



Chitosan and modified chitosan for essential oils encapsulation: A Review

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ARTICLE INFO	ABSTRACT
<i>Article history:</i> Received: 20-09-2025 Received in revised form: 13-04-2026 Accepted: 13-04-2026 <i>Keywords:</i> Chitosan; modified chitosan; essential oil; encapsulation; nanoencapsulation	The encapsulation of essential oils (EOs) in chitosan matrices addresses their volatility and instability while enabling controlled release. This review provides a critical analysis of chitosan and modified chitosan systems for EO encapsulation. It examines the molecular interaction mechanisms (electrostatic, hydrogen bonding, hydrophobic) and the decisive influence of chitosan properties such as degree of deacetylation, molecular weight, pH sensitivity on encapsulation performance and the inherent stability–bioactivity trade-off. The work systematically compares four principal encapsulation techniques: emulsification, ionic gelation, spray drying, and coacervation. Each method is evaluated based on its mechanism, efficiency, advantages, and limitations, with a focus on scalability and industrial suitability. The analysis concludes that method selection must be application-specific, as no single technique is universally optimal. Finally, key challenges to commercialization are identified, including raw material variability, process scalability, cost, and regulatory hurdles for nano-formulations. Future perspectives highlight the need for stimuli-responsive systems, green processing, and integrated design to bridge the gap between promising lab-scale research and viable commercial applications in food, pharmaceutical, and agricultural sectors.

1. Introduction

Essential oils (EOs) are volatile compounds derived from aromatic plants, utilized across multiple sectors, including cosmetics, pharmaceuticals, and biopesticides. Their diverse biological activities encompass antioxidant, antimicrobial, anti-inflammatory, insecticidal, and neuroprotective properties [1-3]. EOs, including orange, lavender, and tea tree, are utilized in cosmetics as natural fragrances, active ingredients in formulations, and natural preservatives, thereby improving product appeal and efficacy [4]. EOs are antibacterial agents in the pharmaceutical field and can be used as additives in nanotechnology formulations to improve skin penetration [2,5]. EOs, as biopesticides, demonstrate potential efficacy as larvicides and acaricides, particularly against *Anopheles stephensi* mosquitoes [6]. Despite its advantages, EOs have notable disadvantages, including high volatility, susceptibility to light, oxygen, and temperature degradation, and low solubility in water, which can diminish stability and bioavailability [1,2,7]. Various strategies have been developed to overcome these obstacles, including the encapsulation method in carrier systems such as nanoemulsions and microencapsulation, along with chemical modifications to enhance the physical properties and stability of EOs [2,7].

An effective method for enhancing the stability and efficacy of EOs involves utilizing chitosan as an encapsulation matrix. As a biopolymer, chitosan possesses biocompatible and

biodegradable characteristics that facilitate the creation of nanoparticles capable of protecting EOs from degradation and enhancing their bioavailability [8]. Encapsulation performance is governed by molecular-level interactions—such as electrostatic forces and hydrogen bonding—between chitosan and EO constituents, as well as by key chitosan parameters including degree of deacetylation and molecular weight. These factors must be carefully considered to achieve rational system optimization. Nevertheless, chitosan also presents intrinsic limitations, including low solubility under neutral pH conditions and suboptimal physicochemical properties [9]. Modifications to chitosan, such as cross-linking with glutaraldehyde, enhance its stability and loading capacity and the effectiveness of applications such as *Siparuna guianensis* essential oil in larvicides [10]. Chitosan is also used as nanogels, which offer better release control and high stability, and as composite films for food packaging with antimicrobial properties [11]. Chitosan has undergone various modifications, including incorporating other polymers like alginate and chemical alterations such as grafting synthetic polymers or adding functional groups, to enhance its solubility, thermal stability, and binding capacity with EOs [12,13]. For example, introducing sulfate groups into the chitosan chain increases solubility and thermal stability, which is important in EOs encapsulation applications [14,15]. The advantageous properties of chitosan highlight its strong potential for applications in food, pharmaceutical and biomedical fields, particularly through technological innovations tailored to the delivery of active ingredients.

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Therefore, chitosan and its modifications play an important role in EOs encapsulation. Its ability to form electrostatic complexes with negatively charged compounds in EOs improves encapsulation efficiency and stability and provides better antimicrobial and antioxidant properties [16,17]. Nevertheless, a critical gap exists in the literature: while numerous studies report successful encapsulation, a synthesized comparative analysis of different techniques (e.g., ionic gelation, spray drying, coacervation)—evaluating their trade-offs in encapsulation efficiency, burst release, scalability, and cost—is lacking. Moreover, the practical challenges of commercialization, including regulatory pathways and long-term stability-bioactivity trade-offs, are often overlooked. Chitosan-based encapsulation systems provide effective protection for EOs against environmental degradation, improve their biological activity, and facilitate controlled release. This is exemplified by the use of *Cymbopogon martinii* essential oil in combating fungi and drug-resistant *Klebsiella pneumoniae* [8,11]. To address this, the present review provides a comprehensive and critical analysis. It aims to: (1) elucidate the fundamental interaction mechanisms between chitosan and EOs; (2) analyze the impact of chitosan's physicochemical properties on encapsulation outcomes; (3) critically compare major encapsulation methods, highlighting their advantages, limitations, and suitability for specific applications; and (4) discuss key commercialization challenges and future research directions. Chitosan-based technology, enhanced through various modifications that improve solubility, stability, and mechanical strength, holds significant potential for the development of more efficient and effective delivery systems across diverse industrial and health applications.

2. Essential Oils and Their Chemical Composition

Essential oils (EOs) are complex mixtures of volatile and semi-volatile organic compounds that define the aroma, fragrance, and flavor of plants [18,19]. EOs can be extracted from various parts of plants: flowers (roses), leaves (peppermint), fruits (lemons), seeds (fennel), grasses (lemongrass), roots (sweet root), rhizomes (ginger), wood (cedar), bark (cinnamon), sap (frankincense), tree flowers (ylang-ylang), bulbs (garlic), and dried flower buds (cloves). Most EOs are colorless or pale yellow; however, certain varieties, like blue chamomile and European valerian, exhibit green hues [20]. EOs exhibit hydrophobic characteristics and possess a lower density than water, indicating their lipophilic nature and solubility in organic solvents. However, the solubility of EOs in water can occur, contingent upon the polar components present within them [18,21].

EOs can be classified according to several criteria, including the origin of the plant, chemical composition, functional groups, odor characteristics, and therapeutic properties. Based on their chemical composition, EOs can be divided into two major groups: terpenoids and phenylpropanoids. Terpenoids originate from isoprene units and consist of monoterpenes, sesquiterpenes, diterpenes, and triterpenes [22]. Monoterpenes are the simplest terpenoid molecules. Monoterpenes consist of 10 carbon atoms with hydroxyl groups scattered in non-specific locations along the chain. Examples of monoterpenes extracted from various plants are geraniol, terpineol (lilac), limonene (citrus fruit), myrcene (hops), linalool (lavender), and pinene (pine tree). Sesquiterpenoids are compounds consisting of 15 carbon atoms with the molecular formula $C_{15}H_{24}$. A common example is ginger extract, which contains a sesquiterpenoid compound

called zingiberene [18,22–24]. Phenylpropanoids originate from the shikimate pathway and consist of phenylpropene, coumarin, and lignin. These two compounds cause EOs to have antimicrobial, anti-inflammatory, antioxidant, analgesic, and antispasmodic properties. The composition of chemical and bioactive compounds in EOs varies among plant species and is influenced by factors such as geographical location, plant maturity, season, and the specific part of the plant from which the essential oil is extracted [18].

3. Extraction Method

EOs can be extracted using various methods, which generally depend on the plant material used. Inadequate extraction procedures can compromise the chemical composition of EOs, potentially diminishing their bioactivity and natural characteristics, which are critical determinants of EOs quality. In severe instances, improper extraction methods may lead to undesirable alterations in color, odor, or flavor, along with physical changes like increased viscosity [25].

EOs can be extracted using conventional and innovative methods. Conventional extraction methods include steam distillation, solvent extraction, cold pressing, hydro-diffusion, and hydro-distillation. These methods are time-consuming and energy-intensive processes that yield low extraction rates. Harsh processing conditions can affect the flavor and reduce the quality of EOs. Innovative methods are designed to address the limitations of conventional approaches. Innovative methods include microwave-assisted, ohmic-assisted, ultrasound-assisted, pulsed electric field, and supercritical fluid extraction [26–28].

4. Utilization of Essential Oils

EOs are multifunctional compounds utilized across various industries, including medicine, food, cosmetics, and agriculture. EOs can be applied in traditional and contemporary practices due to their diverse biological activities and natural properties. EOs have antimicrobial, antiviral, and antifungal properties, making them a potential alternative to synthetic drugs [29,30]. Damiescu et al. (2022) reported that EOs exhibit antiviral activity against SARS-CoV-2, suggesting their potential as an adjunct in COVID-19 treatment [31]. Referring to the article by Girao *et al.* [32], EOs such as lavender, eucalyptus, peppermint, rosemary, and clove show significant analgesic effects on acute nociceptive and neuropathic pain models due to their biological activity and therapeutic properties.

In addition to medicine, EOs can also be used in the food industry. Their notable antimicrobial and antioxidant properties make them effective natural preservatives against foodborne pathogens, prolong shelf life [33], enhance flavor and aroma, and function as active packaging [34]. Olmedo et al. [35] incorporated oregano and rosemary essential oils into flavored cream cheese to inhibit lipid oxidation, rancid flavors, and fermentation. In addition, *Salvia officinalis* (sage EOs) showed effectiveness against *Listeria monocytogenes*, contributing to food safety in seafood [36]. In the field of cosmetics, the addition of EOs can increase the effectiveness of products for skin care, hair care, and fragrance formulations [37]. Ameliana et al. [38] investigated the impact of citronella oil concentration on the quality of shampoo and its antifungal efficacy against *Candida albicans*, a primary contributor to dandruff. The results showed that citronella oil can be effectively formulated into shampoo and can enhance antifungal properties, thereby inhibiting the

growth of dandruff-causing fungi. Rattanachitthawat et al. [39] demonstrated that essential oil extracted from *Clausena harmandiana* can inhibit collagenase, elastase, and hyaluronidase, indicating their potential application as anti-wrinkle agents in skin care products.

The use of EOs in agriculture is increasingly recognized for its various benefits, which include pest control, seed priming, and the promotion of environmentally friendly practices. EOs serve as a natural alternative to synthetic pesticides, thereby increasing plant resistance and overall productivity. EOs derived from the peel of *Citrus maxima* exhibit significant insecticidal activity against various pests, including mosquitoes and insects that attack stored grains, making them powerful biopesticides [40]. EOs can enhance seed germination and increase drought resistance. For example, EOs derived from rosemary, sage, and lavender have been shown to significantly increase wheat germination rates and yield parameters under semi-arid environmental conditions [41]. The EOs sector can enhance the circular bioeconomy by utilizing distillation by-products for extracting bioactive compounds, producing biochar, and developing other environmentally friendly products, which minimizes waste and improves soil health [42].

5. Limitations of Essential Oils

While EOs offer numerous benefits in industrial applications and exhibit bioactivity, their application is hindered by limitations such as volatility, hydrophobicity, and instability. EOs consist of approximately 95% volatile constituents and 5% non-volatile constituents [43]. The quality of EOs can be affected by environmental variables such as air, heat, light, and oxidation [44]. In addition, their hydrophobic nature means that EOs are insoluble in water-based media. EOs from plants are unstable due to their thermolability. They can easily be oxidized or hydrolyzed during processing and storage. When exposed to environmental stimuli, EOs are susceptible to oxidation, chemical changes, or polymerization [43]. For example, argan oil contains high levels of tocopherols and unsaturated fatty acids. Upon exposure to light and oxygen, tocopherols and fatty acids degrade more rapidly, resulting in the formation of oxidation products such as hydroperoxides and conjugated dienes, which alter the oil's odor and flavor and ultimately

reduce its shelf life [45]. Advancements in technology can address these limitations, particularly through encapsulation methods.

6. Encapsulation of Essential Oils

Encapsulation technology enhances stability and regulates the release of bioactive compounds by physically isolating them from their environment [46]. Encapsulation can inhibit oxidative degradation, reduce harmful interactions with other nutrients, mask unwanted odors, prevent the evaporation of volatile constituents, extend shelf life, and aid in controlled release. EOs are typically found in liquid form, and their encapsulation is generally achieved by dissolving them in an organic solution with a carrier material, followed by emulsification. The encapsulated entity is referred to as the core material, while the coating material is referred to as the carrier or wall material [27].

Ideally, coating materials should have low hygroscopicity, low viscosity, high solubility, low cost, chemical inertness, and biocompatibility [27]. The most commonly used coating materials for encapsulation are chitosan, gum arabic [46], starch, cellulose, phospholipids, and proteins (albumin, casein) [47]. Encapsulation can be achieved through various methods, with microencapsulation and nanoencapsulation frequently employed for EOs [27].

7. Chitosan as an Encapsulation Material

Chitosan is the second most abundant biopolymer globally. Chitosan, a polysaccharide composed of poly β -(1-4)-2-amino-2-deoxy-D-glucopyranose, is derived from the deacetylation of chitin. This biopolymer can be extracted from the exoskeletons of marine organisms, including crabs, shellfish, and shrimp, as well as from the cell walls of fungi [48,49]. During chitin deacetylation, multiple N-acetylglucosamine groups are transformed into glucosamine units [50]. Chitosan contains two significant functional groups in its chemical structure: the hydroxyl (-OH) group and the amino (-NH₂) group. These functional groups make chitosan soluble exclusively in acidic media [48]. The solubility of chitosan is influenced by several factors, including polymer molecular weight, degree of acetylation, pH, temperature, and polymer crystallinity [50].

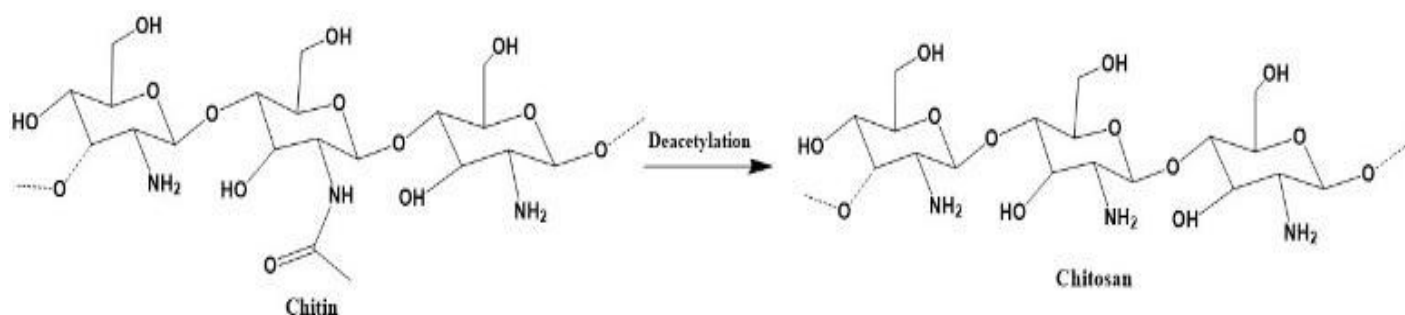


Fig. 1. The deacetylation process of chitin into chitosan adapted from Negi & Kesari [51]

Chitosan has important characteristics such as biodegradability, antitumor, antimicrobial, anti-inflammatory, antioxidant activity, and film-forming ability. Its applications have been explored in the biomedical and pharmaceutical industries, as well as in cosmetics, food and feed production, water treatment, and other areas [52,53]. These characteristics make chitosan popular as a coating material for EO. The NH₂ groups on the chitosan surface facilitate quick grafting of functionalized molecules, leading to diverse material

applications [51]. Mukurumbira et al. [54] reported that chitosan serves as an optimal wall material for the encapsulation of EOs, as it not only protects them from environmental factors that cause evaporation and degradation but also imparts antimicrobial properties synergistically with the oils.

7.1. Interaction mechanisms between chitosan and essential oils

The effectiveness of chitosan as an encapsulating matrix for

essential oils is determined by several molecular interactions, the significance of which varies according to the polymer's characteristics, ambient factors, and the essential oil's composition. The interactions largely consist of electrostatic interactions, hydrogen bonds, and hydrophobic forces, which do not function independently but rather compete and overlap inside the encapsulation system. Electrostatic interactions serve as the principal driving force in the first attachment phase. Chitosan possesses fundamental amino groups ($-NH_2$) along its polysaccharide backbone. In acidic and physiological environments, the amino groups become protonated, yielding a positively charged polymer with an average zeta potential ranging from +20 to +60 mV, contingent upon the pH and extent of deacetylation [55]. The positive surface charge markedly affects the initial association phase, enhancing Coulomb interactions with essential oil components that contain polar functional groups or partial negative charges. Electrostatic interactions constitute the structural foundation for the production of complex coacervates and the assembly of nanoparticles in diverse chitosan-based encapsulation systems [56].

The efficacy of electrostatic interactions is significantly influenced by pH levels. In acidic circumstances (pH 3–5), significant protonation increases oil affinity and retention, but progressive deprotonation at near-neutral pH (pH 6–8) diminishes charge density and improves chitosan's capacity to retain oil constituents [57]. Subsequent computational analysis and molecular docking revealed that the magnitude of electrostatic attraction is influenced by the charge densities of the two interacting entities and the dielectric properties of the surrounding medium [58]. Zeta potential investigations demonstrate that chitosan nanoparticles often display values between +30 and +50 mV, which promotes colloidal stability via electrostatic repulsion and prevents particle agglomeration [59].

Besides electrostatic interactions, hydrogen bonding plays a significant role in interfacial stability, particularly for essential oil constituents with polar functional groups. Chitosan offers multiple hydrogen bond donor and acceptor sites via its amino group at the C2 position and hydroxyl groups at the C3 and C6 positions [60], facilitating interactions with alcohols, phenols, aldehydes, and ketones present in essential oils [61]. The efficacy of hydrogen bonding is constrained by polymer hydration, pH-dependent protonation, and competition with air molecules, which can diminish its role in very aqueous environments [62]. These interactions are typically shown by FTIR spectrum shifts in the N–H bending and O–H stretching areas following the addition of oil [63]. In intricate coacervation systems, supplementary hydrogen bonding with anionic polymers like gum arabic or alginate can augment oil retention [64].

In nonpolar oil components, hydrophobic interactions and van der Waals forces gain significance. Numerous essential oils are mostly composed of monoterpenes and sesquiterpenes, including limonene, α -pinene, and β -caryophyllene, which are devoid of polar functional groups and hence cannot retain hydrogen, yet can engage through London dispersion forces (Oliveira et al., 2025). The intensity of these interactions escalates with molecule size and polarizability, elucidating the superior encapsulation effectiveness generally noted for sesquiterpene-rich oils when hydrophobic interactions prevail [13].

The intrinsic hydrophilic characteristics of natural chitosan,

attributed to its many hydroxyl and amino groups, restrict its attraction for nonpolar terpenes. Chemical changes that incorporate hydrophobic groups, such as acylation, markedly enhance oil retention by reinforcing hydrophobic–hydrophobic interactions. Acylated chitosan (e.g., oleyl or palmitoyl derivatives) has been shown to enhance encapsulation efficacy by roughly 10–15% relative to native chitosan, a phenomenon clearly linked to intensified van der Waals interactions with nonpolar oil components [13]. In contrast, thorough hydration of protonated chitosan in an acidic aqueous medium can create a hydrophilic barrier that inhibits these interactions, underscoring the significance of polymer modification and formulation management. The interactions governing essential oil encapsulation inside a chitosan matrix are generally non-uniform, significantly impacted by system circumstances, and tend to compete rather than complement one another. The predominance of electrostatic forces in the initial phases of particle production and stability in an acidic milieu wanes as the level of protonation declines.

7.2. Influence of chitosan physicochemical properties

The physicochemical properties of chitosan critically govern its performance as a carrier for essential oils. The physicochemical features of chitosan, including the degree of deacetylation (DDA), molecular weight (Mw), and pH responsiveness, collaboratively influence encapsulation efficiency, nanoparticle stability, and release behaviors. Nonetheless, enhancing one facet frequently constrains others; thus, the formulation of the encapsulating system must be customized for the specific application.

The extent of deacetylation is a crucial parameter as it regulates the solubility and charge density of chitosan. An elevated degree of deacetylation augments the quantity of protonated amino groups, enhances electrostatic interactions with polar or negatively charged constituents of essential oils, and optimizes encapsulation efficiency [65,66]. Nonetheless, augmenting the charge density results in the development of a more compact polymer network, which diminishes molecular mobility and impedes diffusion-controlled release. This is beneficial for applications necessitating continuous release, but less appropriate for those requiring fast release. A high degree of deacetylation (DDA) also results in heightened sensitivity of chitosan to pH variations. In these circumstances, the nanoparticle system may potentially compromise its stability due to environmental alterations [67].

The molecular weight of chitosan influences the formation and functionality of nanoparticles within the encapsulating system. At elevated molecular weights, the polymer chains exhibit increased interconnectivity, leading to bigger nanoparticles and enhanced mechanical strength. This is typically linked to enhanced colloidal stability and the matrix's capacity to safeguard volatile essential oils against environmental factors [68]. A denser polymer structure restricts oil mobility within the matrix, resulting in slower diffusion and altering the release profile towards prolonged release [69]. Elevating molecular weight (Mw) enhances solution viscosity, potentially obstructing nanoparticle formation, diminishing dispersion uniformity, and complicating processing and scalability. An excessively rigid matrix can further inhibit release to levels that diminish functional efficacy, underscoring a distinct trade-off between stability and release.

Chitosan's pH sensitivity allows for controlled release mechanisms. At lower pH levels, the polymer becomes positively charged and retains essential oils better, enhancing their stability. In contrasting neutral or alkaline environments, the nanoparticles can dissolve more rapidly, leading to quicker release rates. This property is particularly beneficial in targeted delivery applications, where stability is crucial in varied environments [69]. However, the pH-sensitive characteristics of chitosan do not consistently yield a uniform release response. The protonation of amino groups in acidic circumstances influences swelling, electrostatic interactions, and the stability of the polymer matrix. Certain studies indicate heightened oil retention at low pH attributed to augmented electrostatic forces [66], whereas others suggest expedited release resulting from excessive swelling or partial breakdown of the chitosan matrix [70]. The disparate data indicate that the pH response does not yield a consistent release pattern instead, it is contingent upon the prevailing release mechanism, such as diffusion, swelling erosion, or surface desorption [71]. Inadequate management of these conditions may lead to environmental changes that can precipitate a fast release, especially from the oil fraction that is loosely adhered to the nanoparticle surface.

The physicochemical features of chitosan impose rather restricted formulation limits, limiting opportunities for optimization. Enhancing the degree of deacetylation (DDA) and molecular weight (Mw) is frequently linked to improved encapsulation efficiency and system stability; however, this is typically accompanied by diminished release flexibility, processing challenges, and decreased adaptation to environmental fluctuations. In contrast, chitosan with a lower degree of deacetylation (DDA) and molecular weight (Mw) is more amenable to processing and facilitates oil dispersion; nevertheless, its long-term stability and retention are often constrained [69]. The findings highlight that robust oil-polymer interactions, although advantageous for stabilization, may restrict controlled release when it is the primary objective [10,72]. In this setting, successful chitosan-based encapsulation systems must be developed by equilibrating competing physicochemical effects, rather than optimizing individual parameters. To highlight that each physicochemical parameter of chitosan confers both advantages and inherent limitations in essential oil encapsulation, the key trade-offs associated with degree of deacetylation, molecular weight, and pH responsiveness are summarized in Table 1.

Table 1. Summary of trade-offs in chitosan physicochemical properties for essential oil

Parameter	Increase Leads To (Advantages)	Trade-offs/Limitation
Degree of Deacetylation (DDA)	- Increased charge density of $-NH_3^+$ groups - Enhanced electrostatic interactions with polar or negatively charged oil constituents - Improved encapsulation efficiency and oil retention	- Decreased polymer chain mobility - Slower release rates - Potential instability under pH variations due to elevated charge density
Molecular Weight (Mw)	- Formation of larger and mechanically stronger nanoparticles - Enhanced colloidal stability - Better protection against volatilization and degradation	- Increased solution viscosity Enhanced antioxidant and anticancer activity - Difficult nanoparticle production and dispersion - Suppressed release due to dense polymer network
pH Sensitivity	- Enhanced electrostatic interactions under acidic conditions - Potential pH-triggered release behavior	- Swelling or partial dissolution at low pH Improved encapsulation efficiency - Risk of burst release - Non-uniform release mechanisms across environments

8. Modified Chitosan for Essential Oils Encapsulation

Chitosan's natural properties exhibit limitations in specific applications, particularly in the encapsulation of EOs. Consequently, it is necessary to modify chitosan to enhance its properties. Chitosan can be modified through various methods, including chemical and physical approaches such as cross-linking, grafting, and mixing with other materials [48]. Detsi et al. [73] state that modified chitosan enhances encapsulation properties, resulting in improved biocompatibility, biodegradability, and reduced toxicity. Chemical or enzymatic modification, combined with other polymers, creates an enhanced matrix for encapsulating natural extracts, EOs, and bioactive compounds.

Cross-linking methods frequently employ agents like sodium tripolyphosphate (TPP) to enhance efficiency and loading capacity [51]. Ma et al. [69] effectively encapsulated oregano essential oil within chitosan nanoparticles, utilizing tripolyphosphate as a cross-linking agent, and attained an

encapsulation efficiency of 92.90%. Furthermore, chitosan modification through grafting involves the attachment of new functional groups to the polymer chain, such as amino, carboxyl, sulfur, phenolic, or other specific structural groups, while preserving the integrity of the original framework to maintain its properties [53]. Chitosan modification with folic acid, applied to coat solid lipid nanoparticles containing essential oil from *Satureja khuzistanica*, enhances encapsulation efficiency and targeting stability while improving selective toxicity to cancer cells, specifically MCF-7 [74]. Another example is chitosan modified with caffeic acid, which serves as a nanogel to encapsulate *Lippia origanoides* essential oil, resulting in an increased antioxidant capacity and an encapsulation efficiency of $42 \pm 2\%$ [75]. Chitosan can be modified by combining it with other polymers, including alginate, cellulose, or PVA [53]. A study reported that the encapsulation of Bali orange essential oil with alginate/chitosan complexes showed a high encapsulation efficiency value of 85.18%. This indicates that alginate/chitosan complexes can retain EOs within the particle core [76]

9. Essential Oils Encapsulation Technique with Chitosan and Modified Chitosan

9.1. Emulsification

Emulsification is an effective approach to improve the solubility and integration of hydrophobic substances such as EOs in the aqueous phase. Oil-in-water (O/W) emulsions improve the dispersion of EOs in food and non-food matrices, enhancing stability and controlled release, antimicrobial activity, and antioxidant properties. Emulsions are classified into three categories based on droplet size: macroemulsions (0.5–100 μm), nanoemulsions (50–500 nm), and microemulsions (10–100 nm) [46,77]. One of the main disadvantages of macroemulsions is their physical instability and low delivery capacity. Emulsions with smaller particle sizes have a larger surface area to volume ratio, which contributes to increased stability, dispersibility, bioavailability, and reactivity of the active ingredient [26].

For example, Ferreira et al.[10] reported that encapsulating *Siparuna guianensis* essential oil in chitosan nanoparticles resulted in prolonged mosquito repellent activity compared to the free essential oil. Nonetheless, emulsification techniques possess intrinsic limitations. Emulsion systems are prone to physical instabilities, including coalescence and Ostwald ripening, and frequently demonstrate burst release phenomena due to elevated

oil exposure at the droplet interface. Moreover, regulation of long-term release is typically constrained by the liquid composition of emulsions, which fail to offer sufficient diffusion barriers.

Consequently, in numerous studies, oil-in-water (O/W) emulsification is employed not as a conclusive step, but as a preliminary phase succeeded by ionic gelation or cross-linking utilizing agents such as sodium tripolyphosphate (TPP) or calcium chloride, to generate more stable solid particles or hydrogel beads that can more effectively regulate the release of essential oils [78,79]. Table 2 provides an overview of studies on essential oils (EOs) encapsulation with chitosan and modified chitosan employing the emulsification technique.

9.2. Ionic Gelation

Ionic gelation is a widely used technique for encapsulating various bioactive compounds, including EOs. This technique involves the formation of cross-links between polymers and oppositely charged ions, resulting in hydrogel beads that can efficiently encapsulate and protect sensitive compounds [80]. The hydrogels produced from this process have the ability to increase the solubility of hydrophobic compounds, making them excellent carriers for essential oils.

Table 2. Encapsulation of essential oils (EOs) using the emulsification method

Encapsulant Materials	EO	Result	Trade-offs	References
Chitosan	Thyme essential oil	- Controlled EO release (73.41% in 48 hours) - Potential as an insecticide - Effective against <i>Anopheles stephensi</i> mosquitoes.	- Nanoemulsion: Swift release for prompt starting effects (91.68%), although the duration of effectiveness is comparatively brief. - Chitosan encapsulation: The initial release is inhibited, leading to an extended duration of efficacy despite a slower initial reaction.	[81]
Alginate/Chitosan beads	Carvacrol and oregano oil	- The droplet size is 16–20 nm - High encapsulation efficiency (78%) - The carvacrol loading is 3% - Controlled release profile, reducing initial burst effect and providing sustained release over time	High stability under acidic conditions, but loss of matrix integrity and collapse under alkaline pH due to deprotonation.	[82]
Chitosan	<i>Cymbopogon khasiana</i> × <i>Cymbopogon pendulus</i> oil	- Droplet size 103.56 nm - Zeta potential +33.91 mV - EE 83.15%; Antifungal MIC 0.08 $\mu\text{L}/\text{m}$ <i>S. cumini</i> seed protection for 1 year - Controlled delivery with enhanced antifungal, antiaflatoxigenic, and antioxidant activities compared to free essential oil	An initial burst release of 27.03% occurred before reaching the slow-release phase.	[83]

These hydrogels also have the advantages of high stability, good loading capacity, and controlled release of compounds. The application of the ionic gelation method in

essential oil encapsulation is known to increase the stability of EOs while expanding their applications in various fields [46].

Alginate and chitosan are the most frequently utilized

polymers in the ionic gelation method. Chitosan is favored due to the presence of amino groups on its surface, which facilitates its ability to cross-link with other functional materials [43]. Commonly used cross-linking agents are TPP and HMP (hydroxymethyl melamine prepolymer). Mixing chitosan solution with EO and TPP results in the formation of nanoparticles through continuous agitation, which ultimately allows encapsulation [84]. A study by Hellali and Ayachi (2023) [66] revealed the significant potential of chitosan–TPP and alginate/chitosan-based ionic gelation systems, with rosemary essential oil encapsulation efficiency over 98% and particle size under 100 nm. This system demonstrated pH-sensitive release, exhibiting significant retention at acidic pH and excellent release at neutral pH, indicating its potential for targeted delivery applications. Nonetheless, the robust matrix preservation presents a trade-off, resulting in diminished immediate biological efficacy, as analgesic action significantly declines in comparison to the unencapsulated oil. Moreover, elevated chitosan concentrations resulted in particle size heterogeneity (high PDI) and sustained burst release attributed to oil adsorption on the surface. Ma et al. (2022) [69] employed a statistical optimization method utilizing the Box–Behnken Design on a chitosan–TPP nanoparticle system containing oregano oil, achieving a high encapsulation efficiency of 92.90%, a relatively small particle size of 182.77 nm, and exceptional colloidal stability with a zeta potential of +40.53 mV. This nanoencapsulation also improved antibacterial efficacy against *Pseudomonas spp.* Nonetheless, this system demonstrated an initial burst release of 41.27% within the first five hours, alongside restricted loading capacity attributable to the saturation of chitosan binding sites and a propensity for aggregation at elevated polymer concentrations.

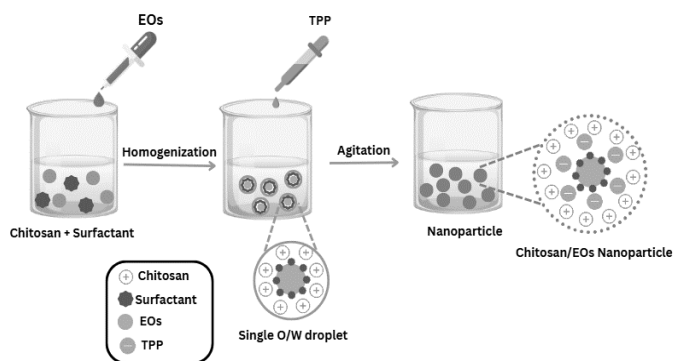


Fig. 2. Schematic image of nanocapsulation of EOs by ionic gelation method; adapted from Hedayati et al. [46]

In addition, the ionic gelation method has been applied in the synthesis of chitosan nanoparticles loaded with ginger oil. The chitosan solution, dissolved in acetic acid, was combined with ginger oil, and encapsulation was performed using the emulsion-gel method. TPP was added to the chitosan–ginger oil emulsion following the mixing process. TPP ions interacted with chitosan, causing ionic gelation. This cross-linking process produced stable nanocapsules capable of encapsulating ginger essential oil. The efficiency of ginger oil encapsulation reached 23.1%, with increased antioxidant and antimicrobial activity. The minimum inhibitory concentration (MIC) achieved was 0.97 µg/mL for *Escherichia coli*, 1.9 µg/mL for *Staphylococcus aureus*, 3.90 µg/mL for *Salmonella typhimurium*, and 0.97 µg/mL for *Pseudomonas aeruginosa* [85]. Despite the encapsulation efficiency values being somewhat moderate relative to other systems, this work distinctly demonstrates the intrinsic trade-offs associated with chitosan–TPP-based ionic gelation. Elevating

the TPP concentration diminished the encapsulation effectiveness owing to the contraction of the polymer matrix, whilst augmenting the oil content reduced the electrostatic stability of the system.

This study illustrates that ionic gelation enhances the stability, bioactivity, and controlled release of essential oils, albeit with a trade-off among encapsulation efficiency, loading capacity, colloidal stability, and the requirement for prompt biological action. Consequently, optimizing ionic gelation systems necessitates a comprehensive approach that harmonizes matrix structure, formulation composition, and the desired end application, rather than concentrating on a singular aspect. Table 3 provides an overview of studies on essential oils (EOs) encapsulation with chitosan and modified chitosan employing the ionic gelation technique.

9.3. Spray drying

Spray drying is a recognized encapsulation technique that has been extensively developed in the pharmaceutical, chemical, and food industries [86]. Spray drying is an economical and versatile encapsulation method suitable for encapsulating EOs, providing high efficiency and stability [26]. In this method, a liquid solution containing wall and core materials is transformed into a dry powder. The encapsulation process involves creating an emulsion of the solution with the core and wall materials, followed by homogenization, atomization in a drying chamber, and dehydration of the particles. The evaporation of the liquid phase in the drying chamber results in the entrapment of EOs within the wall material, leading to the formation of small particles. The size of the capsules produced by this method varies due to several factors, including particle size, emulsion viscosity (water/oil), feed flow rate, concentration, atomization pressure, and the temperature of the air entering and exiting the spray dryer. These factors significantly affect the quality and dimensions of the encapsulated particles. The selection of wall material significantly influences the effectiveness of encapsulation. Biopolymers are the preferred materials for encapsulating EOS due to their cost-effectiveness, non-toxicity, and availability [26,87,88]. Chitosan is a biopolymer commonly utilized for encapsulation through the spray drying method. The encapsulation of EOs with chitosan using the spray drying method has been investigated by several researchers from various perspectives. Several studies have investigated the appropriate concentration and composition of chitosan.

Kanwal et al. [89] reported the encapsulation of tuna fish oil (TFO) utilizing a chitosan matrix combined with maltodextrin at a 1:1 ratio as the wall material. The research systematically assessed the impact of different oil loads on the oxidative stability, encapsulation efficiency, and physical properties of the microcapsules. The findings indicated that the formulation with a 10% oil load had the most favorable performance, evidenced by the maximum oxidative stability during 30 days of storage (peroxide value 2.94 ± 0.04 ; anisidine value 1.54 ± 0.02) and exceptionally high encapsulation efficiency ($91.27 \pm 0.05\%$).

The findings suggest that the stability of the spray-dried system is primarily influenced by the equilibrium between the oil content and the protective ability of the coating matrix; therefore, a moderate oil load (10–20%) is desirable for functional food applications. At elevated oil concentrations (40%), encapsulation effectiveness significantly decreased to 71.82% due to the augmented proportion of surface oil that was inadequately confined within the matrix. The surface oil immediately facilitated the acceleration of oxidative deterioration during storage, evidenced by the rise in peroxide

and anisidine levels. From a procedural standpoint, emulsions with low oil content demonstrated increased viscosity, which facilitated the development of a protective film during drying; however, excessive viscosity could impede feeding and atomization in the spray drying phase. Paula et al. [90] described a different approach including the development of chitosan-based encapsulation systems integrated with regional Brazilian tree exudate gums, specifically cashew gum (CG), angico gum (AG), and chichá gum (ChG). Differences in gum type and the chitosan-to-gum ratio significantly influence loading capacity (LC), encapsulation efficiency (EE), and storage stability. In the Ch:CG and Ch:ChG systems, an increased chitosan ratio consistently improved loading capacity (LC) and encapsulation efficiency (EE), achieving around 15% and 60%, respectively, whereas in the Ch:AG matrix, increased gum ratios offered superior oil protection during spray drying. The Ch:CG and Ch:ChG systems exhibited a significant benefit by sustaining steady oil content for up to 365 days of storage in dark settings, demonstrating exceptional long-term protective efficacy. However, increased chitosan ratios generally resulted in bigger particle sizes due to electrostatic attraction among NH_3^+ groups, hence restricting the production of low-nanoscale particles. Moreover, elevated gum content expedited oil release due to the hydrophilic characteristics of the gums, which facilitated matrix swelling, but augmented chitosan fractions diminished the

release rate. Regarding storage stability, angico gum (AG) shown a higher oil loss after 300 days compared to CG and ChG, highlighting the significance of polysaccharide selection for the enduring efficacy of encapsulation systems.

Zhang et al. [91] reported the advancement of a sophisticated spray-drying method that combined chitosan, methyl cellulose (MC), and alginate for the encapsulation of tea tree oil (TTO). This three-component system attained a microencapsulation efficiency of 89.4% and an oil embedding rate of 90.4%. This study's primary innovation is the utilization of amphiphilic methyl cellulose as an emulsifier and an internal wall component, thus obviating the necessity for synthetic surfactants or chemical cross-linking agents. Electrostatic interactions between positively charged chitosan and negatively charged alginate reinforced the capsule wall structure, while MC stabilized the original emulsion, yielding spherical microcapsules with superior protection against volatility. In the absence of encapsulation, TTO entirely evaporated in around 5 hours, while the microencapsulated system saw an oil loss of merely 7.3% after one month of storage.

Nonetheless, the heightened complexity of this system was accompanied by processing and stability issues. Elevated intake temperatures ($\approx 210^\circ\text{C}$) were necessary for thorough drying; nevertheless, excessive temperatures could lead to shell fracturing due to rapid solvent evaporation.

Table 3. Ionic gelation method for EO encapsulation

Polymer	EO	Advantages	Applications	Trade-offs	Ref
Pectin/Chitosan	Jasmine essential oil	- A "green" (organic solvent-free) ionotropic gelation method. - Enhances cytotoxicity towards breast cancer cells by 13-fold while preserving normal cell integrity.	Breast cancer MCF-7 cell therapy	Encapsulation efficiency (EE%) is quite low (24–30%) because the hydrophobic nature of the oil is opposite to the hydrophilic polymer matrix, making the oil easily washed off the surface.	[92]
Chitosan nanocomposites	Cinnamomum	- The formulation showed better antioxidant activity compared to pure oil due to the nanostructure's ability to inhibit the volatilization of the active ingredient. - Enhances thermal stability	- Food preservation - Natural additives - Plant protection against pests and diseases - Eco-friendly packaging	The formulation showed better antioxidant activity compared to pure oil; nevertheless, the maximal encapsulation efficiency (EE) attained is rather low at 32.9%.	[93]
PLA/Chitosan	Cinnamomum cassia	- Enhances antimicrobial activity against <i>E. coli</i> (99.3%) - Provides sustained release	Active packaging	The addition of oil over 3% v/v significantly diminishes fiber diameter and induces the formation of beads (defective beads within the fiber).	[94]
Chitosan–corn flour	<i>Cinnamomum cassia</i> and <i>Cinnamomum camphora</i> var. <i>linalooliferum</i>	Decreases water vapor permeability (WVP) in starch films and prolongs the shelf life of fruit while preventing fungal infection.	Food packaging, pharmaceuticals, and medical supplies	A high concentration of cinnamon oil (5 wt%) enhances water vapor permeability (WVP) via altering the starch's crystal structure to a more open C-type configuration.	[95]

Table 3 (continued). Ionic gelation method for EOs encapsulation

Chitosan–carbomer nanoparticles	<i>Origanum vulgare subsp. viride</i>	- Significantly enhanced encapsulation efficiency (up to 99.25%) - Mechanical stability - Antimicrobial activity - Insect-repellent properties	- Drug delivery systems - Treatment of infections or immune modulation - Biopesticides - Extended food shelf life	As the oil load increases, the particle size swells and efficiency begins to decrease.	[96]
Chitosan nanoparticles	<i>Chincho</i> essential oil	- The organogel method improves the bioavailability of lipophilic oils in an aqueous environment. - Spherical and homogeneous particles with minimal MIC against <i>S. aureus</i> - Antibacterial activity - Encapsulation efficiency of 52.64%	Food safety and preservation	Offers highly stable preservation of the active ingredient; nonetheless, the release rate is notably sluggish, achieving only approximately 18–22% within six hours.	[97]
Chitosan nanoparticles	<i>Helichrysum italicum</i>	Increases skin hydration for 60 minutes	Dermatological applications	Duration of clinical biometric testing in this study was very limited (only 60 minutes)	[98]
Chitosan–gum arabic	Saffron	- Produces nanoparticles with very small sizes (16.24 nm to 23.38 nm) - Encapsulation efficiency (EE) 86.4%	Improved food quality and shelf life	- Increasing polymer concentration enhances wall rigidity but leads to larger particle size. - Higher temperatures improve active compound retention, whereas lower temperatures allow sufficient time for structural compaction or collapse.	[99]
Alginate–Chitosan microcapsules	Sweet orange oil	Enhanced stability and antibacterial properties	Preservation of aquatic products (freshwater lobster)	Burst release effect during the initial release stage	[100]
Pectin/Chitosan hydrogel beads	Coffee essential oil system	- Increased stability - Improved encapsulation efficiency - Controlled release	- Environmentally friendly alternative to chemical preservatives - Anti-inflammatory and hepatoprotective effects - Moisturizing and UV protection - Controlled delivery system through the gastrointestinal system	Oil incorporation enhances the structural integrity of CAP pectin but compromises CSP; alkaline exposure induces ester group degradation through saponification	[101]
Chitosan nanoparticles	Clove essential oil	- Enhanced antioxidant and antibacterial activity - Controlled release	- Active packaging - Antiseptic, analgesic, and anticancer - Fragrances and sanitation products - natural pesticides	Higher oil loading decreases encapsulation retention; increasing oil content promotes particle growth and reduces colloidal stability	[102]

Moreover, augmenting oil loading above the emulsification threshold of MC (>0.8 mL) diminished encapsulation effectiveness, whereas an excessive addition of chitosan elevated emulsion viscosity and impeded atomization. Moreover, the hydrophilic characteristics of alginate and chitosan rendered the microcapsules susceptible to ambient humidity, potentially resulting in matrix swelling and premature oil release during storage. These findings underscore that the efficacy of chitosan-based spray-drying systems relies on attaining an appropriate equilibrium among encapsulation efficiency, structural integrity, processability, and final storage conditions.

9.4. Coacervation

Coacervation is a technique used to encapsulate bioactive and heat-sensitive substances, categorized into two types: simple and complex coacervation. In simple coacervation, electrolytes are introduced to modify the ionic forces that lead to the formation of polymer salts, while microcapsules are isolated using water-soluble solvents or by adjusting the pH and temperature. Nonetheless, the industrial applications of simple coacervation remain constrained [27]. Complex coacervation involves the interaction of oppositely charged polyelectrolytes in an aqueous medium, leading to the creation of phase-separated structures known as polyelectrolyte complexes, coacervates, or complex coacervates. Complex coacervation microcapsules generally have low water solubility and exhibit high thermal stability [46]. There are various factors that influence EO encapsulation using the complex coacervation method, including polyelectrolyte concentration, temperature, and pH. In polymer-based encapsulation systems, natural polymers are often preferred as wall materials owing to their wide availability, eco-friendly characteristics, and superior biodegradability [103].

Several researchers have used complex coacervation methods for EOs encapsulation. Souza et al. [104] produced chitosan microcapsules encapsulating limonene essential oil for insect-repellent textile applications by a coacervation/precipitation method utilizing the NaOH dripping process. The limonene emulsion in a 0.5% chitosan solution was introduced into NaOH solutions with different concentrations (0.50–1.45 wt%), which caused the precipitation of chitosan under basic conditions and the formation of capsule walls around the oil droplets. The research findings demonstrate that alkali concentration is a critical process parameter influencing particle morphology, microcapsule size, wall thickness, and release kinetics; specifically, an increase in NaOH concentration leads to thicker, more compact capsule walls and a reduced oil volatility rate. This work addresses a deficiency in the literature concerning the influence of alkali concentration on chitosan coacervation and illustrates the possibility for enhanced process efficiency through the utilization of low concentrations of chitosan and surfactants. This optimization entails a trade-off between enhanced long-term protection and restricted fast release, alongside an elevated danger of aggregation resulting from the system's heightened viscosity at elevated NaOH concentrations.

Ariff et al. [105] proved the application of complex coacervation by evaluating the release profile of citronella oil (CO) in a simulated floor cleaner medium based on Tween 80. The formulated gelatin–chitosan system demonstrated excellent thermal stability, and release kinetics analysis using the Korsmeyer–Peppas model indicated a Super Case II mechanism ($n > 0.85$), confirming that oil release was governed by matrix erosion and capsule wall swelling, rather than exclusively by diffusion. Nonetheless, the occurrence of burst release in the

preliminary phases, attributed to the surface oil content and uneven particle size, was recognized as a significant constraint that could lead to fluctuation in the release rate on an industrial scale. This discovery validates that maintaining size uniformity is a considerable difficulty in intricate coacervation systems.

Tavares et al. [106] described an advanced coacervation method focusing on the thermal and structural safeguarding of essential oils, namely by the encapsulation of ginger oil utilizing a mixture of gum arabic (GA) and chitosan (CH), then subjected to freeze drying. This work presents complicated coacervation as a viable alternative to the frequently employed spray drying, specifically for safeguarding the heat-sensitive volatile constituents of ginger. The GA/CH system demonstrated superior coacervate yield and encapsulation efficiency relative to the protein-polysaccharide system, as validated by rheological characterization using creep and recovery tests. This enhancement in encapsulation efficacy was attained at the cost of reduced water solubility and the development of porous particle architectures resulting from the freeze-drying method, which may potentially augment gas diffusion during storage. The method's great sensitivity to pH and mass ratio further substantiates the trade-off between encapsulation efficacy and process robustness.

Evcin et al. [107] demonstrate efforts to improve structural protection through increased wall complexity by employing a complex coacervation system utilizing three biopolymers—gelatin, gum arabic, and chitosan—for the encapsulation of lemon and eucalyptus essential oils. This technique generates relatively diminutive microcapsules (1–2 μm), which is beneficial for the uniformity of scent dispersion. The use of ambient drying resulted in particle aggregation, suggesting that heightened wall complexity does not necessarily correspond with enhanced physical stability. Moreover, despite the encapsulation effectiveness of 75–78%, this figure remains inferior to certain well-optimized two-polymer systems, suggesting that augmenting the biopolymer quantity does not inherently enhance oil adsorption performance. This study clearly delineates the trade-offs among small particle size, agglomeration propensity, long-term stability, and fragrance release attributes.

Andrade et al. [63] reported the encapsulation of oregano oil via chitosan/gum arabic (CHI/GA)-based complex coacervation, employing a comprehensive methodology that included GC–MS method validation in accordance with ICH guidelines and formulation optimization utilizing a Box–Behnken design. This system attained a high encapsulation effectiveness (about 95%) and exhibited commendable colloidal stability during storage for a duration of up to 120 days. The optimization results indicated intrinsic limitations, such as the sensitivity of the CHI/GA ratio to particle size and charge, heightened polydispersity at elevated storage temperatures, and the matrix's capacity constraints for oil loading. The results affirm that the efficacy of the complex coacervation process relies on both the effectiveness of adsorption and the colloidal stability and size uniformity during storage. Herjandi et al. [108] presented the integration of complex coacervation in a therapeutic context, utilizing both *in silico* and experimental methods for the microencapsulation of *Citrus aurantiifolia* peel extract as a potential treatment for breast cancer. Despite achieving a high encapsulation efficiency of 99.65%, this investigation identified a significant trade-off among matrix strength, extract content, and release rate. Augmented cross-linking and matrix complexity improved thermal stability and adsorption efficiency; nevertheless, they led to diminished extract content and prolonged release, potentially constraining bioavailability. The lack of *in vitro* validation and

additional pharmacokinetic assessment underscores the disparity between encapsulation efficacy and genuine medicinal significance.

Taken together, these studies demonstrate that chitosan-based complex coacervation is a highly versatile encapsulation platform; however, its successful implementation depends on a

careful balance between process parameters, matrix complexity, encapsulation efficiency, and release behavior tailored to the intended application. The recurring trade-offs among structural protection, process efficiency, and functional performance highlight that no single encapsulation strategy is universally optimal.

Table 4. Comparative overview of major encapsulation methods for essential oils, highlighting principles, performance, and inherent trade-offs

Method	Encapsulation Principle	Typical Particle Size	Encapsulation Efficiency (EE)	Advantages	Trade-offs	Representative Study
Emulsification	Dispersion of essential oils in an aqueous phase (oil-in-water, O/W) using surfactants; liquid-based systems	Macro: 0.5–100 μm ; Nano: 50–500 nm; Micro: 10–100 nm	Low–moderate	Simple processing; improves dispersibility, initial bioactivity, and matrix compatibility	Physical instability (coalescence, Ostwald ripening); high burst release; limited long-term release control	[10,77]
Ionic Gelation	Ionic cross-linking between positively charged chitosan and multivalent counterions (e.g., TPP, HMP, Ca^{2+}) forming hydrogel particles	<100–300 nm	High (≈ 80 –98%)	Good colloidal stability; pH-responsive behavior; improved release control	Initial burst release; limited loading capacity; aggregation at high polymer concentrations	[66,69]
Spray Drying	Atomization of an emulsion followed by rapid solvent evaporation to form dry microparticles	1–20 μm	Moderate–high (≈ 60 –92%)	High industrial scalability; continuous operation; cost-effective	Thermal degradation risk; surface oil; humidity sensitivity during storage	[89–91]
Coacervation	Electrostatic interaction between oppositely charged polymers forming a dense capsule wall around oil droplets	300 nm–5 μm	High–very high (≈ 75 –99%)	Excellent thermal protection; high encapsulation efficiency; formulation flexibility	Sensitive to pH and mass ratio; agglomeration; scale-up challenges	[63, 104, 105]

9.5. Critical comparative analysis

According to the comparison in Table 4, the four encapsulating technologies have complementing attributes while also having intrinsic constraints for long-term stability, scalability, and industrial viability. Emulsification is the most simple and efficient method for enhancing the initial dispersibility of essential oils in aqueous environments. Nonetheless, due to its inherent characteristics as a predominantly liquid system with minimal diffusion impediments, its long-term stability is comparatively low, rendering it vulnerable to coalescence, Ostwald ripening, and burst release. Consequently, this method is infrequently employed as a definitive solution on an industrial scale unless integrated with advanced solidification techniques. Ionic gels can attain high encapsulation effectiveness (80–98%) and exhibit remarkable colloidal stability; however, they face initial burst release and scaling challenges due to aggregation tendencies at elevated polymer concentrations.

Compared to the two methods, spray drying is the most industrially advanced approach due to its continuous operation, ease of scalability, and relative cost-effectiveness. This process is highly appropriate for the mass manufacturing of encapsulated powders that exhibit excellent physical stability during storage, contingent upon the regulation of humidity conditions. The application of higher temperatures in the atomization and drying process significantly constrains extremely volatile and heat-sensitive essential oils [90], frequently leading to excessive surface oil and potentially diminishing oxidative stability during

prolonged storage. Simultaneously, sophisticated coacervation provides significant benefits for encapsulation efficiency and thermal protection, along with considerable formulation flexibility through the choice of polymer types and ratios. However, this advantage is accompanied by significant challenges in the industrial context, especially the process's sensitivity to pH, composition, and drying conditions, along with concerns over reproducible performance and a tendency for agglomeration, which can hinder quality control on a large scale. In conclusion, there is no single method that is absolutely superior for all applications. Therefore, the selection of an encapsulation method must take into account the ultimate application objectives, long-term stability requirements, production capabilities, and both technological and economic constraints at the industrial scale, employing a contextual rather than a universal perspective.

10. Challenges and Future Perspectives

Recent literature trends (2020–2025) indicate a clear shift from laboratory-scale performance optimization toward techno-economic feasibility, reproducibility, regulatory compliance, and long-term safety as the dominant challenges governing successful commercialization of chitosan-based encapsulation systems. The translation of chitosan-based essential oil encapsulation systems from laboratory-scale research to industrial implementation faces interconnected challenges related to cost, reproducibility, regulatory approval, and functional performance. Although multiple encapsulation

strategies have been validated at the academic level, commercialization is frequently constrained by raw material variability and underestimated economic burdens. Chitosan quality is highly dependent on biological source and extraction route. Marine-derived chitosan typically exhibits high molecular weight (500–1000 kDa) and moderate degrees of deacetylation (70–85%) but suffers from seasonal availability and post-extraction impurities, whereas fungal-derived chitosan offers higher purity and lower allergenic risk at the expense of limited scalability. Insect-derived chitosan is emerging as a sustainable alternative, though industrial infrastructure remains underdeveloped [109, 110]. As a result, fluctuations in chitosan physicochemical properties directly translate into inconsistent processing behavior and unpredictable production costs.

Encapsulation method selection further determines economic feasibility. Spray drying remains the most industrially established technique due to its continuous operation and proven scalability; however, high capital investment, energy consumption, and risk of thermal degradation restrict its use for heat-sensitive essential oils and small-scale manufacturers [111]. Ionic gelation, while operating under mild conditions and requiring lower initial investment, is limited by batch-wise processing, long residence times, and sensitivity to polymer concentration and pH, which increase labor and quality-control demands [69]. Coacervation achieves high encapsulation efficiencies but involves multi-step processing and stringent control of phase behavior, resulting in increased batch-to-batch variability and scale-up complexity [112]. Importantly, hydrophobic modification, and encapsulation method, complicating the simultaneous optimization of stability, efficacy, and scalability [116, 117].

Future research must therefore move beyond isolated parameter optimization toward integrated system-level design. Emerging trends include stimuli-responsive chitosan systems, green crosslinking agents such as vanillin and polyphenols, deep eutectic solvent-based processing, and continuous manufacturing approaches that improve reproducibility and reduce batch variability [118]. Bibliometric and market analyses indicate accelerating interest in chitosan-based encapsulation, with publication output increasing by approximately 15–20% annually and encapsulation representing the fastest-growing application segment [111]. Recent regulatory guidance updates and growing investment in continuous processing technologies suggest that, while significant barriers remain, the field is approaching a transition point where coordinated advances in materials design, safety assessment, and process engineering may enable viable commercial deployment [113].

11. Conclusion

Chitosan has demonstrated considerable potential as a polymeric matrix for the encapsulation of essential oils (EOs), owing to its chemical functionality, biocompatibility, and its ability to form structured networks through electrostatic and hydrogen-bonding interactions. The literature consistently indicates that chitosan-based systems improve the physicochemical stability of EOs by reducing volatilization, oxidative degradation, and environmental sensitivity, while also enabling modulation of release behavior depending on formulation parameters.

The performance of these encapsulation systems is strongly influenced by intrinsic polymer characteristics. The degree of deacetylation (DDA) determines charge density and the extent of intermolecular interactions, whereas molecular weight (Mw) governs chain entanglement, matrix compactness, and diffusion

improvements in encapsulation efficiency beyond ~85% often require disproportionate increases in process complexity, diminishing economic return.

Regulatory and safety considerations represent an equally significant bottleneck. While bulk chitosan is generally regarded as safe and approved for several food and biomedical applications, the regulatory status of chitosan nanoparticles, modified derivatives, and composite systems remains fragmented and application-specific [111]. Divergent regulatory frameworks between EFSA and FDA demand extensive toxicological evaluation of nanoscale materials, including chronic exposure, impurity profiling, and ADME studies, increasing development costs and timelines [113]. Residual crosslinkers and surfactants used in ionic gelation and emulsification, such as tripolyphosphate or Tween-based stabilizers, introduce additional safety uncertainties due to limited long-term exposure data, particularly in food-related applications [69].

Beyond economic and regulatory barriers, chitosan-based encapsulation systems are governed by an inherent stability–activity trade-off. High molecular weight and highly deacetylated chitosan improve encapsulation efficiency and storage stability but often result in dense polymer networks that slow essential oil diffusion, reducing immediate bioactivity [69, 114]. In contrast, low molecular weight chitosan enables faster release and stronger short-term antimicrobial effects, frequently accompanied by burst release and reduced long-term protection [115]. This trade-off is further influenced by pH responsiveness, pathways. Variations in these parameters directly affect encapsulation efficiency, colloidal stability, and release kinetics. A recurring pattern observed across studies is the presence of a stability–bioactivity balance. Systems prepared with higher Mw and higher DDA generally form denser and more stable matrices that support prolonged release, although this may restrict rapid diffusion of active compounds. In contrast, lower Mw chitosan tends to facilitate faster release but may compromise long-term structural stability and increase the likelihood of burst release.

Comparative evaluation of encapsulation techniques highlights that each method operates through distinct physicochemical mechanisms. Emulsification enhances dispersion but offers limited long-term structural integrity. Ionic gelation achieves high encapsulation efficiency under mild conditions through electrostatic crosslinking, yet issues related to burst release and scale-up remain. Spray drying provides industrial feasibility and improved storage stability, although thermal exposure can affect volatile EO components. Coacervation, based on polyelectrolyte complex formation, enables high encapsulation efficiency and protective capacity but requires careful control of pH and polymer ratios. These observations indicate that method selection should be aligned with the intended application, considering stability requirements, release profile, and practical feasibility rather than encapsulation efficiency alone.

Despite extensive laboratory-scale studies, several limitations continue to constrain broader implementation. Variability in chitosan source and composition affects reproducibility and processing behavior, while differences in regulatory frameworks for nano-scale systems and modified derivatives complicate translational pathways. Future research should therefore emphasize integrated formulation strategies in which polymer chemistry, processing conditions, and functional performance are evaluated simultaneously. Further efforts to correlate molecular structure with macroscopic behavior will be essential for developing reproducible and application-oriented systems. Overall, the advancement of chitosan-based EO

encapsulation depends on a balanced understanding of molecular interactions, material properties, and application-specific constraints. Continued refinement of polymer design and encapsulation strategies is necessary to bridge the gap between laboratory findings and practical implementation.

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