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Microencapsulation Methods for the Stabilization and Controlled Release of Active Food and Pharmacological Ingredients

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ABSTRACT

Natural antioxidants play an important role in preserving food quality and promoting human health by reducing oxidative stress. However, the sensitivity of these compounds to environmental factors such as heat, light, and oxygen severely limits their direct application. Microencapsulation technologies offer an effective approach to overcome these limitations by increasing the stability of antioxidants and enabling controlled release. This review examines recent developments in the encapsulation of natural antioxidants, focusing particularly on basic encapsulation techniques such as wall materials, spray drying, spray cooling, extrusion, lyophilization, coacervation, cocrystallization, fluidized bed coating, and interfacial polymerization, as well as release mechanisms and release kinetics. A thorough understanding of the relationship between encapsulation materials, manufacturing processes, and release behavior is critical for the design of stable and efficient delivery systems. These technological advances offer broad application potential in the food, nutraceutical, and pharmaceutical fields by improving the bioavailability, functionality, and shelf life of antioxidant compounds.

INTRODUCTION

Aromatic and medicinal plants hold significant value in the pharmaceutical, food, cosmetic, and nutraceutical industries due to their rich content of bioactive compounds. The most prominent active substances in these plants are phenolic compounds, essential oils, and terpene compounds (Grynyk & Yezhov, 2023; Hussein et al., 2025; Karaogul et al., 2025; Kodanovi et al., 2020; Proestos et al., 2008). Nowadays, some phenolic compounds such as oleuropein, thymoquinone, thymol, and carvacrol have attracted great attention thanks to their strong therapeutic potential (Celik & İlhan, 2023; Nedjip & Karaogul, 2025). Phenolic compounds exhibit a wide structural diversity, ranging from simple phenolic acids to flavonoids and stilbenes (Alifakı, 2019; Jaganath & Crozier, 2010). Natural antioxidants such as polyphenols, carotenoids, flavonoids, and vitamins play an important role in reducing oxidative stress, which is closely associated with chronic diseases such as cardiovascular diseases, neurodegenerative disorders, cancer, and aging (Forman & Zhang, 2021; Gulcin, 2025). Therefore, phenolic compounds and essential oils; They have a wide range of uses in functional foods, pharmaceutical formulations, cosmetics, and nutraceutical

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applications (Başyiğit & Baydar, 2017; Biçer et al., 2003; Bosnalı & Ocak, 2019).

A major limitation to the practical utilization of these bioactive compounds arises from their inherent instability. Phenolic compounds and essential oils exhibit high sensitivity to environmental parameters such as oxygen exposure, light, temperature fluctuations, humidity, and pH variations. This susceptibility results in their rapid degradation during processing, storage, or gastrointestinal passage, ultimately compromising their biological activity and lowering their functional effectiveness in target systems (Cao et al., 2021; Gulcin, 2025; Mrázková et al., 2023).

In an effort to resolve stability-related limitations, microencapsulation has gained prominence as a scientifically robust approach to protecting bioactive compounds. This technique entails embedding the substances within optimized carrier systems that serve as a protective interface, reducing their susceptibility to destabilizing factors such as oxygen exposure, light, temperature variations, humidity, and pH changes. By mitigating the impact of external stress factors, the encapsulating system markedly reduces degradation rates, securing the physicochemical stability and functional properties of the compounds. This enhanced stability is closely linked to extended shelf life and enables fine-tuned control of release kinetics, making both sustained and site-specific delivery feasible. In addition to its protective role, microencapsulation provides a framework in which antioxidant capacity and biological functionality are preserved throughout processing, storage, and eventual utilization, ensuring consistent performance under variable conditions. The flexibility and effectiveness of microencapsulation make it a valuable tool for multiple industrial domains, particularly in functional foods, active packaging, oral pharmaceutical systems, and cosmetics (Alifakı, 2019; Bińkowska et al., 2024; Bosnalı & Ocak, 2019; Desai & Jin Park, 2005; Sébastien Gouin, 2004; Jackson & Lee, 1991; Keshani et al., 2015; Munin & Edwards-Lévy, 2011; Nikmaram et al., 2017).

Over the past decades, a wide array of encapsulation methods—such as spray drying, coacervation, emulsification, liposomal entrapment, and nanoencapsulation—has been developed to enhance the stability and functionality of bioactive molecules. These techniques differ markedly in their technical and economic attributes, including scalability, cost, compatibility with various materials, release control, and encapsulation efficiency. At the same time, various wall materials including natural polysaccharides, proteins, lipids, and synthetic polymers have been systematically studied to enhance encapsulation efficiency, improve protection, and refine delivery behaviors of active ingredients (Karaogul, 2025; Bosnalı, 2019; Keshani, 2015).

This review brings together the latest developments in microencapsulation technologies aimed at improving the stability and bioavailability of natural antioxidants. It considers technological innovations, wall material selection strategies and the mechanistic understanding of release and kinetic processes, emphasizing their growing importance in the food and pharmaceutical sectors. It discusses both technological and material aspects, examining encapsulation techniques, material selection principles, and the mechanisms governing release and kinetics, with emphasis on food and pharmaceutical applications. In addition, the article discusses current challenges, regulatory and safety aspects, and the most promising future directions for the controlled delivery of antioxidants through encapsulation.

MICROENCAPSULATION METHODS

In recent decades, growing interest in microencapsulation has stimulated the development of numerous methods tailored to meet distinct functional and technological objectives across research and industry. The choice of an encapsulation method is rarely arbitrary; rather, it is shaped by a combination of factors such as the physicochemical nature of the core and coating materials, the intended release characteristics, production efficiency at scale, and the ultimate field of application. Among the most frequently applied methods are spray drying, spray cooling, coacervation, extrusion, lyophilization, cocrystallization, fluid bed coating and polymerization, particularly interfacial polymerization. Each of these approaches presents distinct advantages and inherent limitations with

respect to capsule morphology, particle size distribution, production costs, and stability, all of which have a decisive impact on the quality and performance of the final product (Barbosa-Nuñez et al., 2025; Colin et al., 2024; Díaz-Montes, 2023; Sébastien Gouin, 2004; Kumar et al., 2024).

Spray Drying

Spray drying is the most widely used microencapsulation technique in the food industry. Spray-drying microencapsulation is an effective strategy to address limitations of phenolic compounds such as low solubility and bioavailability. It was used in the late 1950s to prevent food spoilage, to preserve flavors and oils against oxidation and to convert liquids into powder (Kanat & Gülel, 2021). The advantages of spray drying over other methods are that it has large and simple equipment, a wide range of coating materials, the potential for large-scale production, high product yield, and low cost of storage, transportation and processing (Desai & Jin Park, 2005; Karaogul & Ugurtay, 2025; Özer, 2021).

Spray Cooling

Spray cooling is the cheapest microencapsulation technology using low temperature. Microencapsules prepared by spray cooling are insoluble in water due to the lipid coating. This technique has some disadvantages such as low encapsulation capacity of the microparticles and expulsion of the core during storage (Desai & Jin Park, 2005; Kanat & Gülel, 2021).

Extrusion

Extrusion is a method applied at low temperatures. It is used for encapsulation of volatile and unstable taste substances. The main advantage of the extrusion method is the prolonged shelf life and prevention of oxidation due to the provision of an oxygen impermeable barrier. The disadvantage of this method is that the use of very large particles (500-1,000 mm) limits the applications. There are very limited wall materials available for encapsulation by extrusion (Sebastien Gouin, 2004).

Lyophilization

Lyophilization is a method involving the dehydration of frozen materials under a vacuum sublimation process. It requires the removal of water from the compound (active ingredient) without sending the sample to high temperatures (Kanat & Gülel, 2021). This method ensures an excellent quality product as it minimizes the changes associated with high temperature. It is commonly used in flavorings and sweeteners. However, its commercial viability is decreasing due to the high cost and long processing time (Marques et al., 2006).

Coacervation

Coacervation is a method to deposit polymers (coating material) around the core by altering its physicochemical properties such as temperature, ionic strength, pH and polarity (Azeredo, 2008). Coacervation is a relatively simple, low-cost process that does not require high temperatures or organic solvents. Coacervation is divided into simple and complex coacervation. In complex coacervation, two or more coating materials are used, while in simple coacervation only one type of coating material is used (Kanat & Gülel, 2021).

Cocrystallization

Cocrystallization is a new coating method resulting from the combination of a sucrose matrix and core material. Sucrose syrup is concentrated to supersaturation and the temperature is adjusted to prevent crystallization. A predetermined amount of core material is added to the concentrated syrup, which is stirred vigorously. With the help of the stirring process, the sucrose and the seed material become intertwined and encapsulation occurs (Kanat & Gülel, 2021; Koç et al., 2010).

Fluidized Bed Coating

Fluidized bed coating was discovered by D.E. Wurster in the 1950s and is also known as the Wurster process (Koç et al., 2010). The principle of the fluidized bed coating process is based on the formation of capsules in the form of layers as a result of spraying the coating liquid onto the particles in the bed through the spray nozzle. There are 3 different fluidized bed coating methods: top, bottom and angle spraying (Desai & Jin Park, 2005).

Interfacial Polymerization

Interfacial polymerization is a versatile microencapsulation technique that enables precise control over capsule structure and release behavior. Multi-scale evaluations indicate that formulation parameters, including amine functionality and pH, play a key role in determining the degree of crosslinking, structural stability, and the tendency toward aggregation. The technique is based on reactions between complementary monomers at the boundary of two immiscible phases, resulting in the formation of a polymeric shell around the core. Applications such as polyurea microcapsules incorporating chitosan oligosaccharide have shown high encapsulation efficiency and a well-regulated release profile. This approach provides considerable versatility for developing stable and functional microcapsules across different industrial fields (Dhanusha & Vijayalakshmi, 2023; Ricardo et al., 2021; Yu et al., 2021).

WALL MATERIALS FOR MICROENCAPSULATION OF FARMACEUTICAL INGREDIENTS

Phenolic compounds are well known for their wide-ranging biological effects, yet their use is often limited by problems such as low solubility, instability, and poor bioavailability. To improve or resolve such issues, it is crucial to select the optimal wall materials and effective encapsulation methods that can affect the functional properties of the encapsulated ingredients (W. Lu et al., 2021). Wall materials, also referred to as coating or carrier materials, play a crucial role in the efficiency, stability, and release characteristics of microencapsulated natural antioxidants (Kariduraganavar et al., 2019). The selection of wall material is very important in optimizing the effectiveness and functionality of active ingredients, especially in pharmaceuticals. Biodegradable polymers are crucial for micro-/nanocapsules in drug delivery, with natural and synthetic polymers being used. The design of drug-delivery systems has advanced to exploit biochemical changes for targeted release. Challenges include improving stability, biodistribution, drug loading, and interaction with biological barriers (Díaz et al., 2015; Makhathini et al., 2023). The filler material consists of fine particles or droplets, while the coating material envelops it, allowing it to take its final shape, forming the microcapsule (Bosnalı & Ocak, 2019; Umer et al., 2011). The coating material protects the active compound from the effects of the external environment and allows its release at the appropriate rate (Paulo & Santos, 2017). The selection of an appropriate wall material depends on factors such as antioxidant solubility, compatibility, protection ability, biocompatibility, and intended food application (Kariduraganavar et al., 2019). An ideal coating material to be used in microencapsulation should have the following properties. It should be inert against the filling material, the wall width should be at the desired level, It should harmonize with the interior material, It should stabilize the filling material, controlled release should take place under certain conditions, It can be flexible, fragile, robust or thin, It should be affordable and readily available (Bosnalı & Ocak, 2019). Coating materials can be used as natural, semi-synthetic or synthetic polymers (Paulo & Santos, 2017). Common wall materials include Polysaccharides (maltodextrin, gum Arabic, waxy starch (Makhathini et al., 2023), alginate (Díaz-Montes, 2023)), Proteins (whey protein, casein, gelatin (Barbosa-Nuñez et al., 2025; Makhathini et al., 2023)) and Lipid-based carriers (mono- and diglycerides, waxes) (H. Lu et al., 2021).

Polysaccharides

Polysaccharides are carbohydrate polymers formed through glycosidic linkages and are produced naturally by different organisms (plants, animals, and microorganisms) for structural and energy functions. They can also be synthesized chemically or enzymatically. Their favorable properties, such as viscosity and solubility, make them useful in many industrial applications as emulsifiers, gelling agents, flavor carriers, and encapsulating agents (Díaz-Montes, 2022, 2023).

Polysaccharides are widely used as wall materials because of their biodegradability, film-forming properties, and Generally Recognized as Safe (GRAS) status. Common polysaccharides used for this purpose include maltodextrin, gum arabic, alginate, pectin, and chitosan (Díaz-Montes, 2022, 2023; Lisitsyn et al., 2021). Maltodextrin is popular because of its low viscosity at high solids content and good solubility, making it ideal for spray drying

processes (Sobulska & Zbicinski, 2021; Xiao et al., 2022). However, it has limited emulsifying properties, often requiring combination with other materials. Gum arabic offers excellent emulsification and film-forming properties, which improve encapsulation efficiency and oxidative stability (Premi & Sharma, 2017; Wangkulangkool et al., 2023; Zahran et al., 2022). It is frequently used in coacervation and spray drying techniques (Paula et al., 2019). Alginate and pectin are used for their gel-forming abilities, especially in ionic gelation encapsulation methods (Colin et al., 2024; Morales-Medina et al., 2022). Chitosan, a cationic polysaccharide, provides antimicrobial properties and enhances controlled release behavior (Picos-Corrales et al., 2023; Wiggers et al., 2022; Yan et al., 2021).

Gum Arabic and maltodextrin are favorable wall materials for microencapsulating pomegranate peel extract with high antioxidant and antimicrobial properties. Gum Arabic demonstrates superior antioxidant retention, showing 1.4-fold higher FRAP activity and 10.7-12.6% higher DPPH scavenging activity compared to waxy starch - encapsulated pomegranate peel extract. Maltodextrin (MT) encapsulation had higher levels of metabolites such as ellagic acid and punicalagins. pomegranate peel extract powder shows potential as a natural antioxidant and antimicrobial agent for food preservation, with GA and MT as favorable wall materials (Makhathini et al., 2023).

Proteins

Owing to their biocompatibility, biodegradability, low toxicity, and structural flexibility, proteins play an important role in the formulation of micro- and nanocapsule platforms. Sources include albumin, collagen, elastin, keratin, and a range of plant-based proteins. Their functional properties have led to widespread use in pharmaceutical delivery systems, food formulations, and biomedical technologies. Protein matrices can form stable capsule structures with gaseous, liquid, or solid cores, which can be reinforced fthrough covalent bonds, hydrogen bonds, or chemical crosslinkers. Owing to these characteristics, proteins present a credible and effective alternative to synthetic polymers (Ramos et al., 2022).

Gelatin is well known for its strong film-forming ability, particularly when interacting with polysaccharides during complex coacervation (Ramos et al., 2022). Owing to its wide application in food science and biomaterials, gelatin functions as a versatile protein that can form functional structures through coacervation with various polysaccharides (Derkach et al., 2022). In their study, Derkach et al. (2022) provided a comprehensive description of the structural features and intermolecular interactions within gelatin–polysaccharide complexes. Complementarily, (Xiong et al. 2021) investigated the thermodynamic behavior and pH-dependent characteristics of gelatin–pectin coacervation, offering further insight into the mechanisms governing complex formation. Furthermore, the study by (Shaddel et al., 2018) demonstrated that gelatin and gum Arabic can be employed in encapsulation processes for active compounds such as blackcurrant extract. Collectively, these findings highlight that gelatin functions not only as a film-forming biopolymer but also as an effective carrier and protective matrix for functional food ingredients.

Whey protein isolate (WPI) is widely valued for its strong emulsifying capacity and barrier functionality, which makes it a suitable carrier for hydrophobic bioactive compounds such as curcumin, essential oils, and polyphenols (Jiang et al., 2024; Xie et al., 2022).

WPI and other proteins help stabilize antioxidants through hydrogen bonds and hydrophobic interactions, reducing degradation and improving bioavailability. Polyphenol–protein complexes, which are mainly stabilized by non-covalent forces bat bay hydrophobic forces, are considered a promising strategy for creating effective delivery systems for functional ingredients (Li et al., 2021).

The performance of wall materials in encapsulation is highly influenced by storage conditions. Díaz et al., (2015) comparatively studied the preservative efficacy of different wall materials in blackberry juice microencapsulation. Maltodextrin and gum Arabic provided similar levels of protection under low water activity conditions, but this effectiveness decreased significantly under high humidity conditions. In contrast, whey protein concentrate provided better protection under higher humidity

conditions. These results indicate that the selection of the appropriate wall material is directly related to the product's storage conditions (Díaz et al., 2015). Maltodextrin and its combination with whey protein isolate demonstrated the highest retention of anthocyanins, whereas pure whey protein isolate exhibited the greatest total phenolic content and antioxidant activity. Microcapsules formulated with pure whey protein isolate released the highest amounts of total phenolic compounds and antioxidant activity in intestinal fluids during in vitro digestion (Norkaew et al., 2019).

In the past two decades, carbohydrate, gum, and proteins materials have been widely employed in encapsulation due to their ability to ensure stability, protect bioactive compounds, and maintain acceptable sensory qualities, along with other critical product attributes. Nevertheless, factors such as cost, availability, and compatibility with different extracts present both advantages and limitations. Consequently, recent research has focused on improving encapsulation outcomes through the exploration of alternative materials and material combinations, including beta-cyclodextrin, sodium alginate, and inulin (Mazár et al., 2025).

Lipids and Phospholipids

Waxes, fatty acids, and phospholipids are among the most frequently used lipid-based wall materials in encapsulation processes. These compounds are particularly suitable for use in spray cooling (also referred to as spray freezing) and liposomal encapsulation techniques. In the spray cooling process, the active substance is blended with a molten lipid phase and solidified by exposure to a stream of cold air. This results in the formation of stable capsule structures, while the relatively mild processing conditions help to limit heat-induced degradation (Favaro-Trindade et al., 2021; Figueiredo et al., 2022; Koh et al., 2022; H. Lu et al., 2021).

Lipid coatings are frequently employed to regulate the release profile of encapsulated materials while simultaneously limiting the permeation of moisture and oxygen. These properties contribute to improved stability of active compounds and are especially valuable in formulations containing sensitive bioactives (Ozkan et al., 2020).

The physicochemical properties of wall materials encompassing both their intrinsic characteristics and process-dependent physical features—play a decisive role in maintaining the stability of encapsulated compounds by protecting them from environmental stressors such as moisture, heat, light, and oxygen (Labuschagne, 2018). Lipid-based vesicular systems have been developed to enhance the in vivo stability and pharmacokinetic performance of active ingredients, with lyophilization frequently employed to further increase their structural stability (Boggula et al., 2022). Lipids, either alone or combined with complementary materials such as starches and proteins, provide an effective encapsulation matrix for protection, stabilization, and controlled release (Garti, 2008; Kumar et al., 2024; Zhu, 2017).

In liposomal structures, phospholipids, thanks to their ability to form a bilayer membrane, provide protection against oxidative degradation and increase the bioavailability of bioactive compounds. Because of these properties, phospholipids are widely used as carrier matrices. Numerous studies in the literature address the stability and release profile of phenolic compounds in such systems (Rahim et al., 2025).

Synthetic Polymers

Synthetic polymers play an important role in micro- and nanoencapsulation technologies for the protection and controlled release of bioactive compounds. Among synthetic polymers, polycaprolactone (PCL), poly(lactic-co-glycolic acid) (PLGA), and polyethylene glycol (PEG) are widely used in various encapsulation strategies. These materials are generally categorized based on their responsiveness to environmental and biological stimuli, a property that plays a decisive role in determining encapsulation efficiency, solubility, stability, and release characteristics (Karidurаganavar et al., 2019). Although early work on cell microencapsulation faced limitations due to polymerization conditions that were not compatible with mammalian cells (Olabisi, 2015), improvements in processing have made these polymers more advantageous compared with natural alternatives. In particular, they contribute to greater consistency between production batches and help minimize immune responses. Within the food

industry, polyvinyl alcohol has proven effective as an encapsulating agent for delivering bioactive components in a variety of products, including bread, fruit juices, and dairy-based matrices (Barbosa-Nuñez et al., 2025). Today, synthetic polymers—used on their own or in combination with natural materials—are increasingly employed to create delivery systems with improved stability and controlled release characteristics for applications in pharmaceutical, food, and cosmetic formulations.

CONTROLLED RELEASE MECHANISMS OF MICROENCAPSULATED ACIVE FARMACEUTICAL INGREDIENTS

Controlled release represents a crucial feature of encapsulation technologies, allowing active compounds to be delivered gradually, thereby improving their functional stability, bioavailability, and sensory impact (Alemzadeh et al., 2020). This technique enables the controlled release of encapsulated active ingredients in response to specific stimuli. The rate and mechanism of release depend on the structure of the core and, in particular, the properties of the matrix material. Hydrophilic matrices allow faster release through diffusion, whereas lipophilic (fat- or wax-based) matrices exhibit slower release governed by erosion (Favaro-Trindade et al., 2021).

The release behavior of encapsulated materials depends on several interacting parameters, including the physicochemical nature of the core substance, the structural and chemical characteristics of the wall matrix, and the surrounding environmental conditions such as temperature, pH, and enzymatic activity (Figueiredo et al., 2022).

In lipid-based systems such as spray chilling or spray cooling, the diffusion of the active compound through the solidified matrix and the gradual erosion or leaching of the lipid phase are the predominant release mechanisms. Both the concentration and type of surfactant influence these dynamics: moderate levels of surfactants facilitate molecular diffusion, whereas excessive amounts can restrict migration through the matrix. Thermal and enzymatic responsiveness further modulate release profiles. Lipid carriers may undergo temperature-induced softening or melting, while enzymatic degradation by lipases can trigger release within the gastrointestinal tract (Favaro-Trindade et al., 2021). Such responsiveness enables the encapsulated actives to remain stable during processing and storage but to be liberated under physiological conditions. The use of lipid matrices for microencapsulation of heat- or oxidation-sensitive vitamins, natural pigments, organic acids, and essential oils is an effective method for both increasing oxidative stability and enabling targeted release in the gastrointestinal tract (Carvalho et al., 2019; Sartori et al., 2015; Tulini et al., 2017). In simulation tests, lipid microcapsules showed low release levels in gastric conditions, while release rates significantly increased in the intestinal environment. This suggests a controlled release pattern compatible with absorption sites (Paucar et al., 2016; Sartori et al., 2015).

Although release from lipid particles is often assumed to occur only through matrix melting, bioactive pharmaceutical ingredients located on the particle surface can directly diffuse into the environment, causing a burst release. Additionally, osmotic pressure, slow water diffusion, and mechanical rupture also influence the release rate (Sébastien Gouin, 2004).

The physical organization of the core and the structural properties of the matrix are two key factors that directly shape release kinetics. Interactions between the carrier material and the encapsulated molecules can affect both the release rate and the total release amount by altering the crystalline structure and diffusion behavior of the system. Indeed, vitamin C microparticles produced using palm oil or vegetable oil maintained long-term antioxidant stability, and a gradual release of approximately 10–15% was observed over 180 minutes (Carvalho et al., 2019).

Similarly, encapsulation processes with lipid matrices contribute to the preservation of the viability of probiotics during gastric transit. For example, cocoa butter microparticles protected *Lactobacillus acidophilus* and *Bifidobacterium animalis* strains against gastric conditions; however, partial loss of viability due to premature dissolution at body temperature was reported.

Table 1. Comparison of Microencapsulation Techniques Based on Working Principle, Wall Materials, Advantages, and Disadvantages

Microencapsulation Method	Working principle	Wall Material(s)	Advantage	Disadvantage	Reference
Spray Drying	The emulsified core and wall material are microencapsulated by spraying into hot media.	Gelatin/Gum arabic/maltodextrin/ sodium alginate/whey protein concentrate	Cheap,simple, high encapsulation ability, stable product, easy to encapsulate large batches	Temperature-sensitive products may deteriorate, partial products are difficult to control.	(Desai & Jin Park, 2005; Sousa et al., 2022; Suganya & Anuradha, 2017)
Spray Cooling	It has the same principle as spray drying. The emulsified substances are sprayed into the cold medium.	Gum arabic/sucrose/gelatin	Encapsulation of volatile and temperature-sensitive products without damage.	Fragmented products are difficult to control, small fragments have low encapsulation efficiency,	(Poshadri & Aparna, 2010; Sousa et al., 2022; Suganya & Anuradha, 2017)
Extrusion	It is the process of coating by holding the core and coating material together under high pressure.	Sodium alginate	The material is completely entrapped in the coating material with ease, the temperature is low, the capsules are highly resistant to oxidation.	It is difficult to separate the capsule from the water bath and drying, it contains highly viscous molten carrier material.	(Poshadri & Aparna, 2010; Sousa et al., 2022)
Lyophilization	It is the process of dehydrating the substance under vacuum and low temperature.	Maltodextrin/gelation	It is very successful in encapsulating heat sensitive, unstable and water insoluble substances.	High cost, long processing time, high care in handling and storage after encapsulation.	(Desai & Jin Park, 2005; Poshadri & Aparna, 2010)
Coacervation	It is based on the principle that the polymeric phase of the coating liquid separates and coats the core. It is caused by the electrostatic attraction of the core and the coating material.	Cellulose/carboxy methylcellulose/ethylcellulose/cellulose acetate phthalate	It can be encapsulated at room temperature, high throughput in sensitive foods.	Complex, expensive, coating agents can be toxic, coacervates can be unstable, can leave residues.	(Desai & Jin Park, 2005; Poshadri & Aparna, 2010; Sousa et al., 2022; Suganya & Anuradha, 2017)
Cocrystallization	Microencapsulated by vigorous mixing with concentrated sucrose syrup.	Sucrose	Cheap, simple, long shelf life due to entrapment in sugar crystals	High sugar content, high viscosity of the coating liquid	(Desai & Jin Park, 2005; Poshadri & Aparna, 2010; Sousa et al., 2022; Suganya & Anuradha, 2017)
Fludized Bed Coating	As the pulverized core material moves on a horizontal moving belt, the coating material is sprayed onto it.	Gum arabic/lactose	Encapsulation of the desired region of the core, taste masking, high film-forming properties	Degradation of heat-sensitive substances due to high temperature	(Sousa et al., 2022)

The addition of higher melting point lipids or soy lecithin as a stabilizing agent to the formulation significantly increased viability rates and intestinal release (Bampi et al., 2016; Tulini et al., 2017). Lecithin addition has also been reported to facilitate homogeneous distribution of core material, reduce crystallinity, and promote the formation of micelle regions that increase loading efficiency (Schubert et al., 2006). Further evidence from protein-loaded triglyceride microparticles prepared via spray congealing indicates that water permeation into the matrix produces internal pores, facilitating sustained diffusion of solutes. This interplay between hydration, pore formation, and solute mobility defines a key principle of diffusion controlled release (Zaky et al., 2010).

The controlled release mechanism occurs in micro- and nanocapsules through the combined action of a series of processes, including diffusion, erosion, enzymatic degradation, and thermal migration. Each of these processes is determined by the physicochemical and structural properties of the encapsulating system. A thorough understanding of these mechanisms provides the basis for developing systems with greater stability, functionality, and bioavailability in food, nutraceutical, and pharmaceutical products.

APPLICATION AREAS AND FUTURE PERSPECTIVES

Microencapsulation is a promising and emerging application for sensitive substances such as oils, flavor components, vitamins, minerals, color components and enzymes that are easily affected by external environmental conditions. Controlled release applications have shown that microencapsulation technology is very important for the food industry. Microencapsulation technology is used in many different sectors such as pharmacology, chemistry, cosmetics, food and paint to improve the functional properties and extend the shelf life of manufactured products (Karaogul et al., 2025; Kumar et al., 2024).

Pharmacological and Medical Applications

Essential oils possess a wide range of biological properties, including chemopreventive effects against cancer, antifungal, antiviral, antimicrobial, analgesic, anti-inflammatory, antioxidant, and antiparasitic activities. In terms of antioxidant activity, the essential oil of *Nigella sativa* L. seeds has shown significant activity in the elimination of hydroxyl radicals. The essential oil of M. armillaris shows marked antioxidant potential by altering superoxide dismutase activity and enhancing the concentrations of vitamins E and C. In addition to medical and pharmacological applications, essential oils are used in perfumes, cosmetics, hygiene products, disinfectants, repellents, candles, phytochemicals, preservatives, and food additives. They are used in microencapsulation processes to extend their shelf life (Khan et al., 2014; Sousa et al., 2022; Trombetta et al., 2005).

Food Applications

The food sector is probably the sector where the microencapsulation of essential oils is most extensively explored, with the encapsulation of flavors being one of the great interests of this industry. Flavors are necessary for some foods, to promote consumer satisfaction and the consumption of those products. Nevertheless, the flavor stability of foods has been a challenge for this sector in order to achieve quality and acceptability (Sousa et al., 2022).

In the fields of food, cosmetics, and personal care, essential oils (EOs) are widely utilized for their natural aromatic properties, which stem from their unique chemical composition. Within the food industry, EOs have gained attention for their role as natural preservatives, addressing the critical need to extend shelf life while maintaining product safety and quality (Burt, 2004). Shelf life refers to the duration in which a food product remains safe for consumption and retains its sensory, physical, chemical, microbiological, and functional attributes. One technique used to enhance stability is encapsulation, which can protect spices by preserving their qualities and preventing unwanted interactions with other substances (Gupta et al., 2016; Karaogul & Ugurtay, 2025). For instance, cinnamaldehyde—the key aroma compound in cinnamon—exhibits antimicrobial activity. When encapsulated, it can effectively inhibit yeast growth in baked goods. This approach allows cinnamon to provide flavour without negatively affecting the dough's leavening process (Sousa et al., 2022).

Cosmetic and Cleaning Applications

In the detergent and cosmetics industries, essential oils (EOs) are commonly encapsulated using microcapsule technology to enable controlled release. This approach enhances both the longevity of fragrance and the functional properties of the oils in products such as perfumes, creams, and deodorants (Carvalho et al., 2016). Natural aromatic compounds like patchouli (*Pogostemon cablin*), citronella (*Cymbopogon winterianus*), sandalwood (*Santalum album*), bergamot (*Citrus aurantium*), rosemary (*Rosmarinus officinalis*), peppermint (*Mentha piperita*), and vetiver (*Chrysopogon zizanioides*) are frequently used for their pleasant scents and beneficial properties (Lubbe & Verpoorte, 2011). These essential oils are widely incorporated into various consumer goods including soaps, shampoos, detergents, and fabric softeners. For example lavender, rose, sandalwood, microcapsules containing essential oils are incorporated into perfumes or scented body lotions. When the skin is rubbed or exposed to heat, the microcapsules break and gradually release the fragrance, increasing longevity (Sousa, 2022).

Over time, EOs have also found application in healthcare settings, particularly for combating hospital-acquired infections. They have been used as disinfectant solutions for cleaning medical instruments and surfaces, and in aerosol form in spaces like operating rooms and waiting areas to help reduce microbial contamination (De Billerbeck, 2007; Sousa et al., 2022).

Agrochemical Applications

One of the most significant causes of quality losses in agricultural products is infestation by pests. These organisms not only reduce product quantity and quality but also cause serious economic losses. Furthermore, carcinogenic secondary metabolites produced by some species pose a risk to both human and animal health. While chemical pesticides are widely used to address this problem, their intensive use has increased insect resistance and caused lasting environmental damage. Therefore, plant-derived essential oils are emerging as a more environmentally friendly alternative for pest management. The monoterpenoids found in essential oils disrupt the octopaminergic system in insects, creating an effective defense mechanism. Microencapsulation technologies are increasingly being used in biopesticide formulations to maintain the stability of these compounds and mimic natural release processes (Malešević et al., 2016; Minozzo et al., 2021; Sousa et al., 2022).

Textile Applications

Integrating insect-repellent essential oils into textiles is an effective strategy for protecting against mosquito-borne diseases (Govindarajan & Sivakumar, 2015). Lemongrass, cedarwood, geranium, pine, cinnamon, basil, thyme, garlic, and mint are the main herbs used for this purpose. Lavender and peppermint oils repel mosquitoes with their scents, while eucalyptus and cloves have deterrent effects, and cedarwood has lethal properties (Khanna & Chakraborty, 2018). Lemongrass oil is one of the most potent repellent ingredients. Litsea and lemon oils in microemulsion form have been found to have similar effects (Soroh et al., 2021). Citronella oil, converted into microencapsulates, is particularly effective against Aedes aegypti and can be applied to cotton and polyester fabrics (Bezerra et al., 2016). Biobased citronella formulations show higher repellent effect compared to synthetic forms (Sousa et al., 2022).

Conclusion

In pharmaceutical and food technology, microencapsulation has emerged as an important formulation strategy for safeguarding sensitive active ingredients and controlling their release. Engineering capsules at micro and nanoscale levels provides opportunities to modulate pharmacokinetic parameters, achieve targeted delivery, and protect chemical stability throughout manufacturing and storage.

A key determinant of these outcomes is the composition of the encapsulating wall material. The selection of wall materials is central to pharmacological performance. Polysaccharides and proteins provide biocompatibility and enzymatic degradability, while lipid-based carriers provide hydrophobic barriers that protect active pharmaceutical ingredients from hydrolysis and oxidation, enabling sustained or enteric release. Spray cooling and spray freezing methods are

providing promising results in the encapsulation of heat sensitive drugs and antioxidants. These techniques allow for the gradual and controlled release of compounds under physiological conditions. The addition of surfactants such as lecithin to the formulation not only increases encapsulation efficiency but also helps regulate diffusion within the lipid matrix. Release processes can be controlled by diffusion, erosion, osmotic pressure, temperature, and enzyme mediated mechanisms. A thorough understanding of the physicochemical interactions between the core material and the matrix is crucial for predictable and reproducible management of release behavior.

Within pharmaceutical formulations, micro and nanocapsules provide several practical benefits, including improved absorption, protection from degradation in the digestive tract, and controlled release at targeted sites. Ongoing studies increasingly emphasize the development of stimuli-responsive systems that combine polymeric and lipidic materials to enhance therapeutic precision and improve treatment adherence. Such innovations have the potential to transform drug delivery strategies, advance personalized medicine, and advance next generation pharmaceutical formulations.

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