique (Dubey, Shami & Rao, 2009). There are three types of fluid bed coatings: top spray, bottom spray and tangential spray. In the top spray method, the coating solution is sprayed in a counter-current direction to the fluidizing air onto the freely suspended particles, while the air is passed through the bed to keep them suspended. Thus, the encapsulated particles travel to the chamber and are then circulated into the product container, thereby continuing the cycle. The bottom spray fluidized bed coating chamber is comprised of a cylindrical nozzle and a perforated bottom plate. The coating material is applied by spraying it at the bottom, allowing it to move upward. This method reduces particle defects compared to other types. Tangential spray fluidized bed coating features a rotating disc at the base of the coating chamber, which, when elevated, creates a gap through which particles pass into the spraying zone for encapsulation as represented in Fig. 5. The process involves the following stages: 1) Bed fluidization with an air stream; 2) Addition of emulsion in the agglomerator to form encapsulates; 3) Air-drying of particles.



(a) (b) (c)

Figure 5. Schematic representation of fluid bed coating techniques: a) top spray, b) bottom spray and c) tangential spray

Table 4.
Different core and wall materials used in the fluid bed coating method

Core material	Wall material	Inference	Reference
Persian lime essential oil	Maltodextrin and whey protein concentrate	Essential oil 29.68% , maltodextrin 41.28% and whey protein concentrate 30% as optimized composition.	Sharifpour, Rahimi, Javanmard & Basiri, 2025
Phoenix dactylifera L. phenolic compounds	Layer 1-maltodextrin, layer 2 A. mauro-rum gum and Layer 3 - MCT oil	Microcapsule had good phenolic compounds prepared at 45°C and a concentration of 20% of maltodextrin and 20% A. Mauro-rum gum. The release of phenolic compounds reaches a maximum of 64% within 24 hours.	Afshari, Javanmard, Ramezan, Bassiri & Ahmadi Chenabron, 2023
Orange oil	OSAn - modified starch and maltodextrin	Sample processed for 25 mins exhibited a high percentage of orange oil retention. Gran samples had a low level of oxidation.	Reineccius, Patil & Anantharamkrishnan, 2022
Mangosteen peel extract	Polyvinyl alcohol	Mangosteen peel extract microcapsule had IC50 value of 40.68(µg/mL).	Sriwidodo et al., 2022
Cellets 350 (6% ascorbic acid)	Gum Arabic, Hi-maize, sodium alginate, pharma coat	Loss of ascorbic acid while storage for two years was moderate (~30%). Wall materials used in the ratio of gum Arabic: Hi-maize (4:1) had no visible breakage in a microcapsule.	Bui, 2013
Strawberry flavor	Maltodextrin, modified starch (Hi-Cap) and β-cyclodextrin	Spray drying had higher efficiency than fluid bed coating. Optimized microcapsule- 9:1 ratio of maltodextrin-+modified starch (Hi-Cap) and 1.7% β-cyclodextrin.	Pellicer et al., 2019
Mexican plum fruit *(Spondias purpurea* L.*)* extract	Gum Arabic	Vitamin C 70–80%, ABTS 60–70% AC and DPPH 50–60% AC. Antioxidant capacity retention was good in fluid bed coating method than spray drying microcapsules.	Aguilera-Chávez, Gallardo-Velázquez, Meza-Márquez & Osorio-Revilla, 2022

Fluidized bed coating in microencapsulation can be applied to enhance the controlled release of pharmaceuticals, provide taste masking for bitter drugs, protect probiotics in food

products, and create uniform coatings for agricultural chemicals to improve efficacy and handling. Various core and wall materials used in the fluid bed coating method are shown Table 4.

Freeze drying

This method is also known as lyophilization. It helps preserve and stabilize sensitive compounds such as probiotics, pharmaceuticals, nutrients, flavors, and aromatic compounds. It involves freezing the encapsulated mixture, creating solid ice crystals, which are then subjected to a vacuum. The ice sublimates directly from solid to vapor, bypassing the liquid phase. This sublimation leaves behind a porous structure in the encapsulating matrix, which is further dried to remove residual moisture. The low temperatures maintain the activity of heat-sensitive compounds by increasing the shelf life by minimizing microbial growth, and chemical degradation. This method is more complex and costly compared to other drying methods, which include parameters like freezing rate, vacuum pressure, and temperature to achieve high-quality results.

This method is preferred in many industries, including pharmaceuticals, cosmetics, and food, due to its ability to produce stable and functional encapsulated products. For instance, turmeric oleoresin has been microencapsulated using gelatin and modified starch as wall materials, achieving an encapsulation efficiency of 93% (Malacrida, Ferreira, Zuanon & Nicoletti Telis, 2015). Various core, wall materials, and time-temperature regimes used in the freeze drying method are shown in Table 5.

Co-extrusion

Extrusion technology for microencapsulation is a prominent method employed to produce highly dense microcapsules.

Table 5.
Different core, wall materials, and time-temperature used in freeze drying method

Core material	Wall material	Temp.	Time (hours)	Inference	Reference
Anthocyanin extracted from *Antidesma erostre*	Maltodextrin , Maltodextrin : gum Arabic (3:1) and Maltodextrin : Gidyea gum (3:1)	−80 °C	48	Highest encapsulation efficiency is 87.6 % for maltodextrin + gum Arabic as wall material.	Hay et al., 2025
Holothuria atra	Chitosan and sodium Tripolyphosphate	−55 °C	96	Wall material stirred for 60 mins showed superior antibacterial activity. Stirring the wall material for 120 mins resulted in high antioxidant activity and the presence of terpenoids Calcigeroside B and Echinoside B.	Utami, Setianingsih & Tirto Sari, 2024
Chia oil	Whey protein and gum Arabic (1:2)	−80 °C	48	The encapsulation efficiency (% EE) decreased over time, ranging from 46.30–56.69% at the starting, 43.74–54.65% at three months, and 38.00–51.92% at six months of storage.	Wangkulangkool, Ketthaisong, Tangwongchai, Boonmars & Lomthaisong, 2023
Hop extract	Maltodextrin, Arabic gum and their mixture (1:1)	-40 to 17 °C	24	After 35 days, at 35°C, TPC observed in the extract-maltodextrin-Arabic gum and extract-Arabic gum samples with a loss, of 12% and 15%. High phenolic compound was retained by extract-maltodextrin sample at high temperature compared to maltodextrin.	Tatasciore et al., 2023
Pistacia terebinthus L. fruit oil	Gum Arabic and maltodextrin (75:25)	−45 °C	48	Beta-myrcene compound had retention of 96.30%. Spray drying had high retention of alpha-pinene, and linalool compounds at 90.31% and 104.06 %.	Yaman et al., 2023

Table 5. Continued

Turmeric oleoresin	Modified starch and gelatin	< −40 °C	48	After 35 days of storage, curcumin retention loss was 46% due to the presence of light. After 35 days of storage retention of total phenolic compounds increased at −20 and 60 °C.	Malacrida et al., 2015
Chilean papaya waste extract (seed, skin)	Maltodextrin	−40 °C	48	Highest solubility value was 20.7 0.7%. Inhibition zone of microcapsules was > 9 mm. Seed samples had high antimicrobial potential mainly effective against *S. aureus*.	Fuentes, Giovagnoli-Vicuña, Faúndez & Giordano, 2023
Red grape juice	Whey protein isolate-chitosan	−42 °C	48	The anthocyanin mass fraction, measured as 1.4±0.2 mg/g (cyanidin-3-O-glucoside equivalent). The total polyphenolic mass fraction was 3.3±0.6 mg/g (gallic acid equivalents). Flavonoid mass fraction (expressed as catechin equivalents) of (1.6±0.5) mg/g.	Mihalcea et al., 2020
Elsholtzia ciliata ethanolic extract	Skim milk, sodium caseinate, gum Arabic, maltodextrin, beta-maltodextrin, and resistant-maltodextrin	−50 °C	24	Skim milk and sodium caseinate encapsulated samples showed higher EE% of TPC at 61.79% and 77.13%. Gum Arabic and resistant-maltodextrin samples showed high Carr index and Hausner ratio values indicating poor flowability.	Pudziuvelyte et al., 2020
Aqueous polyphenolic extract of pomegranate peel	Maltodextrin and beta-cyclodextrin	- 55 °C	48	1.5% extract of Maltodextrin-10% had yeast and mold growth rate of 0.12 ± 0.06 Log 10 cfu/g at 9 days. Maltodextrin-10% had low level reduction of phenolic compounds.	Sharayei, Azarpazhooh & Ramaswamy, 2020
Red beet extract	Maltodextrin and xanthan gum (99.5% and 0.5%)	–10 °C	48	Samples that can be used in food products at pH 3 to 6 is sample powder of maltodextrin and xanthan gum and dried by freeze drying.	Antigo, Bergamasco, & Madrona 2017

This process is particularly effective when the core material and the wall material are immiscible. The core and wall materials are combined so that the wall material encases the core as they pass through concentric nozzles, forming encapsulated droplets. Solidification is achieved through cooling or by dropping the droplets into a gelling bath, where they solidify through complexation.

This technique typically produces larger encapsulates compared to other methods and is limited to a narrower range of wall materials. An advanced extrusion technique called co-extrusion has been developed and used extensively for probiotic encapsulation in recent years. Co-extrusion encapsulation is distinguished by using a concentric nozzle capable of processing two different materials simultaneously. This type of nozzle is used in spray drying for two solutions. It consists of a pore containing a solution with both the encapsulating materials and the active compound, and a ring-shaped indentation around this pore. The indentation holds a second solution, which may contain the same encapsulating materials as the first solution or different ones. This process results in microcapsules with a mixed morphology (see flowchart of the procedure in Fig. 6).

The co-extrusion technique offers several advantages over traditional methods. Firstly, it provides an additional barrier for the microcapsules, enhancing the protection of the active compounds. This additional layer aids in extending the shelf life of the microencapsulated probiotics and preserves a higher quantity of active compounds, thereby ensuring greater beneficial activity for the consumer.

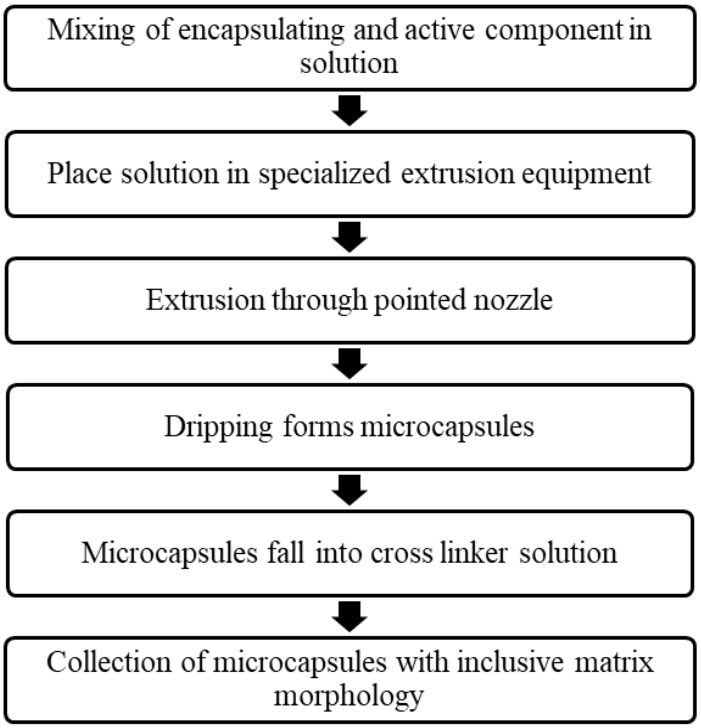


Figure 6. Process of co-extrusion

The concentric nozzle design enables precise control over the size and uniformity of the micro-capsules, which is crucial for maintaining consistency and efficacy. The solidification process in co-extrusion can be tailored based on the desired properties of the microcapsules.

For instance, cooling can be used to solidify materials that harden at lower temperature, while gelling baths can induce complex formation in materials that require specific chemical conditions for solidification. This versatility allows a range of active compounds and core materials, enhancing the applicability of the technique across various industries, including pharmaceuticals, food, and cosmetics.

Furthermore, the co-extrusion process can be adapted to include multiple layers of encapsulating materials, each providing distinct functionalities. This multi-layer approach can provide additional protection against environmental factors such as oxygen, moisture, and light, which can degrade the active compounds. In conclusion, co-extrusion encapsulation shows an advancement in the field of microencapsulation technology. Its ability to process two materials simultaneously through a concentric nozzle, combined with the potential for multi-layer encapsulation, provides enhanced protection and prolonged shelf life for active compounds. This technique is particularly beneficial for the encapsulation of probiotics, ensuring their viability and efficacy in various applications. The versatility and precision offered by co-extrusion make it a valuable tool for producing high-quality microcapsules with tailored properties to meet specific industry needs (Shivakumar, Patel & Desai, 2008; Choudhury, Meghwal & Das, 2021). Various core, wall materials and methods/ratios used in the co-extrusion method are shown in Table 6.

Co-crystallization

Co-crystallization emerges as a novel encapsulation method, offering both economic and adaptable advantages. This improves the physical attributes of active agents, such as solubility, wettability, stability, and taste masking. Specifically, in sucrose co-crystallization, the structure of sucrose transforms into agglomerated crystals, forming a porous matrix suitable for encapsulating active compounds. Despite its potential, only a limited number of studies have explored co-crystallization for encapsulation, although several patents have been issued in this area (Tzatsi, &

Goula, 2021). Although more prevalent in pharmaceuticals, its use in food remains limited.

During co-crystallization, the active component becomes nestled within crystal conglomerates, typically utilizing sucrose as a primary ingredient. The granulated sucrose, initially comprising solid, dense, mononuclear crystals, transforms into irregular, agglomerated, and microsized crystals. This restructuring increases void space and surface area, creating a porous foundation for the incorporation of active in-gredients (Chezanoglou & Goula, 2021).

Table 6.
Different core, wall materials and method/ratio used in co-extrusion method

Core Material	Wall material	Method / Ratio	Inference	Reference
Roselle seed oil (RSO)	Sodium alginate solution with high methoxyl pectin	1:1:1	Effectively preserves Roselle seed oil's nutritional properties, including unsaturated fatty acids and tocopherols. Ensure stability and efficacy during storage.	Goh, Low & Nyam, 2021
Kenaf seed oil (KSO)	Alginate and high methoxyl pectin (HMP)-enhanced alginate	Dual-feed method	Optimal microencapsulation was achieved with 500 Hz frequency, specific flow rates. High efficiency, stability, and smaller particle size.	Chew & Nyam, 2016
Lactobacillus paracasei BGP-1 (probiotic), sunflower oil, coconut fat	Alginate, alginate-shellac blend	Continuous method	Improved probiotic viability and structure when dried via fluidized bed. Effectively protects probiotics, maintaining 90% viability after 60 days, and suits solid food applications.	Silva et al., 2016
Food-grade recombinant *Lactococcus lactis* NZ3900	Sodium alginate and resistant starch	1:1, 2:1, 3:1	2:1 microbeads achieved highest encapsulation efficiency (91.1%) and survivability (78.4%). *L. lactis* microbeads in coconut water had higher stability and viability (11.4 log10 CFU/g) than free cells after 4 weeks.	Lim, How & Pui, 2024
Olive oil	Sodium alginate	Dripping co-extrusion	7 cm dripping height, and 63 g/min total feed rate, it enhanced capsules' diameter, sphericity, rupture strength.	Bennacef, Desobry-Banon, Probst & Desobry, 2022
β-carotene	Ca alginate and Ca alginate-soy protein isolate	6:1	Ca alginate microgels with soy protein isolate showed higher encapsulation efficiency (β-carotene), improved storage stability, reduced gastric fluid release. Better controlled release behavior compared to Ca alginate microgels.	Jin et al., 2023
Rosemary essential oil	Alginate (cross-linked with calcium chloride)	2:1	900 mL/h oil flow, 300 mL/h alginate flow), demonstrated prolonged release and stability.	Dolçà et al., 2015

Table 7.
Different core, wall materials and ratios used in the co-crystallization method

Core material	Wall material	Ratio	Inference	Reference
Unused chokeberries	Sucrose	0.10, 0.19, 0.40, 0.61, 0.70 g of dry extract+1 g sucrose	Total phenolic content of 0.194 ± 0.003 (mg GAE/g). Antiradical activity of 85.22 ± 1.91%.	Tzatsi & Goula, 2021
Marjoram extract	Sucrose	10 ml extract+50g sucrose	10% extract concentration microcapsule had high efficiency in maintaining phenolic compounds when storing for 120 days. Low moisture content and hygroscopicity.	Sarabandi, Mahoonak , Akbari, 2019
Securigera securidaca L. seed extract	Saccharose	3 mg extract+50g saccharose	Total phenolic content of 198.27 ± 0.04 mg of gallic acid/100 g co-crystallized. DPPH inhibiting activity of 56.74 ± 1.49 %.	Nik, Vazifedoost, Didar & Hajirostamloo, 2019

This method is extensively utilized in the nutraceutical and pharmaceutical sectors. It involves incorporating powdered bacteria into a tablet, subsequently coated with an appropriate material through compression. Coating materials like sureteric hydroxypropylmethylcellulose phthalate (HPMCP), pectin, sodium alginate, hydroxypropylcellulose (HPC), and guar gum are utilized. These coatings create a gel layer upon contact with dissolution fluid, enhancing stability during storage. However, HPC exhibits superior rigidity, while sodium alginate is favored in the food in- industry despite poor compressibility. Research indicates that compression coating with gel-forming polymers significantly improves the stabilization of lyophilized probiotic bacteria.

The choice of polymer and compression parameters significantly impacts probiotic viability due to exposure to high pressure while coating (Vivek et al., 2023). Different core, wall materials and ratios used in the co-crystallization method are shown in Table 7.

Spray chilling

Spray chilling, also known as spray cooling, is an innovative microencapsulation technique in both the pharmaceutical and food industries.

This process involves atomizing a mixture containing an active component and a molten wall material, which solidifies into particles upon contact with cooled air, all below the carrier's melting point.

Unlike spray drying, which involves evaporating solvents, spray chilling relies on solidification without mass transfer, making it ideal for encapsulating bioactive compounds such as vitamins, antioxidants, and natural pigments.

The versatility of spray chilling lies in its ability to produce microspheres—microparticles ranging from a few microns to several millimeters—where the active component is uniformly dispersed within a matrix of fats, waxes, lipids, or gelling hydrocolloids. The schematic diagram is represented in Fig. 7.

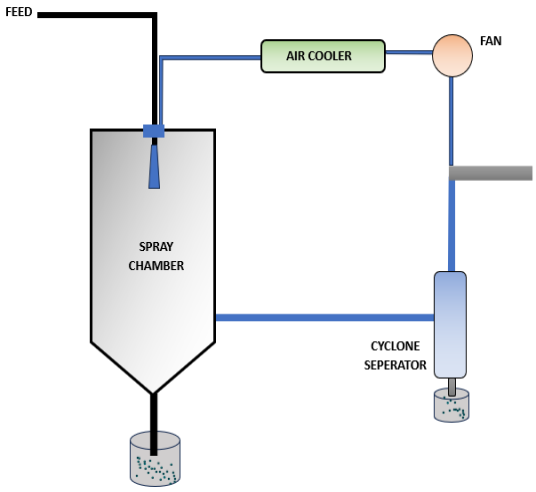


Figure 7. Schematic diagram of spray chiller

This encapsulation morphology enhances stability, reduces hygroscopicity, and can modify solubility and release characteristics, crucial for applications in functional foods and pharmaceutical formulations.

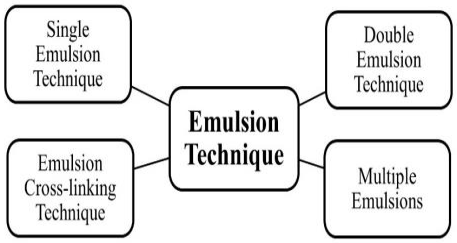


Figure 8. Types of emulsion technique

Advantages of spray chilling include its scalability from laboratory to industrial settings, low production costs, and environmental friendliness due to minimal energy requirements.

The process is facilitated by various atomization methods such as pressure nozzles, vibrating nozzles, and spinning disk atomizers, allowing for precise control over particle size and morphology.

Moreover, the high throughput capability of spray chilling supports efficient production and functionalization of encapsulated materials (De Abreu Figueiredo et al., 2022; Mahapatra, Patil & Dhakane-Lad, 2023; Karami, Babaloo, & Farhadian, 2023). A study aimed to micro-encapsulate red propolis extract using spray drying, spray chilling, and a combination of both. The resulting particles had good physical attributes and effectively preserved flavornoids, formononetin and phenolic compounds during 60 days of storage.

The in vitro digestion process showed varied formononetin release across digestive tracts, with spray-dried particles releasing mainly orally, spray-chilled particles in the intestines, and coated particles gradually. (Sá et al., 2023).

Spray chilling can be used to improve drug functionality and solubility, reduce hygroscopicity, modify taste and odor, and achieve a controlled release profile. It can also be used to make dry powders from skincare products that are fats and melt at low temperarures. Different core, wall materials, and temperatures used in this method are shown in Table 8.

Emulsion technique

In emulsion technique wall material is dissolved in the aqueous medium while the non-aqueous medium is dispersed.

The emulsion is dried under heat at controlled conditions to form microcapsules. There are 4 types of emulsion techniques (Fig. 8).

Single emulsion technique

In single emulsion, a single-phase emulsion is formed where the active ingredient is encapsulated in an oil-in-water (O/W) or water-in-oil (W/O) emulsion as shown in Fig. 9. This method is straightforward and involves mixing the core material with a carrier and stabilizer to form droplets within a continuous phase. Used for encapsulating flavors, fragrances, and pharmaceuticals for controlled release and stability.

Double emulsion technique

Double emulsion involves two stages of emulsification. In a water-oil-water (W/O/W) system, water droplets are first dispersed in oil, which is then dispersed in another water phase. In oil-water-oil (O/W/O) system, oil droplets are then dispersed in water, which is then dispersed in another oil phase as shown in Fig. 10. It is ideal for encapsulating hydrophilic substances within hydrophobic matrices, such as in the delivery of proteins, enzymes, or sensitive vitamins.

Technique of multiple emulsions

These involve more complex structures with multiple layers of emulsions, where the inner core material is encapsulated within several layers of emulsions. Used for advanced drug delivery systems and complex formulations requiring multiple stages of release.

Emulsion cross-linking technique

This technique involves forming a stable emulsion of two immiscible liquids, then cross-linking the dispersed phase to create a solid structure within the continuous phase. This process provides a precise particle size and distribution. In this method cross linking agents like glutaraldehyde, formaldehyde, terphthaloyl chloride, diacid chloride are used (Manjanna, Shivakumar & Kumar, 2010). Applications include creating drug delivery systems, encapsulating active ingredients in cosmetics, and producing controlled-release fertilizers in agriculture. Various core and wall materials used in this method are shown in Table 9.

Table 8.
Different core, wall materials and temperatures used in spray chilling method

Core Material	Wall material	Temperature	Inference	Reference
α-tocopherol (Vitamin E)	Blend of fully hydrogenated soybean oil (FHSO) and soybean oil (7:3)	22 °C (in the absence of light, BOD) -18 °C (absence of light) 25±3 °C (with light)	Optimized microcapsule with interesterified fat (70% fully hydrogenated soybean oil and 30% soybean oil). Encapsulation efficiency exceeded 90%, and X-ray diffraction indicated β polymorphic form presence with stable crystallinity below 30% over 180 days.	De Freitas et al., 2023
Ferrous sulfate	60% hydrogenated palm fat and 40% vegetable fat	-	Effective retention and stability of iron. The microparticles showed varying bioaccessibility and oxidative stability.	Rebellato et al., 2024
Lactobacillus acidophilus	Cottonseed vegetable fat	70 °C for 5 minutes for the microencapsulated probiotic addition (micro formulation). 90 °C for 2 minutes for the control and free probiotic formulations.	Microencapsulation yield of 99.35% . Probiotic counts above 6 log CFU/g during storage.	Silva et al., 2022
Vitamin D3	Vegetable fat	10 °C and 25 °C.	0.1% vitamin D3 produced a good microcapsule. 86.3% vitamin retention after 65 days at 25 °C.	Paucar et al., 2016
Green tea extract powder	Hydrogenated palm oil (PO) and vegetable fat fully hydrogenated and Interesterified (VF)	80 ± 0.5 °C	Lipid microparticles (LMP) and ionic gelation microparticles (IGMP) with encapsulation efficiencies of 83.5% and 72.6%. Lipid microparticles had high antioxidant activity (IC50: 2099.7 µg/mL) compared to ionic gelation microparticles.	Cutrim, Alvim & Cortez, 2019
Ascorbic acid (AA)	Stearic acid + hydrogenated vegetable fat – (SC)	-	Spray drying (SD) and spray chilling (SC) had high encapsulation efficiency >97%. Protected over 85% of ascorbic acid.	Alvim, Stein, Koury, Dantas & Cruz, 2016
Phytosterol mixture	Lipid mixture of low trans-hydrogenated vegetable fat and stearic acid	-	Higher stearic acid content resulted in smaller particles and was effective as phytosterol carriers.	Alvim, Souza, Koury, Jurt & Dantas, 2013

Ionic gelation

Ion gelation is a process used to create a gel-like substance by cross-linking ions in a solution. It involves the interaction between ions and a polymer or a gelling agent, resulting in a three-dimensional network that traps the ions and creates a gel-like structure. The process involves: 1) Mixing the polymer or gelling agent with a solution containing ions; 2) Adjusting the pH, temperature, or solvent to induce ion-polymer interactions; 3) Gelling the mixture

through cross-linking of ions and polymer chains (Manjanna, Shiva-kumar & Kumar, 2010).

Table 9.
Different core and wall materials used in emulsion technique

Core Material	Wall material	Inference	Reference
Quercetin – onion peel extract	Ethyl cellulose	Total phenolic content of 362 mg gallic acid/g extract. Anti-diabetic potential by inhibiting 91 % of alpha-amylase and 90% of beta-glucoside.	Ferreira, Tavares & Santos, 2025
Flavonoid from *Moringa oleifera* leaves (FMOL)	Modified soy protein isolate and gelatin	Inhibition zone with diameter of 15.2 ±0.1–17.2 ±0.0 mm. DPPH radical ranges from 34.86% ± 0.12-73.63% ± 1.02 with concentration of Flavonoid from Moringa oleifera leaves (12.5-800 µ g/mL).	Wei et al., 2023
Green tea polyphenols	Maltodextrin, Gum Arabic, tapioca starch, and maize starch	Highest total phenolic content of 46.25 ± 2.63 mg gallic acid/g dm Highest polyphenols content of 21.16 ±0.01%.	Aktaş et al., 2024
Oregano, thyme and clove leave essential oils	Agave inulin	Encapsulation efficiency ranged between 76.2-96.7%. Highest antimicrobial activity was observed in oregano essential oil.	Ruiz-Gonzalez, Lopez-Malo, Palou, Ramirez-Corona & Jimenez-Munguia, 2019

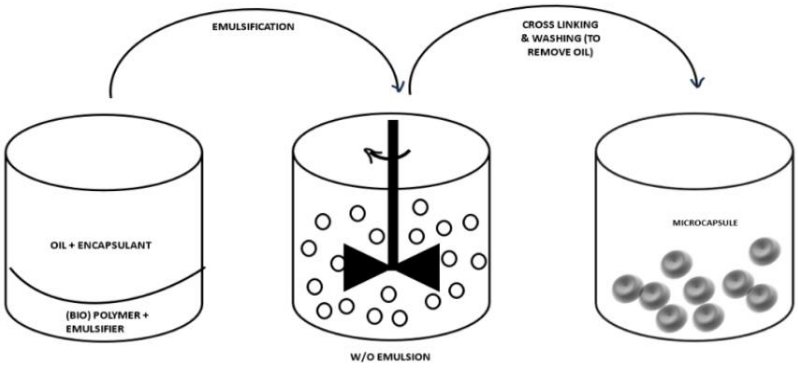


Figure 9. Schematic representation of single emulsion technique

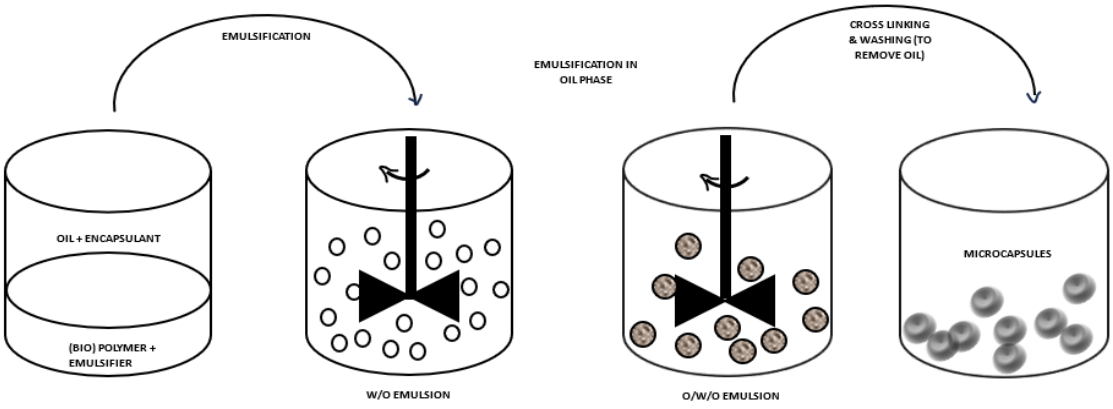


Figure 10. Schematic representation of double emulsion technique

Table 10.
Different core, wall materials and cross-linking agent used in ionic gelation method

Core Material	Wall material	Cross linking agent	Inference	Reference
Malva sylvestris seed oil	Chitosan and Na alginate	$CaCl_2$	Encapsulation efficiency of 86.69%. Drug loading of 3.15%.	Ulusal, Ulusal, Dagli & Toprak, 2024
Green tea extracts	Maltodextrin and Na alginate	$CaCl_2$	Inclusion complexation catechin extracts had increase in crystallinity than ionic gelation. Melting temperature was enhanced between 118.6–225.3 °C. No significant release of polyphenolic compounds.	Mukherjee, Baruah & Uppaluri, 2024
Pequi oil	Na alginate, chitosan	$CaCl_2$	Alginate and chitosan microspheres had an encapsulation efficiency of 96.17%. Only alginate showed an encapsulation efficiency of 67.85%.	Castelo et al., 2024
Hydroalcoholic extracts of *Moringa oleifera* seed	Na alginate and xanthan gum	$CaCl_2$	Optimized microcapsule - 100 mL extract,2.5 g sodium alginate and 0.5 g Xanthan gum. Antioxidant activity over 85%	Herman-Lara, Rivera-Abscal, Gallegos-Marín, & Martínez-Sánchez, 2024
Lionfish *(Pterois volitans* L.*)* muscle	Na alginate	$CaCl_2$	Antioxidant activity of ranged between 43.3 to 64.5%. Free radical scavenging (DPPH) of 22.73%.	Gallegos-Tintoré, May-Canché, Chel-Guerrero, Castellanos-Ruelas & Betancur-Ancona, 2024
Astaxanthin	Pectin, Na alginate and chitosan	$CaCl_2$	Alginate coated microcapsule had release of astaxanthin of 58%. Pectin+chitosan and pectin +alginate+chitosan had lower degree of oxidation than pectin	Vakarelova et al., 2023
Anthocyanin extract from *Hibiscus sabdariffa* L.	Rapeseed oil and pectin	$CaCl_2$	Bioactive compound retention of retention up to 73%	De Moura et al., 2019
Lactobacillus casei	Canola oil, Na caseinate, Na alginate and Na caseinate/Ca alginate		*L. casei*-canola oil-Na caseinate-Ca alginate had high encapsulation efficiency. *L. casei*-canola oil-Na caseinate-Ca alginate microcapsule had a viability 10.4 ± 0.3 log CFU/mL.	Beldarrain-Iznaga, Villalobos-Carvajal, Leiva-Vega, & Armesto, 2020

Ion gelation is widely used in drug delivery systems, where it creates stable, controlled-release gels for medications. This method ensures precise drug release rates and improved bioavailability. The technique's ability to form robust gels makes it ideal for applications requiring durable and consistent gel structures. Different core, wall materials and Cross-linking agents used in this method are shown in Table 10.

CONCLUSION

In conclusion, microencapsulation stands as a pivotal technology with diverse applications across pharmaceuticals, food, and cosmetics, driven by various encapsulation techniques.

Each method offers unique advantages tailored to specific needs. These techniques collectively enable the advancement of targeted delivery systems, improved product stability, and enhanced sensory attributes. With the continuous advancement of microencapsulation technologies, ongoing research and innovation are anticipated to enhance these techniques and broaden their range of applications. By understanding the strengths and limitation of each technique, researchers and industry professionals can strategically select the most

suitable method for their specific applications, ultimately leading to more effective and innovative solutions across various sectors. This comprehensive exploration of these techniques plays a critical role in advancing technological solutions and highlights the potential for continued innovation in microencapsulation technology.

AUTHOR CONTRIBUTIONS

Conceptualization, C.D.V; Methodology, C.D.V. and M.S.; Investigation, formal analysis, validation, writing-original draft preparation, S.D, A.N. and M.A.S; Writing-review and editing, S.R.R.; Supervision, C.D.V.

DATA AVAILABILITY STATEMENT

Data contained within the article.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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TEHNIKE MIKROENKAPSULACIJE: SVEOBUHVATAN PRIKAZ

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Sažetak: Tehnologija mikroenkapsulacije sastoji se od obmotavanja bioaktivnih jedinjenja zaštitnim slojevima u obliku mikrokapsula čije se veličine kreću od 1 do 1000 µm. Ovaj pristup enkapsulira termolabilne sastojke, štiteći ih od temperaturnih oscilacija, promena pH vrednosti i svetlosti, čime se obezbeđuje njihovo kontrolisano otpuštanje u raznim farmaceutskim i prehrambenim primenama. Ova tehnologija može poboljšati biodostupnost, stabilnost i organoleptičke osobine funkcionalnih jedinjenja kao što su flavonoidi, karotenoidi, vitamini i lipofilni nutrijenti (npr. PUFA iz ribljeg ulja).

Ovaj pregledni rad bavi se sveobuhvatnom analizom tehnologija mikroenkapsulacije, uključujući koacervaciju, kompleksnu koacervaciju, suvo prskanje (spray drying), emulzifikaciju, prevlačenje u fluidnom sloju, sušenje smrzavanjem, enkapsulaciju na bazi ekstrudiranja sa isparavanjem rastvarača i enkapsulaciju zasnovanu na elektrovlaknima.

Sve nabrojane metode se razlikuju po veličini čestica, hidrofobnosti i rastvorljivosti, kao i po poroznosti mikrokapsula.

Izbor odgovarajuće tehnike zavisi od osobina materijala jezgra i materijala omotača. Pored toga, rad objašnjava uticaj metoda enkapsulacije na funkcionalnost proizvoda, maskiranje ukusa i poboljšanje fizičkih i termičkih osobina, naglašavajući njihov značaj u razvijajućoj prehrambenoj industriji.

Ključne reči: *mikroenkapsulacija, jonsko želiranje, bioaktivna jedinjenja, kontrolisano otpuštanje, efikasnost enkapsulacije*

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