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Frontiers in Encapsulation Science: Advanced Strategies, Mechanisms, and Multidisciplinary Applications

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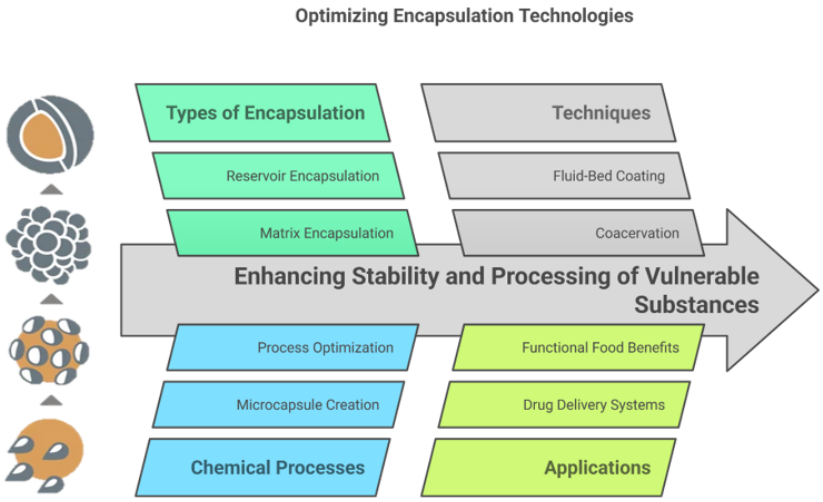
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Graphical Abstract

This review focuses on encapsulation technologies and their role in protecting sensitive substances. It highlights two types of encapsulation: reservoir encapsulation and matrix encapsulation, along with key techniques such as fluid bed coating and coacervation. The process aims to optimize chemical reactions to produce stable microcapsules, which are then used in the food and pharmaceutical industries to enhance the efficacy and stability of active ingredients.



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Abstract: Technological encapsulation has emerged as a crucial technique for optimizing the stability and processing of vulnerable substances in several fields, including medicine and nutritional sciences. This paper examines the various types of encapsulates, including matrix and reservoir, and their applications in food and pharmaceutical technologies. We explore the main chemical processes present in creating microcapsules and encapsulation techniques such as fluid-bed coating and coacervation. This review highlights the significance of encapsulation technologies in enhancing drug delivery systems and the health benefits of functional foods by synthesizing recent research and developments in this field.

Keywords: *Encapsulation, Nanoparticles, Bioactive compound, Medical application.*

Introduction

In recent years, encapsulation has attracted attention. Encapsulation incorporates food ingredients, enzymes, cells, or other materials in small capsules, e.g., to preserve foodstuffs [1]. The vulnerable encapsulated agents (pure substances or mixtures of multiple agents) may be described as coated materials, base materials, payloads, and internal phases. The covering materials may be called shells, wall materials, capsules, carriers, membranes, films, the outer shell, or packing materials [2]. There are two main types of encapsulates: matrix and reservoir types. The active ingredient in the reservoir type is encased in a shell. Other terms include capsule, single-core, mono-core, and core-shell [3,4]. Encapsulation can serve several purposes: (i) protecting sensitive substances from the external environment; (ii) masking the organoleptic properties of the substance, such as colour, taste, and odour; (iii) achieving controlled release of the drug substance; (iv) ensuring the safe handling of toxic materials; (v) enabling targeted drug release; and (vi) improving flow characteristics and simplifying handling, as they exist in solid rather than liquid form [1,4].

A variety of encapsulation methods—ranging from chemical to physical—have been developed, notably spray drying, fluid-bed coating, extrusion, coextrusion, molecular encapsulation, and multiple emulsions. Key chemical processes for forming microcapsules include phase separation, solvent evaporation, interfacial polymerization, coextrusion, coacervation, nanoencapsulation, and the use of liposomes.

Encapsulation has been extensively investigated by the pharmaceutical, food, cosmetics, textile, personal care, agricultural, chemical, biotechnology, biomedical, and sensor industries [5]. In medicine, one main advantage of using these materials is their ability to protect cells from immunological and inflammatory reactions that can occur after transplantation. Numerous applications for encapsulated cells are currently being researched for various illnesses, including diabetes, haemophilia, liver disease, anaemia, and central nervous system deficiencies [6]. When encapsulation technologies were first developed almost 60 years ago, they were intended to improve biotechnology production processes. These technologies enabled the more effective separation of producer cells and their metabolites by enclosing the cells in a protective matrix. These methods are much used in the food industry and have grown in importance in the pharmaceutical sector for the administration of drugs and vaccines [7]. In addition, the bioactive ingredients in functional foods provide health benefits, but it is crucial to preserve their properties during processing and absorption. Encapsulation protects these compounds by a coating material [8]. Delivering functional chemicals—particularly bioactive elements and micronutrients such as vitamins, polyphenols, and carotenoids—is best achieved through encapsulation technology. Despite their limited water solubility and susceptibility to degradation by light, oxygen, moisture, and temperature, these compounds exhibit

important biological activities, including antioxidant, anti-inflammatory, antibacterial, and antiviral properties [9].

The encapsulation of active compounds is growing in both academic and commercial research environments [10]. This review examines the medical applications of encapsulation technologies, specifically concerning nanoparticles, plant extracts, and essential oils. It provides a summary of the properties and selection criteria of wall materials and their effect on the release profiles of encapsulated substances. Furthermore, it discusses how these technologies enhance the stability and bioavailability of therapeutic agents, ultimately leading to improved treatment outcomes. By offering insights into these advances, this review aims to demonstrate that encapsulation improves the delivery and efficacy of therapeutic agents.

Encapsulation Processes

The design and effective use of encapsulation systems require a thorough understanding of the underlying physico-chemical mechanisms, possible interactions between active compounds and coating matrices, the stability of active compounds, and the release profiles from the coating matrix. The selected encapsulation method must ensure high encapsulation efficiency and optimal loading capacity for the active ingredients. The capsules must not aggregate or adhere. In addition, they must have a uniform particle size distribution, with no irregularities such as tails, threads, or bumps on the surface. Finally, the process must be suitable for large-scale production. The choice of encapsulation technique will depend on the characteristics and physical properties of both the core and shell materials [1,11].

Three major classes of processes can be employed to produce the most effective capsules (Table1):

- **Physico-chemical processes** based on variations in the solubility of coating agents.
- **Chemical processes** in which both the synthesis of the membrane or matrix and the encapsulation of the active ingredient occur simultaneously.
- **Physical processes**, such as extrusion or coating.

Table 1. Encapsulation methods.

Technique	Principle	Pros and cons	Core and wall material	Reference
Spray drying	This technique is used for microparticle formation because it is easy to implement on an industrial scale and allows continuous production.	- This technique can encapsulate both hydrophilic and hydrophobic base materials, a fast, flexible, and highly reproducible process. - The chief disadvantages are high operating temperature, difficulty in controlling particle size, and moderate yields for small-batch production	– Flavours and oils – Lipids (mono and diglycerides), proteins (casein, milk serum, and gelatin), and polysaccharides (starches, maltodextrins (MD), gum Arabic (GA), and corn syrups)	[9,12,13]
Pan-coating	In the food and pharmaceutical industries, one of the most basic physical encapsulation methods is coating granules, pellets, or tablets with a coating material solution by spinning them in a pan or other comparable device.	- Precise control of the coating thickness ensures a controlled release of the active ingredients. - Improved shelf life protects sensitive molecules (essential oils, probiotics, nanoparticles) from light, moisture, and oxidation. - Using solvents can pose problems of toxicity and evaporation, with some coatings requiring organic solvents. - the high cost of specific polymers and coating agents. - The potential impact on bioavailability must be taken into account, as a coating that is too thick can slow or prevent the release of the active ingredient.	– Microcrystalline Cellulose pellets – Starch octenyle succinate	[14,15,11]
Air suspension coating	The coating process disperses solid particles in a stream of air, followed by the application of a spray coating to the suspended particles. It differs from spray drying encapsulation, which creates particles with a uniformly mixed polymer matrix encasing the particle.	- The pharmaceutical and cosmetic sectors have established air-suspension particle coating, and the high cost of their finished product allows them to offset the process's expenses. - Coating airborne particles has been slow to develop in the food industry because of the economic constraints associated with the use of inexpensive ingredients and manufacturing processes	– Probiotic *Lactobacillusparacasei* cells – Maltodextrin, proteins (milk, nut), carbohydrates (starches, starch derivatives, gums), latexes (e.g., Eudragits®) and pseudolatexes (ethyl cellulose).	[105.102]
Centrifugal extrusion	Extrusion encapsulation is an efficient method of producing very dense encapsulated products. This method works well for creating particles with a diameter of 400–2,000 μm (16–79 mils).	- This is a simple technique that can be carried out. The advantage of extrusion is that the material is completely insulated by the die wall, allowing effective cleaning of the outside of the extruded product	– Vitamins, spices, and flavourings – Gum Arabic, maltodextrin, and modified starch	[9,35]
Ionic gelation	It is a gentle method because it avoids the use of organic solvents and potentially toxic surfactants. It is mainly based on the use of hydrophilic natural polymers for the preparation of particulate supports, such as chitosan, gelatin, agarose, and alginate.	- It is inexpensive and does not require organic solvents, high temperatures, or specialist equipment. This approach works better when encasing hydrophobic materials	– Betaxanthins (Opuntia *megacantha*), the probiotic *Lactobacillus acidophilus* – Phytic acid (PA) and chitosan	[5,62]
Coacervation	This is the separation of two liquid phases in a colloidal solution. The technique can differ in complexity, being simple when a single polymer is used and more complex when there are two polymers..	- The major disadvantages of simple coacervation by salting are the difficulty in controlling the size of the capsules and the risk of their agglomeration.	– Protein (β-galactosidase, Bovine serum albumin (BSA), Ergosterol) – Poly(ethylene glycol)-block-poly(α,β-aspartate acid), Chitosan, whey protein	[14,64]

Sol-gel method	Almost all reactions with a metal or metalloid element that can form polymer structures in solution through the formation of organic bonds can be called sol-gel reactions. The sol-gel technique is an effective method for creating a host matrix.	- It requires little capital investment and respects the environment. Silica-based sol-gel microparticle encapsulation is regarded as an economically viable method of production	– Enzymes, antibodies, and proteins – Poly(ethylene glycol) (PEG), poly (vinylimidazole) (PVI), or poly(ethyleneimine) (PEI)	[8,46]
Polymerization In situ	The in situ polymerization process, which is mainly used to manufacture nanocomposites, emulsifies the monomer, generally a vinyl or acrylic compound such as styrene or methyl methacrylate, in an aqueous phase enriched with a suitable surfactant.	- High loading capacity for both hydrophilic and hydrophobic compounds because of strong encapsulation efficiency. - Polymer residues: Purification procedures might be necessary for unreacted monomers. - Possible Effect on Bioactivity: Severe polymerization conditions could change how encapsulated compounds function.	– Peptides, proteins, enzymes, drugs, and aluminium nanoparticles – Polyvinylidene fluoride (PVDF)	[33,34]
Polymerization Interfacial	Interfacial polymerization is a step-growth polymerization process that takes place at the interface of two immiscible phases. In contrast to bulk polymerization, it produces polymer materials with unique topological and chemical properties, such as anisotropic shapes, hollow structures, and distinct surface chemistry. This makes it a key technique for producing polymer particles and membranes.	- Sustainable Development: Techniques for interfacial polymerization have improved as a result of developments in polymer chemistry. - Controlled Interface Formation: With the reaction limited to the interface between two immiscible liquids, the characteristics of the film or capsule may be precisely controlled. - Dependency on Solvents: The procedure makes extensive use of solvents, which can be hazardous and cause evaporation problems. -.Cost and Efficiency: It can be difficult to find greener alternatives or reduce the use of solvents, which could raise production prices.	– Drugs, dyes, enzymes – PANI, PPy, poly(3,4-ethylenedioxythiophene) (PEDOT), and polythiophene (PTh)	[35,36]
Polymerization Emulsion	The emulsion is a common method for encapsulating bioactive substances in aqueous solutions. Emulsions split into two immiscible liquids with droplet sizes ranging from 50 to 1,000 nm, one of which is spread inside the other.	- Emulsion polymerization offers the advantage of producing a final product that is normally ready to use without modification. - The principal disadvantages of this method are that surfactants and other additives can adhere to the polymer or be difficult to remove.	– Drugs, peptides, proteins, dyes, pigments, fragrances, photo-initiators, magnetite, and DNA – Chitosan (CHI), alginate sodium (ALG)	[79]
Polymerization Suspension	In order to create polymer particles, suspension polymerization uses an oil-soluble monomer and initiator distributed as liquid droplets with a steric stabilizer and rapid stirring.	- The advantages of this technique are that it is simple, cheap, robust, and environment-friendly. - Restricted to insoluble polymers: its application is limited to polymers that are insoluble in the continuous phase. - Post-processing needed: the finished polymer beads require drying, washing, and occasionally further purification procedures.	– Paraffin wax (core) – Polystyrene shell	[92,97]

The Main Materials Used in the Nano-encapsulation Process

Proper manufacturing using the appropriate wall materials is one of the most important processes in the formulation of nano-encapsulation. Many substances are used to encapsulate solid or liquid components. The materials chosen for encapsulation are selected according to the type, origin, and characteristics of these components, potential coating material limitations, the concentration of encapsulates, the type of release, and stability requirements [7,21]. The materials most commonly used for encapsulation include carbohydrates, gums, polysaccharides (e.g., cellulose, starch, chitin, alginates, pectin), polymers, proteins (e.g., gelatine, corn zein, wheat gluten, soy protein, casein, keratin, collagen, whey), lipids (e.g. wax and oil-based coatings, fatty acids and monoglycerides, resins and rosins, emulsions, and composite bilayer coatings consisting of polysaccharides, proteins, and lipids), as well as other organic and inorganic materials. In this section, we describe some of the most commonly used materials (Table 2) [42,43].

Table 2. General view of encapsulation technologies.

Encapsulant Material	Example	Uses	Reference
Carbohydrate	Starch	The delivery of sensitive ingredients through food	[44]
	Alginate (Alg) hydrogels	Encapsulating probiotics.	[45]
	Celluloses and derivatives	It has been used to immobilize bacteria and yeasts for the production of wine and beer.	[9]
	Gums	Used as a flavour-encapsulating material	[46]
	Chitosan	It has been used in the food industry to encapsulate probiotics and prebiotics, flavours, enzymes, antioxidants, and vitamins.	[9]
	Pectin	Encapsulates the bioactive compounds.	[9]
Proteins	Gelatin	Low moisture or oil phase food components and medications are encapsulated in gelatin.	[47]
	Whey proteins	They offer a useful foundation for spray drying to microencapsulate volatiles.	[43]
Lipids	Waxes and Paraffin	Aroma encapsulation barrier films to gas and moisture (skin on fresh fruits)	[46]
	Liposomes	Encapsulating any compound	[48,50]
	Shellac Resins	Used in coatings for the pharmaceutical industry	[50]

Carbohydrates

Carbohydrates constitute more than 90% of the dry mass of all biomass, with over 90% existing as carbohydrate polymers known as polysaccharides. These natural homo- and copolymers are formed from sugar residues and/or their derivatives [48]. Carbohydrates are commonly used as wall materials

or carriers in spray-dried encapsulations for culinary components [51]. The most widely used carbohydrate-based wall components include starch and starch derivatives (such as maltodextrin), cellulose derivatives (such as carboxymethyl cellulose), gums (including gum Arabic, guar gum, and chia seed gum), and β-cyclodextrin [21]. Starch can be used as a wall material for encapsulating bioactive molecules via electrospinning, allowing the creation of nanocapsules or nanofibres [52]. Starch derivatives, such as succinylated, acetylated, and phosphorylated forms, are effective encapsulating agents during the spray drying of flavours and pigments.

These materials exhibit excellent solubility and reduced viscosity in solution, as well as good emulsifying and drying properties [53]. Poly-β(1,4)-D-glucose units form the long, linear, polydispersed biopolymer known as cellulose. Its biodegradability, abundance as a renewable resource, and compatibility with biological systems make it highly valuable. But, because of their potential for absorption and associated harmful effects, cellulose-based nanocarriers that are not degraded by microbial or colonic enzymes and remain at the nanoscale should be used with caution [52,54]. β-cyclodextrins, alginates, and chitosan are newer carbohydrate-based wall materials that are being researched for various applications in the food industry [20]. One of the most widely used polyanions for microencapsulation is alginate, a natural polysaccharide derived from various species of algae [9,56]. Cyclodextrins are a type of cyclic oligosaccharide composed of six to eight glucose molecules (α-(1→4)-D-glucopyranoside units). Cyclodextrins absorbed in the upper gastrointestinal tract are not digested; instead, they are fully broken down by the colon's microbiota [48]. Because fat-soluble vitamins and hormones have very poor solubility in aqueous solutions, cyclodextrins are used as excipients to enhance their solubility [57]. Chitosan (CS), a cationic polymer composed of D-glucosamine and N-acetylglucosamine residues connected by β-(1→4) linkages, is produced commercially by the partial deacetylation of chitin, which is extracted from crustaceans [58]. Every terrestrial plant organ contains pectin, both in the parenchyma and meristematic tissue. Pectins are non-toxic, poorly soluble in the upper gastrointestinal tract, and resistant to degradation by intestinal or gastric enzymes [47,59]. Gum Arabic is one of the most commonly used wall materials in spray microencapsulation. Although thickeners and gums are generally bland or tasteless, they can significantly influence the flavour and taste of food [46]. Although gum Arabic exhibits many desirable characteristics of an ideal encapsulant, such as high solubility, low viscosity, and good emulsifying properties, it also has drawbacks, including high cost and limited availability [60]. Alginate, a linear polysaccharide derived from brown sea algae, consists of alternating blocks of β-D-mannuronic acid (M residues) and α-L-guluronic acid (G residues), which are joined by a single linkage [54]. Because of its unique colloidal properties—such as gel formation, film formation, stabilization, thickening, and emulsion stabilization—alginate can be used to create biopolymer films

or coating materials [61]. Additionally, alginate, when combined with other wall materials, helps prevent capsule rupture in situ [62].

Proteins

Natural macromolecules (proteins) are composed of linear chains of amino acids. The great diversity of amino acids in the chain arises from the possible sequences and frequency of the 20 amino acids known to exist, or more specifically, from 19 amino acids [48]. Generally speaking, proteins are derived from both plants and animals. Whey protein, casein, gelatine, and collagen are the most commonly used animal proteins in encapsulation; soy protein, zein, and gliadin are the most frequently employed plant-derived proteins [63]. Finding pharmaceutically active proteins for drug delivery research can be challenging. To maintain the biological activity of proteins, the encapsulation mechanism must ensure that they are delivered in their natural folding state [64]. Collagen is a fibrous, insoluble protein mainly found in skin, bones, and connective tissue. It may be hydrolysed under controlled conditions to yield gelatine [43]. Gelatins vary considerably in terms of size and filler distribution. Their specific primary structure is defined by the base collagen. All chains contain almost one in three glycine units, followed by proline and 4-hydroxyproline, which are the most common residues [48]. This material is soluble in water and can form walls when a mixture of water, volatile fragrance compounds, and wall material is spray-dried [65].

Gelatine (20–30%), plasticiser (10–30%) (glycerin or sorbitol), and 40–70% water can be used to produce gelatine films. The gelatin gel can then be dried [66]. Whey proteins, derived from the cheese-making process, account for approximately 20% of the total proteins in bovine milk. As soluble milk proteins, they have high nutritional and biological value, and also they are also rich in essential amino acids. These functional properties make them sought-after ingredients in a variety of food and health products [67,68].

Lipids

Lipids are hydrophobic and insoluble in water. They are widely used to encapsulate hydrophilic substances [21]. Lipids encompass a wide range of structurally diverse compounds and substances, including phospholipids, oils, fats, and waxes. In nature, these are widely distributed [70]. Beeswax and paraffin stand out as the most efficient among them [43]. Waxes are esters of fatty acids. Unlike fats and oils, fatty acids in waxes are esterified with long-chain monovalent primary alcohols rather than glycerol [48].

Liposomes and nanoliposomes are phospholipid bilayer structures composed of a hydrophilic head and two hydrophobic fatty acid tails. Liposomes are synthetic vesicles made of cholesterol and lecithin, naturally occurring phospholipids, which serve as wall components [49]. They are

considered promising vectors for the food industry because they can encapsulate water-soluble, lipid-soluble, and amphiphilic substances [9]. According to Kim *et al.* [73], the use of liposomes in the food sector remains limited because they are unstable, leak the active agent during storage, yield low levels of encapsulation, and their raw materials have a high cost.

The insect *Laccifer lacca* secretes shellac resins, which consist of a complex blend of aliphatic and alicyclic hydroxyl acid polymers. This resin is soluble in alcohols and alkaline liquids. Shellac is only permitted as an indirect food additive in food coatings and adhesives, as it is not classified as a generally recognized as safe (GRAS) substance [43].

Advances in Encapsulating Technologies and Applications

Encapsulation of Nanoparticles

The application of embedded or encapsulated nanoparticles is extremely promising for the controlled delivery of drugs, genes, and other bioactive agents [74]. Microencapsulation provides an efficient solution to the challenges faced by the food, textile, cosmetics, and pharmaceutical industries. It enables the targeted delivery of chemicals in their active state. In the pharmaceutical sector, microencapsulation technology is commonly used for flavour masking, improved stability, and controlled drug release [75]. The encapsulation of drugs is a viable approach to overcoming the drawbacks of traditional dosage forms, including inadequate bioavailability, stability, taste, and odour [76]. In many cases, bioactive drugs must be encapsulated in coating materials to protect them from harsh environmental conditions and treatments, while ensuring their absorption occurs at the right place and time [6].

For example, nanoparticles derived from the polymer poly(D, L-lactide-co-glycolide) (PLGA) have been developed to create safe and effective vectors for carboplatin. Carboplatin is commonly used to treat various malignant tumours, such as ovarian, lung, head, and neck cancers. These nanoparticles are small enough to be efficiently taken up by tumour cells, facilitating the controlled release of the encapsulated payload [78,79]. The precise targeting and controlled activity of anti-cancer drugs in nanocapsules (NCs) make them a highly promising option. They can be employed as agents or vectors for targeted drug delivery, as well as biosensors or tools in medical imaging for cancer detection [80]. As a result, both in vitro and in vivo studies have demonstrated improved coordination with various cancer cells compared to non-targeted liposomes. Liposomes have generally been used as drug carriers within the body, leading to reduced toxicity and enhanced tolerance to administration [81].

One natural phytochemical that has attracted significant interest in cancer prevention and anti-cancer treatment is curcumin (diferuloylmethane) [82]. But, curcumin has limited systemic bioavailability and poor pharmacokinetics, perhaps because it is lipophilic, which has restricted its effectiveness in vivo [83]. To enhance its efficacy in cancer treatment, curcumin was incorporated into nanoparticles

of poly(lactic-co-glycolide) (PLGA), a biodegradable polymer, using nanoprecipitation, with the addition of stabilizers such as poly(vinyl alcohol) and poly(L-lysine) [84]. Most drug delivery systems are designed to improve treatment efficacy by encapsulating active molecules. The local and sustained release of active molecules enhances the stability of therapeutic agents, improves their targeting properties, and prolongs their pharmacological activity through encapsulation [85].

In the field of cell encapsulation, significant advances have been made over the past fifty years. This technology has become essential for eliminating the need for regular medication administration, offering a biocompatible matrix for controlled drug release [86]. Challenges remain, particularly regarding organ transplant rejection, the shortage of functional organs, and the adverse effects of immunosuppressive drugs [87]. Nanoparticles have been employed as a physical approach to modifying and enhancing the pharmacokinetic and pharmacodynamic properties of various drug molecules. In vivo, they have been used to protect the active ingredient in systemic circulation, restrict drug access to specific sites, and facilitate controlled and sustained drug release at the site of action [88].

Lactic acid bacteria are among the many bacteria that produce bacteriocins, which are polypeptide compounds with antimicrobial activity (AMAs). Several techniques have been employed to encapsulate the bacteriocins produced by lactic acid bacteria to protect them from unfavourable environmental conditions and incompatibilities. A process known as electrospinning has been used to incorporate bacteriocins into nanofibres. The potential application of these nanofibres in biomedical fields has been studied, with most research highlighting their promising relevance for scaffold creation in tissue engineering [89,90]. Additionally, liposomes have gained popularity as efficient carriers for DNA, siRNA, and antisense oligonucleotides, further expanding their role in drug delivery [81].

Bimetallic metal nanoparticles play a crucial role because of their unique properties, which differ from those of individual metals. These materials are of particular interest in catalysis [91]. But, during the catalytic process, coalescence migration may readily deactivate them [92]. Therefore, researchers have incorporated metal nanoparticles into nanoshells or nanopores. This physical isolation prevents the particles from merging, thereby enhancing their catalytic stability [93].

For biological applications, gold nanoparticles (GNPs) are the most widely used inorganic nanoparticles because of their distinctive chemical and physical characteristics [94,110]. Biological molecules provide essential interfaces for interactions between the nanoparticles and the biological environment while also conferring biological functionality. Self-assembled protein nanoparticles (SAPNs) have therefore been selected to encapsulate gold nanoparticles [95].

Retinol and its derivative complexes are widely used in the pharmaceutical and cosmetics sectors. Furthermore, retinoids stimulate dermal fibroblasts to produce extracellular matrix proteins such as

collagen I [96]. But, retinol and its analogues, including retinoids, retinol, and retinyl palmitate, have problems of stability and solubility. To overcome these, researchers have incorporated retinol into chitosan nanoparticles for intravenous delivery, which can improve its aqueous solubility and therapeutic efficacy [97].

One of the main problems in developing polymer-based injectable delivery systems is the initial release of the drug, which occurs within the first few minutes of contact with the external environment [98]. Microparticulate systems often experience burst release, which is unpredictable and difficult to control. This can be mitigated by modifying the drug distribution within the polymer matrix or by developing more advanced drug delivery systems [99]. For example, liposomes encapsulated in dextran and alginate microcapsules can control drug release, avoiding the burst effect and improving stability [100,102]. This approach is particularly valuable for treating chronic diseases that require long-term medication, as it ensures sustained therapeutic effects and improves drug retention.

Encapsulation of Essential Oil

Interest in essential oils (EO) is growing in various fields. As natural products, their physicochemical characteristics offer high added value and are environmentally friendly. Moreover, essential oils have various and significant biological activities. For example, they are used in the medical sector for their bactericidal, virucidal, and fungicidal properties, as well as their medicinal virtues [28]. Nevertheless, their volatility, low solubility in water, and sensitivity to oxidation limit their use. Encapsulating essential oils can mitigate these features and enhance their biological activities [103].

Microbiological contamination is a major cause of food spoilage, leading to the deterioration of nutritional, health, and sensory qualities. But, essential plant oils (EO), which are generally recognized as safe (GRAS) by the FAO/WHO (2008) and often have antimicrobial properties, could represent a promising natural alternative to the use of chemical preservatives in food [104,105]. Currently, there are several methods to preserve food: (a) the use of aseptic techniques during handling and packaging, (b) the mechanical elimination of micro-organisms by washing or filtration, (c) the destruction of micro-organisms by disinfection processes, whether physical or chemical and finally, (d) the inhibition of pathogens or saprophytes by controlling environmental conditions [98]. Natural antimicrobials are gaining interest because of growing consumer awareness of food safety. Encapsulation can enhance the concentration of bioactive substances in food matrices, particularly in water-rich phases or liquid-solid interfaces, where microorganisms thrive [99]. There is a project on the encapsulation of essential oils in nanometric delivery systems for use in fruit juices. The aim is to improve their antimicrobial activity while reducing the impact on the quality characteristics of the final product [101].

Beyond food applications, essential oils are also being studied as potential solutions to combat multidrug-resistant (MDR) bacteria, a major global health threat. According to the US Centers for Disease Control and Prevention, MDR infections affect approximately 2 million people annually, resulting in nearly 23,000 deaths [102]. Many plant-derived bioactive compounds, including essential oils, have demonstrated strong antibacterial activity, even against biofilms [103]. For example, ionotropic gelation was used to encapsulate essential oils of Schinus molle, thyme, and cinnamon (*Cinnamomum zeylanicum*) at concentrations of 125, 250, and 500 µg/mL in chitosan nanoparticles. In comparison to chitosan and essential oils alone, chitosan nanoparticles with these oils showed a stronger antimicrobial effect against *Pseudomonas aeruginosa*, which produces carbapenemase, *Staphylococcus aureus ATCC 25923*, *Enterococcus sp.*, *Escherichia coli ATCC 25922*, and *Klebsiella pneumonia* (BLEE +) [104].

Encapsulation of Bioactive Compounds

Since ancient times, herbs have been used as foods, medicines, and cosmetics. These bioactive compounds can be sensitive to environmental stresses such as oxygen, water, and light during processing, storage, and transport. Encapsulation provides effective protection, preserving their nutritional value, bioavailability, solubility, and functionality [105].

Studies have shown that plant extracts can be encapsulated and used as functional ingredients in food matrices. Additionally, they are employed in the production of active packaging, edible films, and food coatings. Among the many benefits that cyclodextrins, which are ring-shaped oligosaccharides, offer to the substances they encapsulate are: i) flavour and odour masking, ii) enhanced water solubility, and iii) regulated release of the encapsulated substance. The use of these cyclodextrins to encapsulate hydrophobic compounds has facilitated the development of functional foods with improved physicochemical and sensory properties [106].

In traditional medicine, various disorders are treated with species of the genus *Plectranthus*. Extracts from *Plectranthus ecklonii*, *P. grandidentatus*, *P. ornatus*, *P. porcatus*, and *P. saccatus* were obtained using infusion, decoction, microwave-assisted, and ultrasonic extraction methods. A comparative study aimed to identify the most bioactive extract for encapsulation in alginate beads. The microwave-assisted extraction of *Plectranthus ecklonii* yielded the highest concentration of polyphenols and exhibited strong antioxidant activity as well as effective acetylcholinesterase inhibition. This bioactive extract was successfully encapsulated in polymer particles [107].

Other plant-derived compounds have also been successfully encapsulated. Research was conducted on the encapsulation of extracts from raspberry, hawthorn, ground ivy, yarrow, nettle, and olive

leaves. This encapsulation was achieved using electrostatic extrusion in microbeads composed of alginate and chitosan, with ascorbic acid used to dissolve the chitosan. Ascorbic acid was employed to improve the solubility of the chitosan, thereby enhancing the antioxidant potential of the encapsulated plant polyphenolic extracts [108]. A study evaluated how encapsulating antimicrobial substances (e.g., herbs, spices, lysozyme, and nisin) affected their efficacy and stability. Two Gram-positive (*Bacillus subtilis* and *Micrococcus luteus*) and two Gram-negative (*Escherichia coli* and *Serratia marcescens*) bacteria were used to investigate the antimicrobial activity. Successful encapsulation was achieved in various polysaccharide particles and liposomes. Liposomes containing plant and spice extracts demonstrated highly effective inhibition against all the bacterial strains examined [109].

The use of microencapsulation is also expanding in the personal care and cosmetics industries. Many physiologically active compounds used in personal hygiene and cosmetic products are unstable and highly sensitive to pH changes, light, temperature, and oxidation. Plants contain phenolic compounds, secondary metabolites with ideal structural characteristics that act as antioxidants and anti-inflammatories. They can deteriorate through sensitivity to light and temperature. An effective method for enhancing their bioavailability and solubility is encapsulation in liposomes [111]. Liposomes also facilitate deeper penetration into the skin, reaching the dermis and epidermis before being absorbed into the bloodstream [112]. Nanoliposomes (PEF-NL) have been used to encapsulate the phenolic-enriched fraction, providing a new delivery system. PEF-NLs offer promising potential in the cosmetics industry for addressing skin pigmentation problems and as a skin whitening agent [113].

The cosmetics industry has also taken an increasing interest in the encapsulation of natural ingredients. This industry is now using another delivery system: the dendrimer. This delivery system consists of highly branched, compact, symmetrical, and spherical polymers [114]. As skincare products continue to evolve, ensuring high quality and rigorous scientific validation becomes increasingly important. Nanoparticles, with their small size and large surface area, are particularly well-suited for delivering active ingredients. A study by Lages *et al*. [59] highlighted the role of lipid nanoparticles in transdermal drug delivery, emphasizing their widespread use in modern cosmetic formulations.

Conclusion

This study investigates the diverse applications of encapsulation technologies in medicine, with a specific focus on nanoparticles, plant extracts, and essential oils. We highlight the critical role of wall materials in determining the efficacy and stability of these therapeutic agents. The integration of encapsulation into medical practices is leading to more effective strategies and improved patient

outcomes. To enhance patient care and develop innovative treatments that fully harness the benefits of encapsulated bioactive compounds, research and development should continue.

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