Review Article

Microencapsulation In Cosmetics: A Comprehensive Review of Technologies and Applications

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ABSTRACT

Microencapsulation has become a transformative technology in the cosmetics and personal care industry, directly addressing the critical challenge of instability in biologically active ingredients. This review delves into the diverse applications of microencapsulation techniques in cosmetics, emphasizing their pivotal role in enhancing the stability, enabling controlled release, and boosting the efficacy of sensitive active compounds. The focus is on a broad spectrum of these ingredients, including retinol, ascorbic acid, α-tocopherol, catechins, caffeine, rosmarinic acid, resveratrol, linoleic acid, lycopene, and benzoyl peroxide, all of which are susceptible to degradation from environmental factors such as heat, light, and oxidation. The article explores how these compounds benefit from encapsulation within a variety of natural and synthetic polymer shells, such as gum Arabic, gelatin, chitosan, and poly (lactic acid). Microencapsulation methods are categorized into three main groups: physical (e.g., spray drying, solvent evaporation, fluidized-bed coating), physico-chemical (e.g., coacervation, ionic gelation), and chemical (e.g., interfacial and in situ polymerization). For each method, its underlying mechanisms, the types of coating materials employed, and critical optimization parameters are highlighted. Key applications within cosmetics are discussed, including the development of products with improved sensory qualities, enhanced skin penetration, and superior protection of active ingredients in formulations like creams, serums, sunscreens, and hair care products. Furthermore, the review outlines essential evaluation methods, such as encapsulation efficiency, particle size analysis, and in vitro/in vivo release studies, underscoring their significance in guaranteeing optimal product performance. By integrating insights from recent studies, this review demonstrates how microencapsulation is a driving force for innovation in the cosmetics sector, providing effective solutions for creating high-value, stable, and impactful personal care products.

Keywords: Microencapsulation, cosmetics, polymers, microcapsules.

1. INTRODUCTION

The global market for cosmetics and personal care products is worth billions of dollars and has experienced significant growth. Product differentiation is necessary for success in this cutthroat and demanding industry, and emerging technologies like microencapsulation can help achieve this. Biologically active ingredients that are unstable and susceptible to changes in temperature, pH, light, and oxidation are frequently found in cosmetic and personal care products. These compounds may therefore experience undesirable reactions that diminish or eliminate their efficacy or even cause the cosmetic product to deteriorate. In order to improve stability, guard against deterioration, and regulate and guide the release of active compounds used in cosmetic goods, microencapsulation technologies have been developed. Microencapsulation has been utilized to create cosmetic formulations with enhanced sensory qualities, stability, and efficacy, and it is becoming more and more popular in this industry [1].

Micro-encapsulation is a process of encapsulating a material containing an active ingredient (core material), in a shell of another material (shell/wall material). This process yields small capsules known as microcapsules, which possess numerous beneficial properties (see Figure 1). These microcapsules typically have diameters ranging from one micron to several millimetres [2]. They can exhibit a variety of structures, including spherical and irregular forms, with configurations that may feature a single core, multiple cores, or even multilayer coatings. The specific structure of the microcapsules is influenced by various factors, including the rigidity of the coating layer, the nature of the core material, and the method of preparation [3].

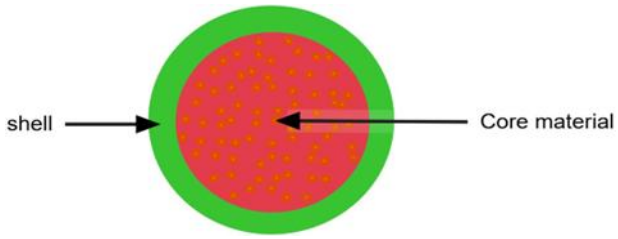

Figure 1: Microcapsule

Microencapsulation preparation techniques are categorized into three main classes: chemical, physical, and physico-chemical methods. Chemical methods encompass in situ polymerization and the use of liposomes; physical methods involve spray-drying and fluidized bed coating, while physico-chemical methods include coacervation and sol-gel encapsulation. Among these techniques, spray drying is the most commonly utilized. The microcapsules generated by each method exhibit distinct characteristics [4]. In nearly all microcapsules, the coating materials are predominantly composed of organic polymers, although wax and fats have also been utilized, particularly in food and pharmaceutical applications, where the coating materials

must comply with FDA specifications. There are four mechanisms through which core materials are released from microcapsules: degradation, dissolution, melting of capsule walls, and diffusion of core substances through a compromised shell. Additionally, abrasion (the gradual erosion of the capsule shell) and biodegradation represent two other mechanisms that are less frequently employed. Microencapsulation technology has found applications across various fields, including drug encapsulation in the pharmaceutical sector, adhesive materials, agrochemicals, live cells, catalysts, vitamin storage, and more [5]. The pharmaceutical industry has reaped significant benefits from microencapsulation technology. A key application of this encapsulation technique in pharmaceuticals is controlled or sustained drug delivery. The primary advantage of microencapsulation is that the core material is entirely coated and shielded from the external environment. Drug formulations with controlled release provide numerous benefits compared to traditional drug forms. Conversely, microcapsules help stabilize and protect the encapsulated drug from rapid inactivation within the patient's body, facilitating its release in regulated amounts.

Microencapsulation is increasingly prevalent in the cosmetics and personal care sectors. Encapsulates can be utilized in numerous ways within cosmetics. Products that are microencapsulated offer a range of advantages, including the protection of active ingredients during application, a gradual release over the skin's surface, and enhanced penetration of substances for improved efficacy. The delivery of active ingredients in cosmetics, whether topical or transdermal, necessitates safe and non-toxic methods to effectively reach targeted areas within the skin. This technology is applied in various cosmetic products, including shower and bath gels, lotions and creams, hair care items, sunscreens and tanning products, makeup, perfumes, soaps, toothpaste, and more. Additionally, it contributes to enhancing the tactile and visual appeal of a wide array of cosmetic and personal care items. Microencapsulation introduces innovation into the cosmetic field, enabling the creation of high-value products that cater to human needs and preferences [6]. This research explores recent findings on encapsulation methods for personal care and cosmetic uses, focusing particularly on topical microencapsulation in cosmetics.

2. COATING MATERIALS

The choice of microencapsulation techniques and coating substances is mutually dependent. Depending on the coating substance or technique utilized, the suitable method or coating substance is chosen. Coating substances, which fundamentally consist of film-forming agents, can be selected from a diverse range of natural or synthetic polymers, based on the material being coated and the desired characteristics of the final microcapsules. The formulation of the coating substance is the primary factor influencing the functional attributes of the microcapsule and its potential to enhance the efficacy of a specific ingredient. Since no single coating substance can fulfil all requirements, in practice, either combinations of coating substances are used, or additives such as oxygen scavengers, antioxidants, chelating agents, and surfactants are incorporated. The commonly used coating substances are [7].

Natural polymers:

- Gums: Gum Arabic, sodium alginate, carrageenan, agar
- Carbohydrates: Starch, dextran, sucrose, chitosan, corn syrup solids
- Celluloses: Carboxymethylcellulose, methylcellulose, ethyl cellulose
- Lipids: Bees wax, stearic acid, phospholipids, paraffin, diacylglycerols
- Proteins: Gluten, casein, Gelatin, albumin, peptides [7,8].

Synthetic polymers:

- Non-biodegradable polymers: Poly methyl methacrylate, Glycidyl methacrylate Epoxy polymers
- Biodegradable polymers: Lactides, Glycolides & their co polymers Poly alkyl cyanoacrylates Polyanhydrides[9]

3. MICROENCAPSULATION TECHNIQUES

A variety of techniques exist for encapsulating core materials. Generally, these methods can be categorized into three main types. The different microencapsulation techniques include:

1. Physical methods
2. Physico-chemical methods
3. Chemical methods

The techniques listed above are commonly employed for the microencapsulation of various pharmaceuticals. The choice of technique will vary based on the physical characteristics of the core substance that needs to be encapsulated [11]

3.1. PHYSICAL METHODS

3.1.1. Spray drying and congealing

Spray-drying is a method of encapsulation that involves atomizing a liquid into a dry powder using an injector along with a stream of hot drying gas.

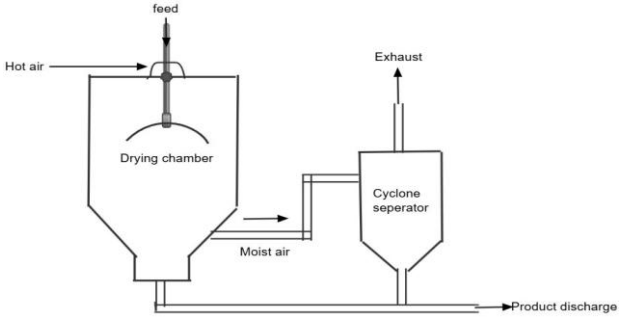

Figure 2: Spray drier

Spray drying consists of 3 stages:

(i) homogenizing the feed liquid with an atomizer

(ii) drying the feed solution using a hot gas carrier to facilitate solvent evaporation,

(iii) collection of the dry particles by cyclone separator.

The liquid feed consists of a core and wall material. The liquid is injected to the drying vessel by a nozzle or atomizer to generate tiny droplets, followed by the evaporation of the solvent. Subsequently, these dried particles are removed from the drying gas into a collector using a cyclone or filter. The properties of spray-dried powders are influenced by the processing factors of spray drying, which include drying temperature, drying air flow rate, feed flow rate, atomizer speed, type of carrier agent, and concentration of the carrier agent.

Common wall materials utilized in spray drying include polysaccharides such as gum Arabic, cyclodextrins, and maltodextrin with varying dextrose equivalent values, as well as proteins like whey proteins, sodium caseinate, soybean proteins, and others such as modified starch, gelatin, gellan gum, and chitosan [10].

Spray congealing can be performed using spray-drying equipment, where a protective coating is applied in a molten state. The core material is dispersed in a melt of the coating material instead of a coating solution. The solidification of the coating occurs by spraying the hot mixture into a stream of cool air. Waxes, fatty acids, alcohols, and polymers that are solid at room temperature but can melt at reasonable temperatures are suitable for spray congealing [11].

- Bo Shu et al. conducted research where Lycopene microcapsules were prepared by spray-drying technique using a gelatin-sucrose wall system, and the effects of core-to-wall ratio, gelatin-to-sucrose ratio, homogenization pressure, temperatures, and lycopene purity on encapsulation yield and efficiency were investigated. Under optimal conditions, the microcapsules exhibited good storage stability, spherical morphology with a smooth surface, and effective lycopene encapsulation within a “bee-net”-like interior structure [12].
- Frascareli et al. investigated the microencapsulation of coffee oil by spray drying, focusing on the influence of process conditions such as wall material composition, inlet temperature, and feed emulsion properties on encapsulation efficiency and product stability. Their results demonstrated that optimized spray-drying parameters significantly improved encapsulation efficiency, oxidative stability, and retention of coffee oil's volatile compounds [13].

3.1.2. Solvent Evaporation

Solvent evaporation refers to the process of removing a solvent from an emulsion that contains a polymer volatile organic solvent in water. This method involves four primary steps:

(i) dissolving the polymer as a coating and active ingredient in an organic solvent to create a suspension, emulsion, or solution;

(ii) emulsifying the organic phase (dispersed phase) within an aqueous phase (continuous phase) through stirring, static mixing, extrusion, or dripping;

(iii) removing the solvent via evaporation or liquid extraction; and

(iv) recovering the particles through filtration or centrifugation, followed by drying the microspheres.

Various process variables can affect the formation of microspheres, including the type of solvent, solvent volume, polymer concentration, type and concentration of emulsifier, rate of solvent removal, addition of buffers or salts to either the internal or external phase, phase volume ratio, and temperature. This technique has been utilized to produce matrices based on polylactide, poly (lactic-co-glycolic) acid, polymethyl methacrylate, dimethylamino borane, ethyl cellulose, polyethylene glycol, polycaprolactone, eudragit, polyvinyl alcohol, and kafirine[10].

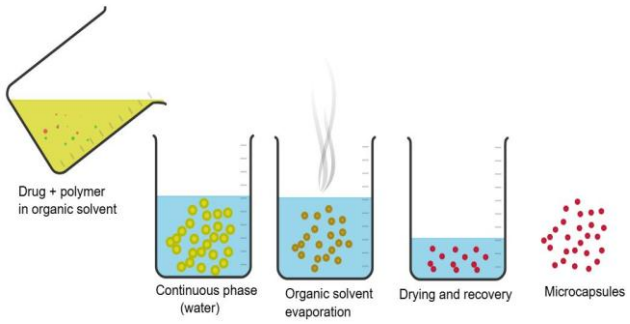

Figure 3: Solvent evaporation technique

- Tiwari et al. systematically studied the solvent evaporation technique for microencapsulation, finding that process variables like polymer concentration, stirring speed, and solvent selection play an important role in determining particle size, encapsulation efficiency, and release performance. Their study emphasized that precise optimization of these parameters is essential for producing uniform, high-performance microcapsules suitable for pharmaceutical and industrial applications [14].
- Freitas, Merkle, and Gander comprehensively reviewed the solvent extraction/evaporation technique for microencapsulation, highlighting the critical role of process parameters such as solvent type, emulsification method, and polymer properties in determining microsphere size, morphology, and encapsulation efficiency. Their findings revealed that precise control over these factors enables the production of microspheres with tailored release profiles and

improved stability, making the technique highly versatile for pharmaceutical and biomedical applications [15].

3.1.3. Fluidized-bed technology (Air suspension technique)

The liquid coating is applied to the particles through spraying, and the quick evaporation facilitates the creation of an outer layer on these particles. The desired thickness and formulations of the coating can be achieved as needed. Various types of fluid-bed coaters include top spray, bottom spray, and tangential spray. In the top spray system, the coating material is directed downwards onto the fluid bed, allowing solid or porous particles to become encapsulated as they enter the coating area. Top spray fluid-bed coaters yield a higher quantity of encapsulated particles compared to bottom or tangential sprays. The bottom spray is also known as 'Wurster's coater' which contain a coating chamber with a cylindrical nozzle and a perforated bottom plate. The cylindrical nozzle is responsible for spraying the coating material. As the particles ascend through the perforated bottom plate and pass the nozzle area, they become encapsulated by the coating material. The coating material adheres to the surface of the particles through the evaporation of the solvent or the cooling of the encapsulated particle. The process continues till the needed thickness and weight are achieved. Although it is a time-intensive process, the multilayer coating technique aids in minimizing particle defects. The tangential spray involves a rotating disc located at the bottom of the coating chamber, matching the chamber's diameter. During the operation, the disc is elevated to create a gap between its edge and the chamber. The tangential nozzle is positioned above the rotating disc, through which the coating material is dispensed. The particles pass through the gap into the spraying zone and become encapsulated. As the particles travel a short distance, increased in yield of encapsulated particles are observed [10].

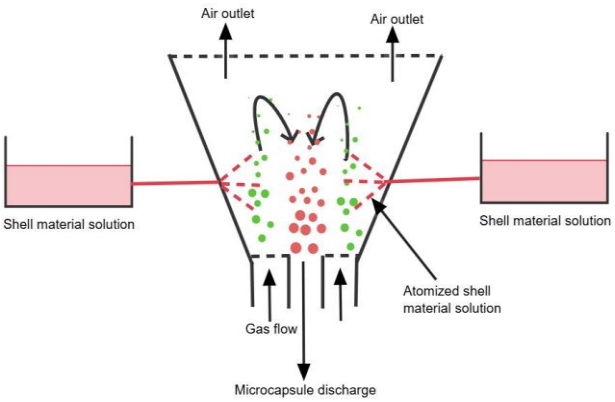

Figure 4: Fluidized bed coater

- Semyonov et al. investigated the microencapsulation of probiotics using an air-suspension fluidized-bed technique, focusing on enhancing the viability and stability of probiotic cultures. Their findings demonstrated that this method effectively produces uniform, protective microcapsules, significantly improving the survival of probiotics during storage and under gastrointestinal conditions [16].
- Schell and Beermann developed a fluidized bed microencapsulation technique for *Lactobacillus reuteri* using sweet whey and shellac as coating materials to enhance acid resistance and gastrointestinal survival. Their study demonstrated that this approach significantly improved the probiotic's stability under simulated gastric conditions, highlighting its potential for functional food applications [17].

3.2. PHYSICO-CHEMICAL METHODS

3.2.1 Coacervation-phase separation

The coacervation technique is characterized as a colloidal phenomenon that entails the liquid-liquid phase separation of either a single polymer or a combination of two oppositely charged polymers in an aqueous solution. This separation is initiated by various interactions, including electrostatic forces, hydrogen bonding, hydrophobic interactions, polarization-induced attractive forces, and the presence of chemical or enzymatic cross-linking agents such as glutaraldehyde or transglutaminase. The coacervation process can be classified as either simple or complex, depending on the number of polymers involved. Simple coacervation is done by just one type of polymer, followed by the addition of strong hydrophilic agents to the colloidal solution, where complex coacervation is done by blending 2 or more types of polymers to form a wall around an active core.

The creation of an emulsion that distributes the core material throughout an aqueous polymer solution is the first step in the complicated coacervation technique. This is followed by the application of a second aqueous solution, which wraps the core material in a uniform layer, facilitated by the addition of salt, adjustments to pH, temperature changes, or dilution of the medium. The final step involves stabilizing the microcapsules through cross-linking, desolvation, or thermal treatment. After filtration or centrifugation, soluble, aggregated, or precipitated complexes are obtained, which are then washed with an appropriate solvent and dried.

Numerous coating materials have been assessed for simple coacervation, including gelatin, alginate, chitosan, glucan, and cellulose derivatives. For complex coacervation, combinations such as gelatin/gum arabic, gelatin/carboxymethyl cellulose, alginate/ polylysine, alginate/chitosan, albumin/gum arabic, and glucan/cellulose derivatives have been evaluated [10].

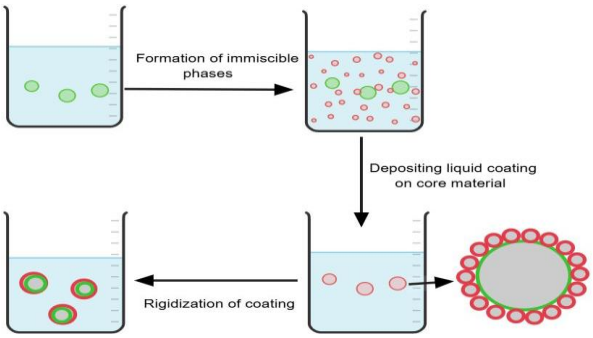

Figure 5: Coacervation technique

- Comunian et al. studied the microencapsulation of ascorbic acid by complex coacervation with gelatin and gum Arabic, to enhance its stability and its release rate. The results demonstrate effective protection of ascorbic acid against degradation, with promising potential for food and pharmaceutical applications [18].
- Nori et al. investigated the microencapsulation of propolis extract using complex coacervation with gelatin and gum Arabic to improve its stability and handling. The study demonstrated that the technique effectively encapsulated bioactive compounds, providing protection and potential for controlled release in food and pharmaceutical products [19].

3.2.2. Ionic Gelation

Ionic gelation is a microencapsulation technique that relies on the crosslinking ability of polyelectrolytes in the presence of multivalent ions such as Ca^{2+}, Ba^{2+}, and Al^{3+}. This technique can be implemented through either extrusion or emulsification/gelation methods. The extrusion method is the most prevalent for creating spherical gel particles, achieved by dripping an aqueous polymer solution through a syringe needle or nozzle into a gelling bath containing $CaCl_2$. The emulsification/gelation method involves creating an emulsion that contains a hydrophobic active component within a polymer solution, which is then dripped into a calcium solution.The gelation technique for encapsulation can be performed either externally or internally. Calcium ions diffuse into the polymer solution from the external source during external gelation. Conversely, in the internal gelation method, a calcium salt solution is added dropwise to the polymer solution, leading to the formation of aqueous core calcium alginate capsules.

Polymers such as alginate, chitosan, pectin, konjac, gellan gum, and carboxymethyl cellulose are utilized in cross-linked gelling systems. Among these, alginate is the most frequently used polymer due to its non-toxic, biodegradable, and biocompatible characteristics, along with its excellent gelling properties under safe and mild conditions [10].

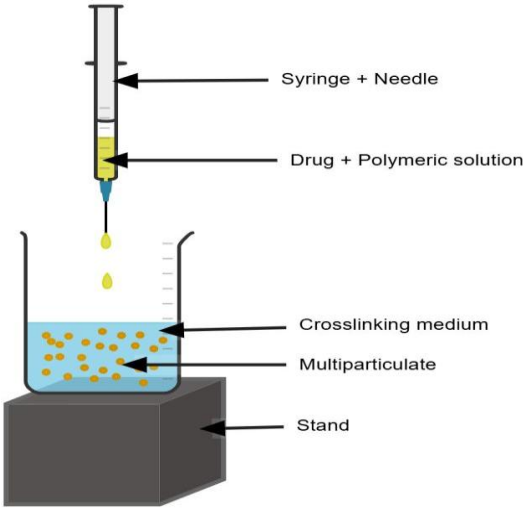

Figure 6: Ionic gelation technique

- Menin et al. studied the microencapsulation of flaxseed oil by ionotropic gelation method. The results showed that the encapsulation significantly improved the oil's resistance to oxidation, enhancing its potential for use in functional food formulations [20].
- Chun et al. studied the microencapsulation of *Lactobacillus plantarum* DKL 109 using the external ionic gelation method to enhance its viability. The encapsulated probiotics showed improved survival under harsh environmental conditions, suggesting potential applications in functional foods [21].

3.3. CHEMICAL METHODS

3.3.1. Interfacial polymerization

The wall formation in this method is defined by polymerization, where hydrophilic and lipophilic monomers come together at an oil-water emulsion and react to create a polymeric membrane on the droplet or particle's surface. Since this form of polymerization does not necessitate catalysts and can occur at low temperatures, the interfacial polymerization technique is suitable for preparing microcapsules. The yield and quality of the polymeric membrane produced through this method can be enhanced by adjusting process parameters such as monomer concentrations, temperature, mixing rate, and reaction time. Four types of polymers are used for the microcapsule production by interfacial polymerization: polyamides, polyurethanes, polyureas, and polyesters.

The interfacial polymerization technique offers several advantages, including the ability to control the average size of capsules and the thickness of the membrane, high loading capacity of active compounds etc. It is also cost-effective, easy to scale up, and characterized by a straightforward and reliable process. But there are disadvantages to the application of this technique. Specifically, producing a large oil-water interface is challenging, as proteins or enzymes may become inactivated, which can alter their biological activities during the polymerization reaction. Furthermore, this technique lacks control over the polymerization characteristics, including the yield and quality of the polymer membrane. Additionally, the need for washing steps to eliminate monomers, by-products, organic solvents, and surfactants can lead to the loss of water-soluble active substances and may harm acid-labile actives due to the formation of HCl by-products, resulting in pH changes, which are other disadvantages of interfacial polymerization[10].

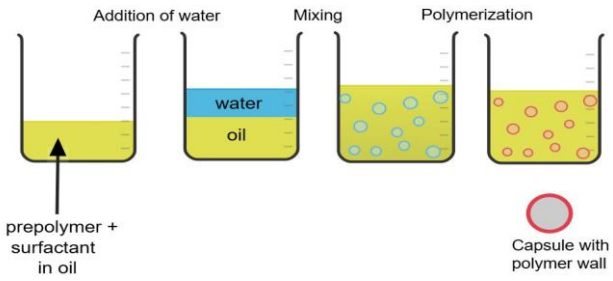

Figure 7: Interfacial polymerization

- Saihi et al. developed microcapsules containing ammonium phosphate using a polyurethane shell formed via interfacial polymerization. The study demonstrated that this technique effectively produced stable microcapsules with potential applications in flame retardant systems [21].
- Lu et al. formulated microencapsulated polyurethane by interfacial polymerization technique. The resulting microcapsules exhibited good thermal stability, efficient encapsulation, and promising potential for thermal energy storage applications [22].

3.3.2. In situ polymerization

The insertion of polymerization monomers into the encapsulation reactor causes the capsule shell to develop, just like in interfacial polymerization. During this process, no reactive agents are introduced to the core material; instead, polymerization is confined to the continuous phase and occurs at the interface created by the dispersed core material and the continuous phase. Initially, a low molecular weight prepolymer is produced, and over time, this prepolymer increases in size, depositing on the surface of the dispersed core material, thereby creating a solid capsule shell [11].

- Brown et al. reported the in-situ microencapsulation of dicyclopentadiene using poly(urea-formaldehyde) shells for self-healing material applications. The study demonstrated successful formation of stable microcapsules capable of storing the healing agent, enabling autonomous repair of polymer composites [23].
- Luo et al. studied the microencapsulation of decabromodiphenyl ether by in situ polymerization in order to enhance its dispersion and thermal stability. The resulting microcapsules exhibited uniform morphology and enhanced thermal protection, indicating their potential for use in flame-retardant materials [24]

3.3.3. Molecular inclusion complexation

Molecular inclusion is a molecular-level encapsulation approach in which a host (polymer) traps a guest (active) substance via a variety of physicochemical factors, such as hydrophobic interactions, van der Waals forces, or hydrogen bonds. These complexes are generated through a reaction that only occurs in the presence of water. The most prevalent "host" molecules are cyclodextrins (CDs), which feature a hydrophilic exterior and a hydrophobic interior comprising 29 units. A guest molecule with apolar characteristics can be trapped within the apolar internal cavity via hydrophobic interactions.

There are three approaches to creating the active-β-cyclodextrin complex. The first approach involves dissolving β-cyclodextrin in water and adding the active compounds to create an inclusion complex in crystalline form. The second approach entails dissolving β-cyclodextrin in a smaller volume of water than the first method to produce a concentrated suspension, followed by mixing in the active compounds to form a crystalline inclusion complex. The final method requires dissolving β-cyclodextrin in a significantly lower water content to create a paste, with the active compounds incorporated during kneading to form an inclusion complex. This third method is considered superior because it does not require post-processing applications, while the last steps of the first two methods involve additional separation and drying [10]

- Zhan et al. studied the formation of molecular microcapsules of eugenol using β-cyclodextrin and its derivatives to enhance its stability and control its release. The inclusion complexes showed improved thermal stability and encapsulation efficiency, suggesting their potential for applications in food preservation and controlled delivery systems [25].
- Fuenmayor et al. reviewed the encapsulation of carotenoids as food colorants through the formation of cyclodextrin inclusion complexes to enhance their stability and bioavailability. The study highlights that this technique effectively protects carotenoids from degradation while improving their solubility, making them more suitable for food industry applications [26].

4. EVALUATION

a. Percentage Yield: The weight measured was divided by the total weight of all non-volatile components used in the preparation of the microcapsule.

% yield = (Actual weight of product / Total weight of excipient and drug) x 100

b. Encapsulation Efficiency: In a 100ml volumetric flask, 25mg of crushed microcapsules were taken and dissolved with a small amount of ethanol, with the volume adjusted to the mark at pH 6.8, and stirred for 12 hours. After stirring, the solution was filtered through Whatman filter paper, and appropriate dilutions were made from the filtrate, with absorbance measured at 206 nm using a UV-spectrophotometer 1800 (Shimadzu).

Encapsulation efficiency= (Actual drug content/theoretical drug content) x 100

c. Micromeritic Properties:

- Particle Size: The average particle size was determined using the optical microscopy method. A tiny quantity of microcapsules, with an average size of 100, were obtained, dissolved in glycerin, and put on a sterile glass slide.
- Angle of Repose: The angle of repose was determined using the fixed funnel method.

Angle of repose $\theta = \tan^{-1}(H/R)$

where, H = Height of the pile

R = Radius of the pile

• Scanning Electron Microscopy: Samples for SEM analysis was prepared using the following method. The shape and surface morphology of the microcapsules were examined using a scanning electron microscope. Double-sided tape was used to mount the microcapsules on the SEM, and under low pressure, a 200 nm-thick gold layer was applied. At a 10KV accelerating voltage, the microcapsules were seen.

d. Drug Release:

• In vitro release studies: The in vitro dissolution profile for each formulation was established using the USP XXII type 2 basket method (900 ml of pH 6.8 phosphate buffer, 100 rpm, 37±0.5°C). Microcapsules were placed in the basket of the dissolution apparatus. An aliquot of 5 mL was taken from the dissolution medium at appropriate time intervals, and the volume withdrawn was replaced with an equal volume of dissolution medium to maintain a constant total volume. The absorbance of the samples was recorded at λmax 206 nm after necessary dilution, using pH 6.8 phosphate buffer as the blank. The results from the in vitro drug release studies, derived from the absorbance data, were compiled and presented graphically as Cumulative % drug released versus Time.

• In Vivo Evaluation: The in vivo assessment of microencapsulated particles entails administering the encapsulated formulation to appropriate animal models, typically through oral, intravenous, or targeted routes, based on the intended application. After administration, biological samples such as blood, urine, faeces, and tissue are collected at specified intervals to evaluate bioavailability, release kinetics, and biodistribution using analytical methods like HPLC, LC-MS, or fluorescence imaging. Functional efficacy is assessed by monitoring physiological responses pertinent to the encapsulated compound, including antioxidant activity, therapeutic effects, or probiotic colonization. Furthermore, safety evaluations, which include tracking body weight, organ histology, and blood parameters, are conducted to identify any adverse effects. The findings are compared to non-encapsulated controls to assess the improved stability, targeted delivery, and effectiveness of the microencapsulation system in physiological conditions [27].

5. APPLICATIONS

5.1. Cosmetics

- Retinol, also known as vitamin A, is utilized in topical cosmetic products such as creams, skin serums, and anti-aging treatments. It functions as an antioxidant and improves the look of dry or damaged skin by minimizing flaking and reinstating suppleness. Vitamin A is extremely sensitive to heat, light, oxygen, and moisture, which can lead to swift degradation during processing, storage, and digestion [28]. Gonçalves et al. (2017) prepared vitamin A microspheres by spray-drying process. The study showed that the microparticles effectively protected vitamin A and enabled sustained release, enhancing its stability for food and pharmaceutical applications [29].
- Ascorbic acid, commonly known as vitamin C, serves multiple biological, pharmaceutical, and dermatological roles as outlined below; it aids in collagen production, offers protection against UV radiation, reduces melanin levels, neutralizes free radicals, and boosts the immune system. These roles are intricately linked to the widely recognized antioxidant characteristics of this substance. Nevertheless, vitamin C is highly sensitive to environmental factors such as air, moisture, light, heat, metal ions, oxygen, and alkaline conditions, leading to its rapid breakdown into biologically inactive forms [28]. Abbas et al. (2012) reviewed various microencapsulation techniques for ascorbic acid to enhance its stability and controlled release. The study highlighted methods like spray-drying, coacervation, and liposomal encapsulation, emphasizing their role in protecting ascorbic acid from degradation and improving its application in food and pharmaceutical industries[30].
- α-Tocopherol, commonly known as vitamin E, is extensively utilized as a potent antioxidant in various medical and cosmetic fields; however, it is quickly broken down because of its sensitivity to light, heat, and oxygen [28]. Chaiyasat et al. (2013) developed microcapsules of vitamin E using poly (l-lactic acid) (PLA) as the encapsulating material. The study demonstrated that the PLA microcapsules effectively protected vitamin E, offering potential for controlled release and improved stability in various applications [31].
- Catechins serve as significant antioxidants found in green tea (Camellia sinensis or Camellia assamica); however, their poor skin penetration has restricted the use of green tea in cosmetic formulations to date [28]. Snoussi et al. (2020) microencapsulated catechin using double emulsion technique to improve its stability and release rate. The study analysed the release kinetics, rheological, and thermodynamic properties, demonstrating effective encapsulation and sustained release of catechin [32].
- Caffeine serves as an active ingredient in anti-cellulite formulations, possesses potential antioxidant properties that shield cells from UV radiation, and helps to slow the skin's photo-aging process. Additionally, it enhances blood microcirculation in the skin and promotes hair growth [28]. Mohammadi et al. (2018) developed alginate-based microcapsules for encapsulating caffeine, incorporating different natural biopolymers (such as gelatin and chitosan) to improve the matrix structure. The study evaluated the microcapsules' physicochemical properties and investigated caffeine release under simulated mouth conditions. Results showed that the type of biopolymer significantly influenced encapsulation efficiency, particle morphology, and release behaviour, with certain combinations providing

controlled release suitable for flavour or functional food applications [33].

- Rosmarinic acid (RA) exhibits several notable biological activities, including antioxidant, anticarcinogenic, antimicrobial, and anti-inflammatory properties. However, despite its potent antioxidant effects, its application in cosmetics is restricted due to poor water solubility, potential discoloration, and chemical instability[28]. Casanova et al. (2016) conducted preliminary studies on the microencapsulation of rosmarinic acid using chitosan and modified chitosan for potential topical delivery applications. The study assessed encapsulation efficiency, particle size, and morphology, as well as the release profile of rosmarinic acid. Results indicated that both chitosan and modified chitosan effectively encapsulated the compound, with modified chitosan showing improved encapsulation efficiency and controlled release, suggesting promise for use in cosmetic or pharmaceutical topical formulations[34].

- Resveratrol, a naturally occurring polyphenol, has garnered significant attention for various applications on the skin due to its properties as an antioxidant that shields cells from oxidative damage, its ability to reduce inflammation, and its potential anti-aging benefits for the skin. Nevertheless, resveratrol suffers from low bioavailability, which is linked to its poor water solubility, low stability under environmental stress, and its difficulty in reaching target sites to deliver the intended health effects. Encapsulation presents a promising strategy to enhance the solubility of resveratrol, stabilize it, and improve its bioavailability[28]. More et al. (2024) developed alginate-based microcapsules for encapsulating resveratrol using the internal gelation technique. The study focused on the fabrication process, characterization of the microcapsules (including morphology, encapsulation efficiency, and stability), and evaluation of resveratrol release kinetics. The results demonstrated successful encapsulation with controlled, sustained release of resveratrol, highlighting the potential of alginate microcapsules for enhancing resveratrol stability and bioavailability in cosmetic or pharmaceutical applications[35].

- Linoleic acid (LA), also referred to as vitamin F, is an unsaturated fatty acid that serves as an emollient and thickening agent in cosmetic products. Research indicates its effectiveness in regulating cells and repairing the skin barrier, in addition to its properties as an antioxidant and anti-inflammatory. Furthermore, linoleic acid is recognized for its ability to lighten hyper-pigmented skin. Due to its low solubility in water, this component is frequently encapsulated in liposomes for topical use[28]. Jimenez et al. (2004) studied the microencapsulation of linoleic acid using spray-drying and evaluated its oxidative stability. The study assessed encapsulation efficiency, particle morphology, and the ability of the microcapsules to protect CLA from oxidation. Results showed that spray-drying effectively encapsulated CLA, significantly improving its oxidative stability, indicating the potential of this technique for enhancing the shelf life and functional properties of CLA in cosmetic formulations [36].

- Lycopene, a fat-soluble carotenoid, is recognized for its potent antioxidant properties that aid the skin's defense mechanisms. Additionally, lycopene serves as a pigment that can enhance skin tone. Nevertheless, it tends to be unstable when subjected to light and moisture[28]. Shu et al. (2006) studied the microencapsulation of lycopene using the spray-drying technique to improve its stability and usability in cosmetic products. The research focused on optimizing encapsulation conditions, evaluating encapsulation efficiency, particle characteristics, and lycopene retention. The results demonstrated that spray-drying effectively protected lycopene from degradation, with suitable wall materials and processing conditions enhancing encapsulation efficiency and stability, making it promising for cosmetic applications [37].

- Benzoyl peroxide (BPO) is frequently utilized in topical products for acne treatment and as an antibacterial agent. Nevertheless, skin irritation is a prevalent side effect, and research indicates that a controlled release of BPO to the skin may alleviate this issue[28]. Desai et al. (2024) reviewed the use of microencapsulated benzoyl peroxide (BPO) for the treatment of rosacea, highlighting its role within the current therapeutic landscape. The review discussed how microencapsulation enhances the tolerability and controlled release of BPO, reducing irritation commonly associated with conventional formulations. The authors compared available treatment options for rosacea and concluded that microencapsulated BPO offers an effective, well-tolerated alternative for managing inflammatory lesions, with improved skin compatibility[38].

5.2. Pharmaceutical applications

• Curcuminoids, the active components extracted from turmeric (Curcuma longa), are well-known for their anti-inflammatory, antioxidant, anticancer, antimicrobial, and wound healing effects, which render them significant for pharmaceutical uses. Nevertheless, their clinical application is constrained by poor water solubility, low bioavailability, and rapid metabolism. Ang et al. (2019) created microencapsulation systems for curcuminoids to improve their stability, bioavailability, and controlled release for pharmaceutical purposes. The research indicated that microencapsulation greatly enhanced the therapeutic efficacy of curcuminoids by shielding them from degradation and facilitating sustained release[40].

• Lorenzo-Lamosa et al. (1998) discovered chitosan microspheres designed for targeted colonic drug delivery. The findings revealed that these microspheres offer controlled release and safeguard the drug from early

degradation in the upper gastrointestinal tract, making them suitable for colon-specific treatments[41].

• Doxorubicin is a potent chemotherapeutic drug, but its clinical application is considerably hampered by severe side effects, especially cardiotoxicity, and non-specific distribution throughout the body. Zhao et al. (2017) developed hollow chitosan-alginate multilayer microcapsules for drug delivery, concentrating on doxorubicin encapsulation. The study showed effective drug loading, controlled release, and validated the system's biocompatibility and anticancer potential through both in vitro and in vivo assessments[42].

• The replacement of non-orally administered therapeutic agents such as insulin, which is typically injected, could benefit from oral encapsulated delivery.

• Gene therapy applications involve the delivery of corrective gene sequences (e.g., plasmid DNA) and hold promise for treating genetic disorders like cystic fibrosis and haemophilia, among others.

• Vaccine delivery: This enhances the administration of vaccines aimed at diseases such as AIDS, tumours, cancer, diabetes, etc.

• Protein drug delivery.

5.3. Food industry [39]

• Microencapsulation technology is useful in integrating minerals, vitamins, flavours, and essential oils in food.

• Furthermore, microencapsulation can streamline the food production process by transforming liquids into solid powders, reducing production expenses by facilitating batch processing with inexpensive powder handling equipment.

• Microcapsules protect sensitive materials during processing and packaging conditions, while enhancing the shelf life of the active ingredients.

5.4. Agriculture `

• In today's world, insect pheromones are emerging as a practical biorational substitute for traditional hard pesticides. In particular, sex attractant pheromones can diminish insect populations by interfering with their mating rituals. Hence small number of specific pheromones are released in the mating season. Polymer microcapsules, polyurea, gelatin, and gum arabic act as effective delivery systems for dispersing the pheromone through spraying the capsule mixture. Additionally, encapsulation safeguards the pheromone from oxidation and light exposure during both storage and release[39].

• Trichoderma harzianum, utilized as a biological control agent, is highly susceptible to both biotic and abiotic influences due to the presence of live spores. As a result, encapsulation enhances its efficacy against phytopathogens, such as in the management of Sclerotinia sclerotiorum (white mold).

• The microencapsulation of Metarhizium conidia via Pickering emulsion has led to increased mortality rates in Spodoptera littoralis larvae, better distribution of fungal cells on foliage, and more effective management of this agricultural pest[43].

5.5. Energy Generation

• Hollow plastic microspheres filled with gaseous deuterium (a fuel for fusion) are utilized to capture nuclear fusion for generating electrical energy. The capsules feature multiple layers. The innermost layer, which compresses the fuel, is a polystyrene shell approximately 3 mm thick. Following this is a layer of poly (vinyl alcohol) also about 3 mm thick, which slows down the diffusion of deuterium from the capsule. The outer layer called as the ablator, is 50 mm thick and is made up of a highly crosslinked polymer derived from 2-butene. During fusion experiments, energy from powerful laser beams is absorbed by the surface of the microcapsule shell. As the outer shell (the ablator) burns away, the reaction force propels the remaining shell inward, compressing and heating the deuterium within. This creates high densities and temperatures at the centre of the capsule, resulting in the fusion of deuterium nuclei to produce tritium, helium, and other particles, which release a tremendous amount of energy. This method is referred to as inertial confinement fusion (ICF). Organic microcapsule ICF targets have been utilized since the 1980s[39].

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REFERENCES

[1] Vinetsky Y, Magdassi S. Microcapsules in cosmetics. InNovel Cosmetic Delivery Systems 2023 May 31 (pp. 295-314). CRC Press.

[2] Casanova F, Santos L. Encapsulation of cosmetic active ingredients for topical application–a review. Journal of microencapsulation. 2016 Jan 2;33(1):1-7.

[3] Tekin R, Bac N, Erdogmus H. Microencapsulation of fragrance and natural volatile oils for application in cosmetics, and household cleaning products. In Macromolecular Symposia 2013 Nov (Vol. 333, No. 1, pp. 35-40).

[4] Peanparkdee M, Iwamoto S, Yamauchi R. Microencapsulation: a review of applications in the food and pharmaceutical industries. Reviews in Agricultural Science. 2016; 4:56-65.

[5] Hendrawati TY, Sari AM, Rahman MI, Nugrahani RA, Siswahyu A. Microencapsulation techniques of herbal compounds for raw materials in food industry, cosmetics and pharmaceuticals. In Microencapsulation-Processes, Technologies and Industrial Applications 2019 Jan 9. IntechOpen.

[6] Budhraja U, Angane P, Shaikh MF, Mishra A. Microencapsulation Technology in Food, Pharma and Cosmetics. Asian Journal of Pharmacy and Technology. 2025 Apr 26;15(2):166-72.

[7] Poshadri A, Aparna K. Microencapsulation technology: a review. Journal of Research ANGRAU. 2010;38(1):86-102.

[8] Jyothi SS, Seethadevi A, Prabha KS, Muthuprasanna P, Pavitra P. Microencapsulation: a review. Int. J. Pharm. Biol. Sci. 2012;3(2):509-31.

[9] Mishra DK, Jain AK, Jain PK. A review on various techniques of microencapsulation. Int J Pharm Chem Sci. 2013;2(2):962-8.

[10] Ozkan G, Franco P, De Marco I, Xiao J, Capanoglu E. A review of microencapsulation methods for food antioxidants: Principles, advantages, drawbacks and applications. Food chemistry. 2019 Jan 30; 272:494-506.

[11] Jyothi NV, Prasanna PM, Sakarkar SN, Prabha KS, Ramaiah PS, Srawan GY. Microencapsulation techniques, factors influencing encapsulation efficiency. Journal of microencapsulation. 2010 May 1;27(3):187-97.

[12] Shu B, Yu W, Zhao Y, Liu X. Study on microencapsulation of lycopene by spray-drying. Journal of food engineering. 2006 Oct 1;76(4):664-9.

[13] Frascareli EC, Silva VM, Tonon RV, Hubinger MD. Effect of process conditions on the microencapsulation of coffee oil by spray drying. Food and bioproducts processing. 2012 Jul 1;90(3):413-24.

[14] Tiwari S, Verma P. Microencapsulation technique by solvent evaporation method (Study of effect of process variables). International journal of pharmacy & life sciences. 2011 Aug 1;2(8).

[15] Freitas S, Merkle HP, Gander B. Microencapsulation by solvent extraction/evaporation: reviewing the state of the art of microsphere preparation process technology. Journal of controlled release. 2005 Feb 2;102(2):313-32.

[16] Semyonov D, Ramon O, Kovacs A, Friedlander L, Shimoni E. Air-suspension fluidized-bed microencapsulation of probiotics. Drying Technology. 2012 Dec 15;30(16):1918-30.

[17] Schell D, Beermann C. Fluidized bed microencapsulation of Lactobacillus reuteri with sweet whey and shellac for improved acid resistance and in-vitro gastro-intestinal survival. Food Research International. 2014 Aug 1; 62:308-14

[18] Comunian TA, Thomazini M, Alves AJ, de Matos Junior FE, de Carvalho Balieiro JC, Favaro-Trindade CS. Microencapsulation of ascorbic acid by complex coacervation: Protection and controlled release. Food research international. 2013 Jun 1;52(1):373-9.

[19] Nori MP, Favaro-Trindade CS, de Alencar SM, Thomazini M, de Camargo Balieiro JC, Castillo CJ. Microencapsulation of propolis extract by complex coacervation. LWT-Food Science and Technology. 2011 Mar 1;44(2):429-35.

[20] Menin A, Zanoni F, Vakarelova M, Chignola R, Donà G, Rizzi C, Mainente F, Zoccatelli G. Effects of microencapsulation by ionic gelation on the oxidative stability of flaxseed oil. Food Chemistry. 2018 Dec 15; 269:293-9.

[21] Chun H, Kim CH, Cho YH. Microencapsulation of Lactobacillus plantarum DKL 109 using external ionic gelation method. Korean journal for food science of animal resources. 2014 Oct 31;34(5):692-8.

[21] Saihi D, Vroman I, Giraud S, Bourbigot S. Microencapsulation of ammonium phosphate with a polyurethane shell. Part II. Interfacial polymerization technique. Reactive and Functional Polymers. 2006 Oct 1;66(10):1118-25.

[22] Lu S, Shen T, Xing J, Song Q, Shao J, Zhang J, Xin C. Preparation and characterization of cross-linked polyurethane shell microencapsulated phase change materials by interfacial polymerization. Materials Letters. 2018 Jan 15; 211:36-9.

[23] Brown EN, Kessler MR, Sottos NR, White SR. In situ poly (urea-formaldehyde) microencapsulation of dicyclopentadiene. Journal of microencapsulation. 2003 Jan 1;20(6):719-30.

[24] Luo WJ, Yang W, Jiang S, Feng JM, Yang MB. Microencapsulation of decabromodiphenyl ether by in situ polymerization: preparation and characterization. Polymer degradation and stability. 2007 Jul 1;92(7):1359-64.

[25] Zhan H, Jiang ZT, Wang Y, Li R, Dong TS. Molecular microcapsules and inclusion interactions of eugenol with β-cyclodextrin and its derivatives. European Food Research and Technology. 2008 Sep; 227:1507-13.

[26] Fuenmayor CA, Baron-Cangrejo OG, Salgado-Rivera PA. Encapsulation of carotenoids as food colorants via formation of cyclodextrin inclusion complexes: A review. Polysaccharides. 2021 Jun 5;2(2):454-76.

[27] Pandya HV. Formulation and evaluation of microcapsules of trihexyphenidyle hydrochloride by solvent evaporation method. International Journal of Pharmaceutical Sciences and Research. 2012 Feb 1;3(2):539.

[28] Casanova F, Santos L. Encapsulation of cosmetic active ingredients for topical application–a review. Journal of microencapsulation. 2016 Jan 2;33(1):1-7.

[29] Gonçalves A, Estevinho BN, Rocha F. Design and characterization of controlled-release vitamin A microparticles prepared by a spray-drying process. Powder Technology. 2017 Jan 1; 305:411-7.

[30] Abbas S, Da Wei C, Hayat K, Xiaoming Z. Ascorbic acid: microencapsulation techniques and trends—a review. Food Reviews International. 2012 Oct 1;28(4):343-74.

[31] Chaiyasat P, Chaiyasat A, Teeka P, Noppalit S, Srinorachun U. Preparation of poly (l-lactic acid) microencapsulated vitamin E. Energy Procedia. 2013 Jan 1; 34:656-63.

[32] Snoussi A, Chouaibi M, Bouzouita N, Hamdi S. Microencapsulation of catechin using water-in-oil-in-water (W1/O/W2) double emulsions: Study of release kinetics, rheological, and thermodynamic properties. Journal of Molecular Liquids. 2020 Aug 1; 311:113304.

[33] Mohammadi N, Ehsani MR, Bakhoda H. Development of caffeine-encapsulated alginate-based matrix combined with different natural biopolymers, and evaluation of release in simulated mouth conditions. Flavour and Fragrance Journal. 2018 Sep;33(5):357-66.

[34] Casanova F, Estevinho BN, Santos L. Preliminary studies of rosmarinic acid microencapsulation with chitosan and modified chitosan for topical delivery. Powder Technology. 2016 Sep 1; 297:44-9.

[35] More KS, Kadavakollu S, Nigar S, Gul K, Sehrawat R, Mir NA. Encapsulation of resveratrol in alginate microcapsules using internal gelation technique: Fabrication, characterization and release kinetics. LWT. 2024 Sep 1; 207:116663.

[36] Jimenez M, Garcia HS, Beristain CI. Spray-drying microencapsulation and oxidative stability of conjugated linoleic acid. European Food Research and Technology. 2004 Nov; 219:588-92.

[37] Shu B, Yu W, Zhao Y, Liu X. Study on microencapsulation of lycopene by spray-drying. Journal of food engineering. 2006 Oct 1;76(4):664-9.

[38] Desai SR, Baldwin H, Del Rosso JQ, Gallo RL, Bhatia N, Harper JC, York JP, Gold LS. Microencapsulated benzoyl peroxide for rosacea in context: a review of the current treatment landscape. Drugs. 2024 Mar;84(3):275-84.

[39] Dubey R, Shami TC, Rao KU. Microencapsulation technology and applications. Defence Science Journal 2009;59(1):82-95.

[40] Ang LF, Darwis Y, Por LY, Yam MF. Microencapsulation curcuminoids for effective delivery in pharmaceutical application. Pharmaceutics. 2019 Sep 2;11(9):451-8.

[41] Lorenzo-Lamosa ML, Remunan-Lopez C, Vila-Jato JL, Alonso MJ. Design of microencapsulated chitosan microspheres for colonic drug delivery. Journal of controlled release. 1998 Mar 2;52(1-2):109-18.

[42] Zhao Q, Han B, Wang Z, Gao C, Peng C, Shen J. Hollow chitosan-alginate multilayer microcapsules as drug delivery vehicle: doxorubicin loading and in vitro and in vivo studies. InNanomedicine in Cancer 2017 Sep 1 (pp. 317-345). Jenny Stanford Publishing.

[43] Zabot GL, Schaefer Rodrigues F, Polano Ody L, Vinícius Tres M, Herrera E, Palacin H, Córdova-Ramos JS, Best I, Olivera-Montenegro L. Encapsulation of bioactive compounds for food and agricultural applications. Polymers. 2022 Oct 6;14(19):4194.