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Review

Cyclodextrin-Based Nanoencapsulation of Essential Oils for Advanced Food Applications

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Abstract: Essential Oils (EOs) are promising natural antimicrobial and antioxidant agents for food preservation. However, their direct application is hindered by high volatility, low water solubility, chemical instability, and intense sensory impact. This review evaluates Cyclodextrin (CD)-based nanostructures as a strategic solution to these limitations. By forming inclusion complexes, cyclodextrins enhance EO stability, improve aqueous dispersibility, and enable controlled release. This paper discusses the fundamental principles of cyclodextrins, explores advanced nanoformulations such as nanosponges and biopolymer composites, and reviews recent research on their application in active packaging and direct food incorporation. While challenges in scalability, regulation, and sensory acceptance remain, CD-based nanoencapsulation represents a versatile and effective approach for harnessing the full potential of essential oils in sustainable food preservation. The integration of CDs into active food packaging systems is highlighted as a particularly promising pathway to extend shelf life while aligning with consumer demand for ‘‘clean-label’’ products.

***Keywords*:** essential oils, biobased preservatives, antioxidant activity, nanoencapsulation, edible coatings, food safety

1. Introduction

In recent years, the demand for natural alternatives to synthetic preservatives has intensified. Essential oils, known for their potent antimicrobial and antioxidant properties, have emerged as prime candidates. However, their inherent characteristics—high volatility, sensitivity to environmental factors, poor water solubility, and strong aroma—severely limit direct application in foods. These drawbacks often result in inconsistent efficacy and undesirable organoleptic changes, restricting their industrial use. These challenges have spurred research into advanced delivery systems designed to protect and optimize the performance of essential oils in complex food matrices.

Among these systems, cyclodextrins have gained prominence. These cyclic oligosaccharides possess a unique hydrophobic cavity capable of encapsulating guest molecules, such as essential oil components, forming stable inclusion complexes. This process can significantly improve the physicochemical properties of essential oils, mitigating their major drawbacks.

This review provides a critical and comprehensive synthesis of recent advances in cyclodextrin-based nanoencapsulation of essential oils, with several distinctive contributions that differentiate it from existing literature.

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First, while previous reviews have broadly covered essential oil encapsulation, this work places particular emphasis on the integration of CD-EO systems into active and edible packaging applications—a rapidly evolving field with significant commercial potential. Second, we offer a comparative analysis of CD-based systems against alternative nanoencapsulation strategies (including liposomes, nanoemulsions, and biopolymer nanoparticles), evaluating their relative advantages and limitations in terms of stability, scalability, sensory impact, and regulatory acceptance. Third, this review critically examines the persistent barriers—including industrial scalability, regulatory hurdles, and sensory acceptance—that must be overcome for successful commercialization, moving beyond purely academic considerations to bridge fundamental science with applied food technology. Finally, by synthesizing quantitative performance data from recent studies and presenting it in comparative formats, we aim to chart a clear pathway for the future development of sustainable, CD-enabled preservation strategies that align with consumer demand for "clean-label" products.

2. Essential oils: A brief overview

Essential Oils (EOs) are concentrated, hydrophobic liquids composed of volatile compounds extracted from aromatic plants. They are commonly obtained through steam distillation, hydrodistillation, or cold pressing, with the extraction method playing a key role in determining both the chemical composition and overall quality of the oil [1].

In plants, EOs are produced as secondary metabolites and serve various biological and ecological functions. In addition to providing characteristic aroma and flavour, they act as natural defence agents against herbivores and pathogenic microorganisms, function as chemical signals between plants, and contribute to reproduction by attracting pollinators. Through these roles, essential oils support plant survival and broader ecosystem interactions [2].

From a chemical perspective, essential oils are complex mixtures of volatile compounds responsible for their strong sensory properties. Although they contain many constituents, only a limited number are typically present at high concentrations, usually ranging from 20 to 90%, while the remaining compounds occur in much lower amounts. This complex chemical profile strongly influences both aroma and biological activity [1].

The main components of EOs can be broadly classified into terpenes and aromatic or aliphatic compounds [2]. Terpenes, particularly monoterpenes (C_{10}) and sesquiterpenes (C_{15}), form the dominant fraction and largely determine the characteristic aroma of the oils [3]. Compounds such as limonene, α-pinene, and myrcene also contribute to antimicrobial and antioxidant effects [3]. In addition, essential oils contain smaller amounts of alcohols, aldehydes, esters, and phenolic compounds [4]. Despite their lower concentration, phenolic compounds such as thymol, carvacrol, and eugenol play a crucial role in biological activity and are particularly relevant for food preservation due to their strong antimicrobial and antioxidant properties [2, 4].

The chemical composition of essential oils is not constant and can vary depending on plant species, plant part used, geographical origin, developmental stage, and extraction method. This variability directly affects aroma, stability, and biological performance. Therefore, understanding the chemical profile of EOs is crucial for food-related applications, as the type and concentration of active compounds determine their antimicrobial, antifungal, and antioxidant effectiveness [1].

The diversity of essential oils available for food applications is vast, with each oil possessing a unique chemical profile that determines its suitability for specific food matrices. Table 1 summarizes some of the most commonly investigated essential oils in food preservation, highlighting their major bioactive constituents, primary modes of bioactivity, and typical food applications. This overview provides a foundation for understanding how the chemical characteristics of different EOs influence their compatibility with cyclodextrin encapsulation and their subsequent performance in real food systems [5].

Table 1. Representative essential oils used in food applications: Major active compounds and typical food matrices

Essential oil	Major active compound(s)	Chemical structure class	Primary bioactivity	Typical food applications	References
Oregano (*Origanum vulgare*)	Carvacrol, Thymol	Phenolic monoterpenoids	Antimicrobial, Antioxidant	Meat and poultry products, dairy, bakery items, fresh produce	[4, 6]

Table 1. (cont.)

Essential oil	Major active compound(s)	Chemical structure class	Primary bioactivity	Typical food applications	References
Thyme (*Thymus vulgaris*)	Thymol, Carvacrol, p-Cymene	Phenolic monoterpenoids	Antimicrobial, Antifungal, Antioxidant	Cheese, meat marinades, edible coatings for fruits	[7, 8]
Cinnamon (*Cinnamomum verum*/*C. cassia*)	trans-Cinnamaldehyde	Phenylpropanoid	Antimicrobial, Antifungal, Antioxidant	Fruit preservation (papaya, apples), beverages, bakery products	[9, 10]
Clove (*Syzygium aromaticum*)	Eugenol, Eugenyl acetate	Phenylpropanoid	Antioxidant, Antimicrobial, Analgesic	Meat products, sauces, edible films, seafood preservation	[4, 11]
Lemongrass (*Cymbopogon citratus*)	Citral (Geranial, Neral), Limonene	Terpene aldehydes	Antimicrobial, Antifungal, Antioxidant	Beverages, dairy products, edible coatings for fresh produce	[6, 12]
Peppermint (*Mentha piperita*)	Menthol, Menthone	Monoterpene alcohol/ketone	Antimicrobial, Cooling/Flavoring agent	Confectionery, beverages, dairy desserts, chewing gum	[13]
Rosemary (*Rosmarinus officinalis*)	1,8-Cineole, α-Pinene, Camphor, Carnosic acid	Terpenes, Phenolic diterpenes	Antioxidant, Antimicrobial	Oils and fats, meat products, bakery, snacks	[14]
Tea Tree (*Melaleuca alternifolia*)	Terpinen-4-ol, γ-Terpinene	Monoterpenes	Antimicrobial, Antifungal	Edible coatings for fruits and vegetables, seafood	[11]
Citrus (Orange, Lemon) (*Citrus* spp.)	Limonene, Citral, Linalool	Monoterpenes	Antioxidant, Flavoring agent	Beverages, fruit juices, confectionery, dairy	[13]
Winter Savory (*Satureja montana*)	Carvacrol, Thymol, p-Cymene	Phenolic monoterpenoids	Antimicrobial, Antioxidant	Fresh meat (pork, beef), poultry products	[15]
Eucalyptus (*Eucalyptus globulus*)	1,8-Cineole (Eucalyptol)	Monoterpene oxide	Antimicrobial, Antioxidant	Edible films and coatings, fruit preservation	[16]

2.1 *Antimicrobial and antioxidant activities*

One of the most important properties of essential oils in food production is their antimicrobial activity. EOs are effective against a wide range of microorganisms, including bacteria, yeasts, and moulds responsible for food spoilage and foodborne diseases. Their antimicrobial action is primarily linked to the chemical reactivity of terpenes, aldehydes, and phenolic compounds produced through plant secondary metabolism [17].

Essential oils exert their antimicrobial effects mainly by interacting with microbial cell membranes [17]. Their hydrophobic components penetrate lipid double layers, increase membrane permeability, and cause leakage of intracellular materials, ultimately leading to cell death [17]. Additionally, EO constituents can interfere with cellular metabolism by inhibiting Adenosine Triphosphate (ATP)-producing enzymes, disrupting ion transport, damaging cell walls, and affecting respiratory pathways [17]. Some essential oils also promote the formation of reactive oxygen species, which damage microbial Deoxyribonucleic Acid (DNA), proteins, and lipids, while simultaneously inhibiting biofilm formation and quorum sensing (bacterial cell-to-cell communication controlling virulence and biofilm formation), thereby reducing microbial virulence and resistance [18].

Beyond antibacterial effects, EOs also exhibit strong antifungal and anti-mould activity. Phenolic compounds, particularly thymol, carvacrol, and eugenol, disrupt fungal cell membranes and walls, interfere with enzymatic systems, and inhibit essential metabolic processes. This activity limits spore germination and mycelial growth, which is especially important for preventing mould contamination in cereals, bakery products, cheese, and fruits [4].

Consequently, essential oils contribute to reducing mycotoxin formation and improving the microbiological safety of food products [4, 18]. In addition, essential oils show significant antioxidant activity, further supporting their role in food preservation [4]. Phenolic compounds and certain terpenes can scavenge free radicals, slow lipid peroxidation, and stabilise oxidation-sensitive food components [4]. This effect is particularly relevant for lipid-rich foods such as oils, meat, and dairy products, where oxidation leads to rancidity and sensory deterioration [4]. By limiting oxidative reactions, EOs help preserve colour, flavour, and aroma while reducing the formation of potentially harmful oxidation products [4].

2.2 *Challenges of direct use in foods*

Despite their strong antimicrobial and antioxidant properties, the direct application of essential oils in food systems faces several limitations. One of the main challenges is their intense aroma and flavour, which can easily alter the sensory profile of food products even at low concentrations. This issue is particularly problematic for foods with mild or delicate flavours, where consumer acceptance may be significantly reduced [4].

Another major limitation arises from interactions between essential oil components and food constituents such as lipids, proteins, and carbohydrates. Hydrophobic EO compounds tend to bind to fat and protein fractions, reducing their availability to act on microbial cells. As a result, antimicrobial effectiveness is often lower in complex or high-fat food matrices compared to simple laboratory media, making matrix-specific optimisation necessary [7].

Chemical instability further restricts the practical use of essential oils [4]. Many EO components are volatile and sensitive to heat, light, and oxygen, leading to degradation during processing and storage [4]. This is particularly problematic for foods requiring thermal treatment, where significant losses of active compounds may occur [4]. In addition, the natural variability in essential oil composition complicates standardisation and reproducibility in industrial applications [19].

These limitations clearly explain why advanced delivery systems, including nanoencapsulation, are increasingly investigated to improve stability, control release, reduce sensory impact, and enhance the overall effectiveness of EOs in real food systems [20]. These limitations collectively underscore the need for advanced delivery systems that can protect essential oils, control their release, and enhance their compatibility with food matrices [21]. As summarized in Figure 1, this overview highlights the key properties and limitations of essential oils that are important for understanding the following sections on nanoencapsulation strategies [21].

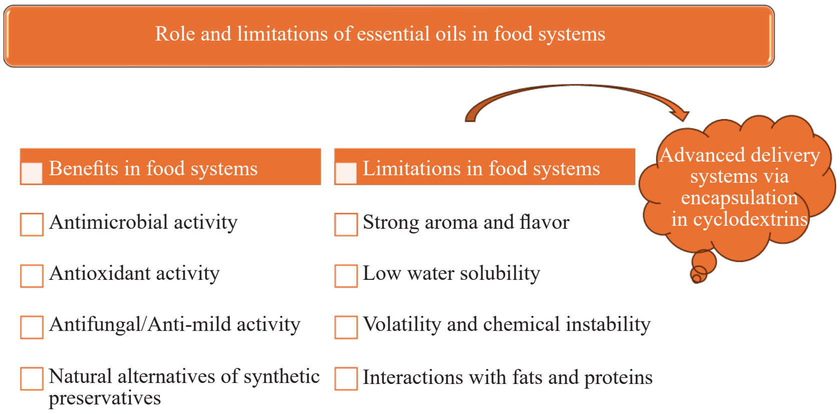

Figure 1. Schematic representation of a cyclodextrin inclusion complex with an encapsulated essential oil molecule. The hydrophobic cavity (interior) encapsulates the guest molecule, while the hydrophilic exterior (hydroxyl groups) enables aqueous dispersion (Author's own illustration)

The inherent limitations of essential oils detailed here—volatility, instability, and strong sensory impact—create a clear imperative for advanced delivery systems. This sets the stage for exploring cyclodextrins as a strategic nanoencapsulation platform designed to mitigate these very challenges [22].

3. Cyclodextrins: Basic principles

Cyclodextrins (CDs) are cyclic oligosaccharides that have gained significant attention in food science and pharmaceutical research due to their ability to interact with a wide range of bioactive compounds. In food-related applications, they are particularly valued for their capacity to form inclusion complexes with flavours, nutrients, and volatile substances such as essential oils, making them effective carriers for sensitive food ingredients. This functional behaviour results directly from their unique molecular structure [13].

Structurally, cyclodextrins are composed of D-glucopyranose units linked by α-1,4 glycosidic bonds, forming a ring-shaped, truncated cone molecule [14]. The number of glucose units determines the overall size of the cyclodextrin [14]. A defining feature of CDs is their amphiphilic character, meaning they have both hydrophilic (water-attracting) and hydrophobic (water-repelling) regions [13]. The hydrophilic outer surface, formed by hydroxyl groups, allows the molecule to disperse in water-based environments, while the hydrophobic inner cavity can host non-polar or slightly polar molecules [13]. This arrangement enables cyclodextrins to encapsulate hydrophobic compounds that would otherwise be poorly soluble or unstable in aqueous food systems [13]. The resulting host-guest inclusion complexes, which are non-covalent associations between the cyclodextrin and the guest molecule, can significantly modify the physicochemical behaviour of the encapsulated compound, enhancing solubility, reducing volatility, and providing protection from environmental stress [13].

The most commonly used CDs in food applications are α-cyclodextrin with six glucose units, β-cyclodextrin with seven glucose units, and γ-cyclodextrin with eight glucose units [14]. The number of glucose units determines the size of the internal cavity and, because of that, the types of guest molecules that can be encapsulated [14]. These structural differences are illustrated in Figure 2, which shows the relative dimensions of their cavities [14]. The formation of inclusion complexes is mainly driven by hydrophobic interactions and van der Waals forces between the guest molecule and the cyclodextrin cavity, while the hydrophilic exterior enhances solubility in aqueous environments and protects the guest molecule from degradation or premature release [13, 14].

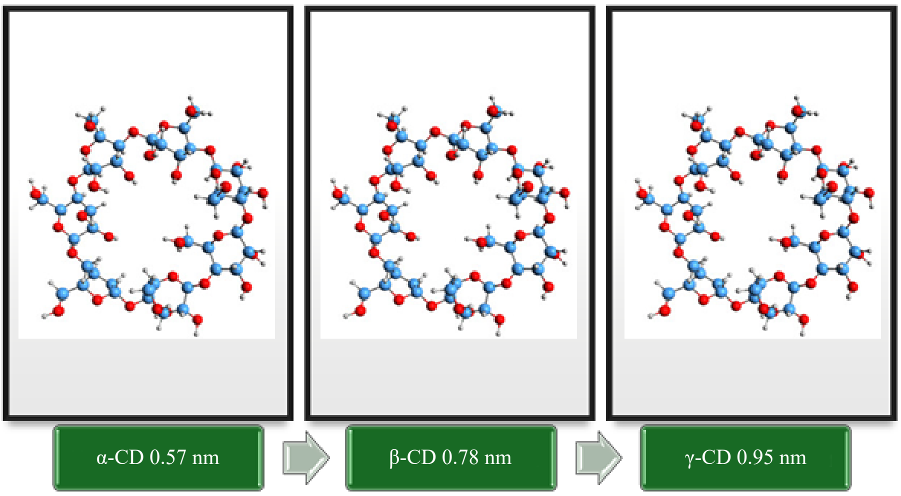

Figure 2. Schematic representation of the molecular structure and cavity dimensions of α-, β-, and γ-cyclodextrins (Author's own illustration based on structural data from [14])

Inclusion complexation with cyclodextrin offers several important functional advantages in food systems. When a guest molecule is encapsulated within the CD cavity, its chemical stability is often improved and its volatility reduced. This occurs because the encapsulated compound is partially shielded from external factors such as oxygen, light, and heat. These effects are especially relevant for volatile and reactive substances, including essential oils, which are prone to rapid evaporation and degradation during food processing and storage. Encapsulation in cyclodextrins can therefore help preserve both the aroma and bioactivity of such compounds, improving their overall effectiveness in food applications [13].

Another significant benefit of CDs is their ability to enhance the apparent solubility of poorly water-soluble compounds. Many bioactive components of essential oils exhibit limited solubility in aqueous food matrices, which restricts their uniform distribution and functional performance. By forming inclusion complexes with cyclodextrins, these compounds can be more evenly dispersed throughout the food system. Improved dispersibility increases the likelihood of interaction with target microorganisms or oxidation-sensitive substrates, thereby enhancing antimicrobial and antioxidant performance [14].

Cyclodextrins can also influence the sensory properties (taste and aroma perception) of encapsulated compounds. Because the guest molecule is partially or fully embedded within the CD cavity, its direct interaction with taste buds and olfactory receptors may be reduced. This masking effect is particularly advantageous for essential oils, which often possess strong and intense aromas that can negatively affect consumer acceptance. Cyclodextrin encapsulation allows the use of effective concentrations of essential oils while minimising undesirable sensory changes in the final food product [13].

In addition to native cyclodextrins, a variety of chemically modified derivatives have been developed to further enhance their functional performance. Such modifications can improve water solubility, increase affinity for specific guest molecules, or enable more controlled release behaviour. Although the fundamental host-guest inclusion mechanism remains unchanged, these derivatives provide greater flexibility in designing tailored delivery systems for bioactive compounds in food applications [14].

An important consideration for the practical application of cyclodextrins in food systems is their regulatory status, which varies by country and by CD type. Native cyclodextrins (α-, β-, and γ-CD) have received widespread regulatory acceptance for food use. In the United States, they are Generally Recognized as Safe (GRAS) by the Food and Drug Administration (FDA). Specifically, α-CD is GRAS for use as a dietary fiber and formulation aid, β-CD is GRAS as a flavor protectant and carrier, and γ-CD has the broadest approval as a GRAS substance for various food applications. In the European Union, α-, β-, and γ-CD are approved as novel food ingredients and food additives, with β-CD designated as E459 and permitted in specific food categories at defined maximum levels (typically up to 1 g/kg in certain products, though this varies by application) [23].

For chemically modified cyclodextrins, the regulatory pathway is more complex. Derivatives such as Hydroxypropyl-β-CD (HP-β-CD) and methyl-β-CD are widely used in pharmaceutical applications but have more limited food approvals. HP-β-CD, for example, is not currently GRAS for general food use in the US, though it may be permitted in specific food-contact applications subject to migration limits. In the European Union (EU), modified CDs require case-by-case evaluation as novel foods or food additives before they can be commercialized. This regulatory distinction is important because while modified CDs often offer superior functional properties—such as enhanced solubility or controlled release—their use in commercial food products may face additional hurdles compared to native CDs. Researchers developing CD-based food systems must therefore consider not only the functional performance of different CD types but also their regulatory status in target markets [23].

In summary, the basic principles of cyclodextrins are closely linked to their cyclic molecular structure, hydrophobic cavity, and ability to form stable inclusion complexes. Through these mechanisms, CDs can improve the stability, solubility, sensory compatibility, and controlled release of bioactive compounds such as essential oils. These properties make these molecules valuable tools for the development of innovative food formulations and advanced delivery systems. An understanding of cyclodextrin structure and inclusion behaviour is therefore essential for evaluating their role in nanoencapsulation strategies discussed in the following chapters [13, 14].

The unique molecular architecture and host-guest chemistry of cyclodextrins provide the foundational toolkit for nanoencapsulation. The following section will detail how these principles are translated into practical CD-based systems—from simple inclusion complexes to advanced nanocomposites—for real-world food applications [24].

4. Cyclodextrin-based nanoencapsulation for food applications

Cyclodextrin-based systems represent one of the most widely investigated nanoencapsulation strategies for food applications, particularly for the delivery of volatile and hydrophobic bioactive compounds such as essential oils [13, 14]. Their relevance in food technology arises from the ability of cyclodextrins to form stable inclusion complexes, which are non-covalent host-guest associations between the cyclodextrin molecule and an encapsulated compound [13, 14]. In recent years, research has expanded beyond simple inclusion complexes to more advanced cyclodextrin-based nanoformats, including nanosponges, polymeric networks and composites with biopolymers, which provide improved loading capacity and controlled release properties [13, 14]. Table 2 provides a comparative analysis of cyclodextrin-based systems and alternative nanoencapsulation strategies used for essential oils in food applications [25].

The formation of inclusion complexes is the most established and commonly used cyclodextrin-based encapsulation approach in food systems. The host-guest interaction of CDs with essential oils is shown in Figure 3. In this process, guest molecules are incorporated into the internal cavity of CDs during preparation methods such as kneading, coprecipitation, freeze-drying, or spray-drying [13].

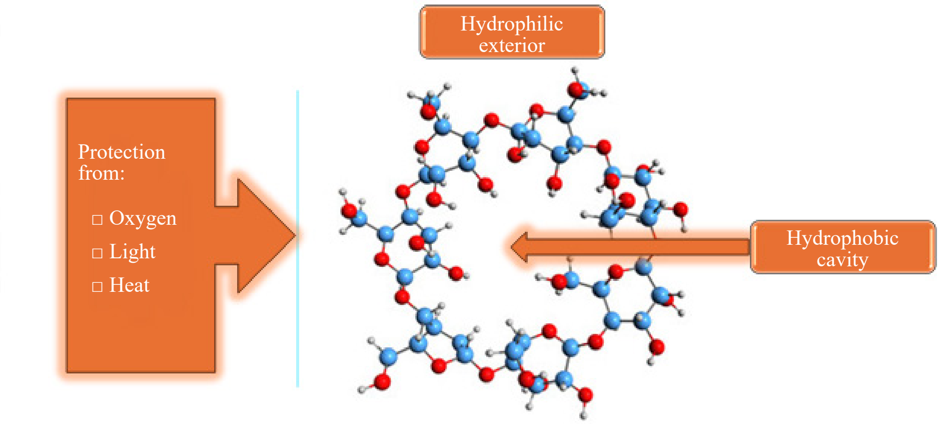

Figure 3. Schematic representation of the formation process of a cyclodextrin inclusion complex with an encapsulated essential oil molecule. Guest molecules are incorporated into the internal cavity of CDs during preparation methods such as kneading, coprecipitation, freeze-drying, or spray-drying (Author's own illustration based on principles described in [13, 14])

These methods are considered suitable for food applications due to their relative simplicity, scalability and compatibility with food-grade materials. The resulting complexes typically exhibit improved physicochemical properties compared to the free guest compounds, including increased apparent solubility, reduced volatility and enhanced resistance to environmental stress factors such as oxygen, light and heat. These improvements are particularly important for essential oils, which are inherently volatile and chemically sensitive [13].

In practical food applications, CD inclusion complexes have been investigated across a wide range of products [11, 14]. In dairy systems, such as yoghurt, cheese and fermented drinks, encapsulation allows hydrophobic bioactive compounds to be incorporated more uniformly without phase separation or excessive flavour impact [14]. In beverages, cyclodextrin complexes enable the stabilisation of volatile compounds in aqueous environments, helping to maintain clarity and aroma stability during storage [14]. In bakery products, inclusion complexes have been applied either directly in dough while processing or indirectly through active packaging systems, where the gradual release of essential oil vapours can inhibit microbial growth on the product surface without negatively affecting the sensory properties of the crumb [11, 14].

Despite their advantages, traditional inclusion complexes are limited by the size of the cyclodextrin cavity and therefore by their relatively modest loading capacity. To overcome these limitations, cyclodextrin-based nanosponges have been developed. Nanosponges are three-dimensional, crosslinked polymeric networks derived from CDs, characterised by a porous structure that combines multiple inclusion sites with additional adsorption spaces within the polymer matrix. This architecture allows nanosponges to encapsulate larger quantities of bioactive compounds and to provide more sustained and controlled release behaviour. From a food technology perspective, these properties are particularly advantageous for applications requiring prolonged antimicrobial or antioxidant activity, such as long-term storage of fresh or minimally processed foods [26].

Table 2. Comparative analysis of cyclodextrin-based systems and alternative nanoencapsulation strategies for essential oils in food applications [25]

Encapsulation system	Principle of formation	Stability & protection	Loading capacity	Release characteristics	Scalability & cost	Sensory impact	Regulatory status in food	Key advantages	Key limitations
CD inclusion complexes	Host-guest inclusion in hydrophobic cavity	High protection against heat, light, oxidation	Low to moderate (1 : 1 molar ratio typical)	Controlled, often triggered by moisture or temperature	Good; native CDs commercially available, scalable methods (kneading, spray-drying)	Low; effective masking of aroma/taste	GRAS status for α-, β-, γ-CD (FDA); approved food additives (European Food Safety Authority (EFSA))	Simple, well-established, effective masking, improves solubility	Limited loading capacity, cavity size restricts guest molecules
CD nanosponges	Crosslinked CD polymers with porous network	Very high; enhanced protection due to crosslinking	High; multiple inclusion sites + adsorption	Sustained, prolonged release (days to weeks)	Moderate; synthesis more complex, requires purification steps	Low to moderate; controlled release minimizes sensory burst	Emerging; specific derivatives may require case-by-case approval	High loading, prolonged release, versatile	Complex synthesis, higher cost, limited commercial availability
Liposomes	Phospholipid bilayer vesicles encapsulating hydrophilic/hydrophobic compounds	Moderate; sensitive to pH, temperature, and osmotic stress	Moderate (hydrophilic core + bilayer)	Variable; can be triggered or sustained	Moderate; requires specialized equipment (e.g., extrusion, homogenization)	Low to moderate; can mask aroma but phospholipids may add flavor	Generally Recognized as Safe (GRAS) for some phospholipids; case-by-case	Biocompatible, can carry both hydrophilic and hydrophobic compounds	Physical instability (aggregation, fusion), sensitive to food processing conditions
Nanoemulsions	Oil-in-water dispersions stabilized by surfactants	Low to moderate; susceptible to Ostwald ripening, coalescence	High; depends on oil phase volume	Rapid initial burst, then sustained	Good; high-energy methods (ultrasonication, high-pressure homogenization) scalable	Moderate; surfactants may affect taste, high EO concentration at interface can increase aroma	Depends on surfactants used; many food-grade emulsifiers available (e.g., Tweens)	High loading, easy to produce, improves bioavailability	Physical instability over time, requires high surfactant concentrations, limited masking
Biopolymer nanoparticles	Self-assembly or crosslinking of proteins/polysaccharides	Moderate to high; depends on polymer type and crosslinking density	Moderate; depends on polymer network structure	Controlled by polymer degradation or swelling	Moderate; methods vary (coacervation, ionic gelation) scalable	Low to moderate; biopolymers generally bland, but release can expose EO flavor	Generally GRAS (chitosan, alginate, whey protein, starch)	Biodegradable, edible, can provide additional functional properties (e.g., film-forming)	May require chemical crosslinkers, sensitive to pH and ionic strength, lower encapsulation efficiency for volatiles

Cyclodextrin nanosponges have been incorporated into edible coatings, food-contact materials and active packaging systems [26, 27]. When applied as part of an edible film or coating, nanosponges act as reservoirs that slowly release volatile compounds onto the food surface, maintaining effective concentrations over extended periods [26]. Studies have demonstrated that such systems can reduce microbial growth on meat and fresh produce, delay spoilage and extend shelf life without direct addition of free essential oils to the food matrix [26]. Additionally, nanosponges can be used in sachets or pads placed inside packaging, providing indirect protection through controlled vapour release [26, 27].

Another important development in cyclodextrin-based nanoencapsulation is the formation of composite systems with food-grade biopolymers. These composites combine the encapsulation capability of CDs with the film-forming, mechanical and barrier properties of biopolymers such as chitosan, starch, cellulose derivatives and proteins. Chitosan-based composites are of particular interest due to the intrinsic antimicrobial activity of chitosan and its ability to form cohesive, flexible films. When cyclodextrin inclusion complexes or nanosponges loaded with essential oils are incorporated into chitosan matrices, a synergistic antimicrobial effect is often observed, resulting from both contact-active inhibition and controlled release of volatile compounds [11, 13].

Starch- and cellulose-based CD composites offer cost-effective and biodegradable alternatives for disposable food packaging materials. In these systems, cyclodextrins help retain volatile bioactives during film processing and storage, preventing rapid loss through evaporation. Protein-based films, such as those derived from whey protein, provide good oxygen barrier properties and mechanical strength, while CDs regulate the release of encapsulated compounds on moist food surfaces. These composite materials have been successfully tested as antimicrobial packaging films and wraps for meat, bakery products and fresh produce, where they have been shown to slow microbial spoilage and improve shelf-life stability [13, 14].

Practically, cyclodextrin-based nanoencapsulation systems must be carefully designed to ensure compatibility with food processing conditions. High temperatures, mechanical shear and moisture can influence inclusion stability and release behaviour, which makes formulation optimisation fundamental. Sensory evaluation is also critical, as excessive release of volatile compounds may still lead to perceptible flavour changes, despite the masking effect provided by cyclodextrins. In terms of safety, several native and modified CDs are approved for food use, although regulatory requirements may vary depending on the application, particularly for active packaging systems where migration limits must be considered [13, 14].

Overall, cyclodextrin-based nanoencapsulation represents a versatile and promising approach for incorporating essential oils and other hydrophobic bioactives into food products and packaging systems. Inclusion complexes offer simplicity and scalability, while nanosponges and biopolymer composites provide enhanced loading capacity and controlled release suitable for advanced food preservation strategies. A thorough understanding of these systems is therefore essential for evaluating their potential role in modern food nanoencapsulation and active packaging technologies [28].

Having established the various CD-based nanoformats available, the next section will examine recent, evidence-based research that demonstrates their enhanced efficacy in real food systems and their innovative integration into next-generation active packaging [29].

5. Recent research on cyclodextrin food applications

5.1 *Enhanced antimicrobial and antioxidant performance*

Recent research has increasingly demonstrated that cyclodextrin nanoencapsulation enhances the antimicrobial and antioxidant efficacy of essential oils when applied in real food systems. This trend represents an important progression beyond in vitro studies. Encapsulation not only protects volatile compounds against environmental degradation but also sustains active compound release. It improves practical effectiveness against spoilage organisms in foods such as meat, dairy, and fresh produce. Nanoencapsulation thus addresses key limitations of direct EO application, including low stability and high volatility [6, 12].

One representative study demonstrated that β-CD inclusion complexes with essential oils can enhance thermal and photochemical stability compared to free oils. When lemongrass (Cymbopogon Citratus (CC)) and oregano (Origanum

Vulgare (OV)) EOs were encapsulated in β-CD at optimized ratios (90 : 10, w/w), the encapsulated oils retained their chemical integrity better under heat and Ultraviolet (UV) stress, showing much slower degradation than unencapsulated essential oils. This improved stability was further illustrated in thermal and photodegradation studies; changes in photochemical degradation are shown in Figure 4 [6].

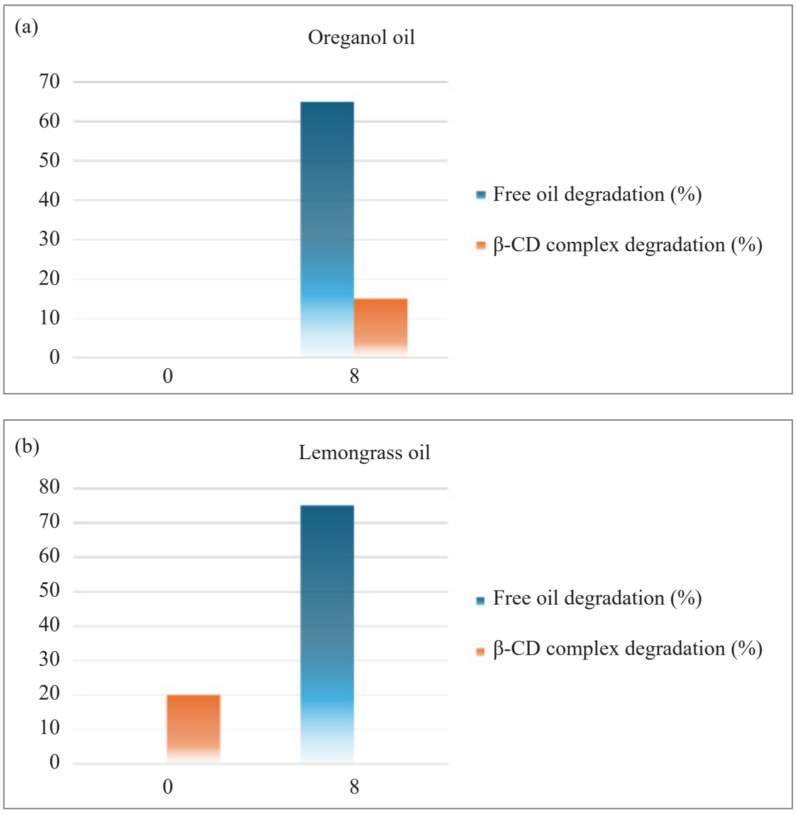

Figure 4. Comparative photochemical stability of free and β-cyclodextrin encapsulated essential oils. (a) Oregano oil (OV) and β-CD-OV complex at 0 h and 8 h of UV exposure. (b) Lemongrass oil (CC) and β-CD-CC complex at 0 h and 48 h of UV exposure (Data adapted from Procopio et al. [6])

Thermal and UV exposure caused significant colour changes and degradation in free EOs. In contrast, β-CD inclusion complexes maintained both colour and chemical content for a longer period. These results indicate that β-CD effectively protects essential oils, supporting their use in food coatings and controlled-release applications to reduce spoilage while preserving quality [6].

Another recent study investigated Lemongrass Essential Oil (LgEO) encapsulated with α-, β-, and γ-cyclodextrins. It was found that γ-CD complexes exhibited the highest antimicrobial and antioxidant activity. They also showed high encapsulation efficiency (approximately 78%) and controlled release properties. In tests against spoilage fungi such as *Botrytis cinerea* and *Penicillium* spp., the γ-CD/LgEO complex showed significantly greater inhibition compared to other formulations. These results highlight its potential for future food preservation applications [12].

In practical food preservation tests, methyl-β-CD/EO hydrogel coatings were applied to chilled pork. Hydrogels containing winter savory (Satureja montana) EO/β-CD complexes reduced *Staphylococcus aureus* counts by about 3.5 log CFU/g over 7 days, meaning the number of bacteria dropped more than 3,000-fold. This indicates strong antimicrobial activity and extended shelf life compared to untreated pork. The effect is due to the sustained release of volatile compounds from the inclusion complexes, which maintained inhibitory concentrations during storage [15].

Similarly, cinnamon (*Cinnamomum verum*) EO/γ-CD inclusion complexes applied to papaya fruits markedly extended shelf life by about 55% relative to untreated fruits under the same storage conditions. The encapsulated cinnamon EO significantly reduced disease severity. It also maintained physicochemical quality parameters for a longer period. This demonstrates that CD complexation can preserve bioactivity while mitigating the strong aroma typical of free cinnamon oil [9].

Together, these studies illustrate that CD nanoencapsulation consistently enhances both antimicrobial and antioxidant activities of essential oils in real food matrices, improves stability, and supports controlled release, making these systems promising for advanced food preservation strategies [6, 9, 12, 15].

5.2 *Cyclodextrin-based materials in active packaging*

Recent research increasingly focuses on the integration of cyclodextrin-based nano-enabled systems into active food packaging, which includes edible coatings, biodegradable films, electrospun nanofibers, and other food-contact materials designed to actively interact with the food or its environment. Unlike conventional passive packaging, active packaging incorporates functional agents, such as encapsulated EOs, that are gradually released to inhibit spoilage microorganisms, reduce oxidation, and extend shelf life [29].

One notable study from 2022 investigated the incorporation of oregano essential oil/β-CD inclusion complexes into Polylactic Acid (PLA)/Polycaprolactone (PCL) electrospun nanofibers. The resulting nanofibrous mats exhibited sustained release behaviour and significantly enhanced antibacterial and antifungal activity, with inhibition rates exceeding 90% against common spoilage microorganisms. When applied to fresh blackberries, the active nanofibers reduced fungal decay by more than 50% and delayed quality deterioration during refrigerated storage, demonstrating their effectiveness in a real food system [8].

In a recent innovative approach, Cheng et al. developed electrospun Polyvinyl Alcohol (PVA)/chitosan composite nanofibrous films incorporating inclusion complexes of 1,8-cineole—the main bioactive component of eucalyptus essential oil—with Hydroxypropyl-β-Cyclodextrin (HP-β-CD). The films were prepared with a 40% (w/w) loading of the inclusion complexes and demonstrated sustained 1,8-cineole release through a non-Fickian diffusion mechanism, indicating that release was controlled by both diffusion and polymer relaxation. Importantly, incorporation of the CD complexes also improved the barrier and mechanical properties of the films compared to control formulations without CDs. When applied to fresh strawberries, the active nanofibrous films extended shelf life to 6 days at 25 °C, whereas control films without CD encapsulation showed quality deterioration within 3-4 days. This study demonstrates the potential of combining modified cyclodextrins with electrospinning technology to create effective active packaging systems for highly perishable fruits [16].

Similarly, Carvacrol/γ-Cyclodextrin Inclusion Complexes (CRV-γCD-IC) were incorporated in electrospun Gelatine/Pullulan (GEL/PUL) nanofibers. These nanofibers exhibited higher essential oil retention during processing and storage compared with non-complexed formulations. They also showed enhanced antimicrobial activity and antioxidant capacity, reducing lipid oxidation of fish oil by approximately 40% under accelerated shelf-life conditions. The encapsulation efficiency and stability of carvacrol were further evaluated for GEL/PUL/CRV nanofibers (without cyclodextrin) and GEL/PUL/CRV-γCD inclusion complex nanofibers, as shown in Figure 5 [30].

Both nanofibers were prepared with an initial theoretical carvacrol content of approximately 10% (w/w). Immediately after electrospinning, the encapsulation efficiency was 70.6% ± 0.8 for GEL/PUL/CRV Nanofiber (NF) and 90.6% ± 4.4 for GEL/PUL/CRV-γCD-IC NF. After two months of storage, carvacrol retention decreased to 57.6% ± 1.3 in GEL/PUL/CRV NF, whereas the γCD inclusion complex nanofibers maintained significantly higher retention of 67.8% ± 0.6 ($p < 0.05$). These results demonstrate that γCD complexation substantially enhances carvacrol stability during processing, storage, and application as an active packaging material [30].

In another recent work, β-Cyclodextrin-Epichlorohydrin (β-CD-EP) inclusion complexes loaded with EOs cinnamaldehyde and thymol were incorporated into chitosan films. The inclusion complexes showed high encapsulation efficiency and loading efficiency, reaching 74.2% and 3.4% for cinnamaldehyde and 79.2% and 5.2% for thymol, respectively. They also exhibited a significant slow-release effect, which enhanced the functional properties of the films. Compared with pure chitosan, the composite films exhibited strongly improved antibacterial and antioxidant activities, particularly against Gram-positive bacteria. This enhancement is attributed to the controlled release of the encapsulated oil components, indicating their strong potential as active packaging materials [31].

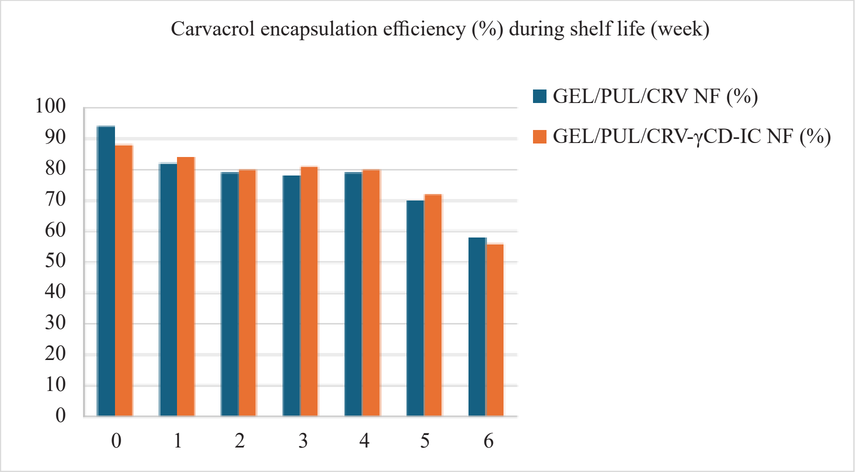

Figure 5. Carvacrol encapsulation efficiency during 6-week storage in gelatin/pullulan nanofibers without (GEL/PUL/CRV NF) and with γ-cyclodextrin inclusion complex (GEL/PUL/CRV-γCD-IC NF) (Data plotted from Ertan et al. [30])

Table 3. Recent studies on cyclodextrin-based systems in active food packaging

CD system	Essential oil/ active compound	Packaging material/format	Food application	Key quantitative findings	Ref.
β-CD inclusion complex	Oregano essential oil	PLA/PCL electrospun nanofibers	Fresh blackberries	• Antifungal activity > 90% against spoilage microorganisms; • Reduced fungal decay by > 50%; • Delayed quality deterioration during refrigerated storage.	[8]
γ-CD inclusion complex	Carvacrol	Gelatin/Pullulan electrospun nanofibers	Fish oil (oxidation model)	• Encapsulation efficiency: 90.6% ± 4.4 (vs. 70.6% without CD); • Carvacrol retention after 2 months: 67.8% ± 0.6 (vs. 57.6% without CD); • Reduced lipid oxidation by ~ 40%.	[30]
β-CD-EP oligomer	Cinnamaldehyde, Thymol	Chitosan composite films	In vitro (antibacterial testing)	• Encapsulation efficiency: 74.2% (cinnamaldehyde), 79.2% (thymol); • Loading efficiency: 3.4% (cinnamaldehyde), 5.2% (thymol); • Significant slow-release effect; enhanced antibacterial activity against Gram-positive bacteria.	[31]
β-CD inclusion complex	Winter savory EO	Methyl-β-CD/ EO hydrogel coatings	Chilled pork	• Reduced *Staphylococcus aureus* by ~ 3.5 log CFU/g over 7 days; • Extended shelf life compared to untreated pork.	[15]
γ-CD inclusion complex	Cinnamon EO	Direct application (coating)	Papaya fruits	• Extended shelf life by ~ 55%; • Significantly reduced disease severity; • Maintained physicochemical quality parameters.	[9]
β-CD inclusion complex	Lemongrass EO, Oregano EO	Powder (for thermal/ photostability)	Model system	• Enhanced thermal and photochemical stability; • Slower degradation under UV and heat stress compared to free EOs.	[6]
α-, β-, γ-CD inclusion complexes	Lemongrass EO	Powder (for antimicrobial testing)	In vitro (fungal inhibition)	• γ-CD complex showed highest activity; • Encapsulation efficiency: ~ 78%; • Greater inhibition of *Botrytis cinerea* and *Penicillium* spp.	[12]
β-CD nanosponge	*Aloysia citriodora* EO	Edible coating	Beef	• Reduced microbial growth; • Delayed spoilage; • Extended shelf life without direct EO addition to food matrix.	[27]
HP-β-CD inclusion complex	1,8-Cineole (eucalyptus EO)	PVA/chitosan electrospun nanofibrous films	Fresh strawberries	• 40% (w/w) loading in nanofibers; • Non-Fickian diffusion release mechanism; • Extended shelf life to 6 days at 25 °C (vs. 3-4 days for control); • Improved barrier and mechanical properties.	[16]

Collectively, these studies demonstrate a clear trend toward the use of CD inclusion complexes and CD-enhanced packaging materials to maintain antimicrobial and antioxidant activity over extended storage periods. By enabling controlled release of bioactive compounds, such systems offer tangible improvements in food quality preservation compared to packaging containing free essential oils, and show strong potential for application in edible coatings, biodegradable films, and electrospun nanofiber-based active packaging [8, 16, 30, 31].

The studies summarized in Table 3 demonstrate the versatility of CD-based systems across different packaging formats and food matrices. Quantitative data reveal consistent improvements in encapsulation efficiency, antimicrobial activity, and shelf-life extension, with many studies reporting reductions in microbial load exceeding 90% or extensions of product shelf life by 50% or more [6, 8, 9, 12, 15, 16, 27, 30, 31].

5.3 *Modified cyclodextrins for essential oil applications*

Beyond classical CD inclusion complexes, chemically modified cyclodextrins and advanced formulations have emerged as powerful tools to further improve the delivery characteristics of essential oils in food systems. Modified CDs, such as succinic acid derivatives, hydroxypropylated CDs, or CD-based metal-organic frameworks, can enhance stability, solubility, and release behaviour of volatile bioactive compounds, addressing key limitations of native CDs in practical applications [10].

One of the studies compared the encapsulation of Cinnamon Essential Oil (CEO) using various β-CD derivatives, Maltosyl-β-CD (Mal-β-CD), Carboxymethyl-β-CD (CM-β-CD), Hydroxypropyl-β-CD (HP-β-CD), and 2,6-Di-O-Methyl-β-CD (DM-β-CD). The results showed that HP-β-CD exhibited the greatest adaptability to cinnamaldehyde (the major bioactive compound in CEO) and that complexes with Mal-β-CD and CM-β-CD demonstrated better controlled release characteristics, leading to enhanced antioxidant and antibacterial activity compared with DM-β-CD and HP-β-CD complexes. This suggests that substituent groups on the CD ring can significantly affect both stability and functionality of encapsulated EOs [32].

Most recently, Li et al. explored the use of succinic acid-modified β-cyclodextrin for encapsulating cinnamon essential oil and evaluated its application in grass carp preservation. The chemical modification introduced carboxyl functional groups that enhanced the CD's affinity for cinnamaldehyde and improved the overall stability of the inclusion complex. The modified CD system demonstrated superior encapsulation efficiency and more sustained release compared to native β-CD complexes. In practical application to grass carp fillets stored under refrigerated conditions, the succinic acid-modified CD/CEO complex significantly inhibited microbial growth, reduced lipid oxidation, and extended shelf life by approximately 4-5 days compared to untreated samples. Sensory evaluation indicated that the modified CD system effectively masked the intense aroma of cinnamon oil while maintaining its antimicrobial efficacy, addressing one of the key limitations of direct EO application in seafood products. This study illustrates the potential of specifically designed CD derivatives for tailoring encapsulation systems to the requirements of particular food matrices [10].

Another important strategy involves CD-based Metal-Organic Frameworks (MOFs) as advanced delivery platforms. MOFs are porous crystalline materials composed of metal ions coordinated to organic ligands, forming highly ordered networks with exceptionally large surface areas and uniform cavities. In food applications, CD-MOFs offer distinct advantages over conventional CD complexes, including higher encapsulation capacity, enhanced protection of bioactive compounds, and more precisely controlled release kinetics [33].

Li et al. systematically investigated thymol encapsulation using α-, β-, and γ-CD MOFs, demonstrating that the choice of CD type significantly influences both loading capacity and release behavior. The γ-CD MOF complex achieved the highest encapsulation content, reaching 286.7 ± 8.4 mg thymol per gram of MOF (Figure 6), which was significantly higher than that of α-CD MOF ($p < 0.05$). This superior loading capacity reflects the better steric fit of thymol molecules within the larger γ-CD cavities and the highly porous MOF architecture that provides multiple encapsulation sites. Importantly, the γ-CD MOF system exhibited a controlled release profile sustained over 35 days under simulated storage conditions, with release data fitting a diffusion-controlled model characterized by a relatively low release rate constant. When applied to cherry tomato preservation, the thymol-loaded γ-CD MOF significantly reduced fungal decay and maintained fruit quality throughout storage, highlighting its strong potential for long-term preservation of fresh produce [33].

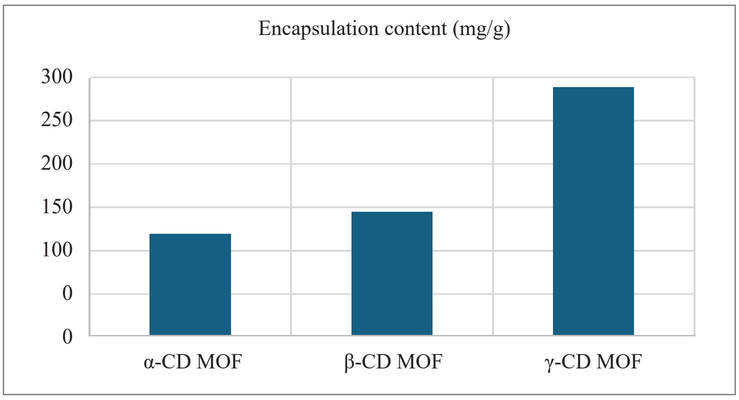

Figure 6. Thymol encapsulation content in α-, β-, and γ-Cyclodextrin Metal-Organic Frameworks (CD-MOFs). Different letters above bars indicate statistically significant differences between samples ($p < 0.05$) (Data plotted from Li et al. [33])

Relevant to active food packaging, inclusion complexes of 1,8-cineole (the main component of eucalyptus EO) with Hydroxypropyl β-Cyclodextrin (HP-β-CD) were incorporated into electrospun Polyvinyl Alcohol (PVA)/chitosan composite nanofibrous films at 40% (w/w) loading. These films demonstrated sustained 1,8-cineole release through a non-Fickian diffusion mechanism, meaning that the release was controlled by both diffusion and polymer relaxation. Incorporation of the CD complexes also improved barrier and mechanical properties of the films. When applied to strawberries, the films extended shelf life to 6 days at 25 °C, compared to control films without CD encapsulation [16].

Table 4. Modified cyclodextrins and advanced formulations for essential oil delivery

CD type/ modification	Essential oil/active compound	Formulation type	Key improvements/characteristics	Quantitative performance data	Ref.
HP-β-CD, Mal-β-CD, CM-β-CD, DM-β-CD (vs. native β-CD)	Cinnamon essential oil (cinnamaldehyde)	Inclusion complexes	• HP-β-CD: greatest adaptability to cinnamaldehyde; • Mal-β-CD and CM-β-CD: better controlled release; • Substituent groups significantly affect stability and functionality.	Enhanced antioxidant and antibacterial activity compared to native CD complexes.	[32]
γ-CD MOF	Thymol	CD-MOF crystals	• Highly ordered porous structure; • Controlled, sustained release; • Diffusion-controlled release model.	• Encapsulation content: 286.7 ± 8.4 mg thymol/g MOF; • Sustained release over 35 days; • Significantly higher than α-CD MOF ($p < 0.05$).	[33]
Succinic acid-modified β-CD	Cinnamon essential oil	Modified CD complex	• Enhanced stability; • Improved controlled release.	Applied successfully for grass carp preservation.	[10]
HP-β-CD	1,8-Cineole (eucalyptus EO)	PVA/chitosan electrospun nanofibrous films	• Non-Fickian diffusion mechanism; • Improved barrier and mechanical properties; • Sustained release.	• 40% (w/w) loading in nanofibers; • Extended strawberry shelf life to 6 days at 25 °C (vs. control).	[16]
HP-β-CD	Various EOs	Inclusion complexes	• Improved water solubility; • Enhanced bioavailability.	Enhanced encapsulation capacity and release profiles.	[14]
Methyl-β-CD	Winter savory EO	Hydrogel coatings	• Sustained release in food matrix; • Effective antimicrobial activity.	3.5 log CFU/g reduction of *S. aureus* on pork over 7 days.	[15]

These studies highlight the significant potential of novel cyclodextrin derivatives and CD-based hybrid materials for improving essential oil stability and controlled release in food systems. Chemically modified CDs provide enhanced encapsulation capacity, sustained release profiles, and improved antimicrobial and antioxidant activity. Quantitative results, including higher loading capacities, prolonged release periods, and better preservation of bioactive compounds, demonstrate that these approaches effectively overcome limitations of conventional CD complexes, offering practical solutions for active food preservation applications [10, 16, 32, 33].

Taken together with the previous subchapters, these studies show that cyclodextrin-based systems, from simple inclusion complexes to modified CDs and nanofibrous or film-based materials, can effectively improve the performance of essential oils in real food systems. The main benefits include better antimicrobial and antioxidant activity, higher stability against heat and light, and more controlled and prolonged release of active compounds. Overall, the results confirm that CD-based technologies are widely applicable in active packaging, edible coatings, and other food-contact materials, providing a solid basis for further development of sustainable and efficient food preservation approaches [4, 6, 8-16, 26, 27, 30-33].

As shown in Table 4, chemically modified cyclodextrins and CD-based metal-organic frameworks offer significant advantages over native CDs, including higher loading capacities (up to 286.7 mg thymol/g MOF), prolonged release profiles (extending to 35 days), and enhanced compatibility with specific essential oil components. These advanced formulations represent the next generation of CD-based delivery systems for food preservation applications [10, 14-16, 32, 33].

6. Challenges and future prospects

Despite the strong potential of cyclodextrin-based systems demonstrated in recent studies, several challenges still limit their widespread application in food preservation. Although laboratory and pilot scale experiments confirm enhanced antimicrobial and antioxidant performance of encapsulated essential oils, translating these findings into industrial practice requires careful evaluation of economic feasibility, regulatory compliance, and long-term performance in real food supply chains [23, 29].

One major limitation is industrial scalability and cost. While native cyclodextrins (α-, β-, γ-) are commercially available and relatively inexpensive, advanced formulations such as modified CDs and CD-based metal-organic frameworks often involve complex synthesis routes and specialized production steps. These preparation processes are not easily scalable and may use reagents or conditions that limit practical use, potentially increasing production costs relative to conventional preservatives and hindering industrial adoption [34].

Regulatory and safety considerations represent another important challenge that must be addressed for successful commercialization. While native cyclodextrins (α-, β-, and γ-CD) benefit from well-established regulatory approval—including GRAS status in the US and food additive designations in the EU, Japan, and other major markets—their incorporation into novel applications such as active packaging introduces new regulatory complexities.

For active packaging systems, regulatory oversight extends beyond the safety of the CD molecule itself to consider the entire functional system [23, 29, 35]. Key considerations include:

(1) Migration testing: When CD-EO complexes are incorporated into packaging materials, it is essential to demonstrate that any substances migrating into food—whether CDs, EO components, or potential reaction products—remain within acceptable limits. In the EU, Framework Regulation (EC) No 1935/2004 and specific measures for plastic materials (EU Regulation 10/2011) require migration testing under foreseeable conditions of use. In the US, FDA regulations under 21 Code of Federal Regulations (CFR) require food-contact substance notifications for new materials or significant new uses of existing substances [23, 29, 35].

(2) Dual regulatory pathways: Active packaging systems may be subject to both food additive regulations (for components that migrate intentionally) and food contact material regulations (for the packaging itself). This dual oversight can create complexity in determining the appropriate regulatory pathway and required safety data [23, 29, 35].

(3) Regional variations: Regulatory requirements differ significantly between jurisdictions. For example, Japan's Ministry of Health, Labour and Welfare has established positive lists for food-contact materials, while China's GB 9685-2016 specifies permitted additives for food-contact materials. Companies seeking to commercialize CD-based

active packaging must navigate this patchwork of regional requirements [23, 29, 35].

(4) Modified CDs and novel formulations: As discussed in Section 3, chemically modified CDs and CD-based metal-organic frameworks face more stringent regulatory review. For these materials, manufacturers may need to submit comprehensive safety dossiers, including toxicological studies, environmental fate data, and detailed migration assessments, before receiving approval for food-contact applications. The novel food regulations in the EU (Regulation (EU) 2015/2283) and similar frameworks in other regions require pre-market authorization for substances not consumed significantly before May 1997 [23, 29, 35].

Beyond direct regulatory compliance, consumer acceptance and labeling considerations are increasingly important. The use of nanotechnology-derived terms (even when applied to CD complexes at the molecular level) may trigger labeling requirements in some jurisdictions, such as the EU's requirement to indicate 'nanoengineered' ingredients on food labels (Regulation (EU) 2015/2283). Consumer perceptions of 'nano' in food can be mixed, with some studies indicating concerns about unfamiliar technologies in food products. Clear communication about the safety, benefits, and natural origin of cyclodextrins (derived from starch enzymatic conversion) can help address potential consumer hesitancy [23].

Finally, the essential oils themselves are subject to regulatory oversight as food ingredients or flavorings. In the EU, many EO components are covered by the Flavourings Regulation (EC) No 1334/2008, which establishes a Union list of authorized flavorings. In the US, they must be either GRAS for their intended use or approved as food additives. When combined with CDs, the regulatory status of the EO component remains unchanged, but the delivery system may affect exposure levels and require additional consideration [23].

Addressing these regulatory challenges requires early engagement with regulatory authorities, thorough safety and migration testing, and careful consideration of target markets during product development. Collaboration between food scientists, regulatory experts, and industry partners is essential to navigate this complex landscape successfully [20, 23, 35].

Sensory impact and consumer acceptance also require further attention. Essential oils are highly aromatic, and even controlled release from CD complexes may influence food flavour and odor during storage. While CD encapsulation can moderate some sensory effects, prolonged release can still affect consumer perception, especially in delicately flavoured products. Furthermore, the concept of nano-enabled or chemically modified materials in food-contact applications may raise concerns among some consumers, underscoring the need for sensory studies and clear communication about safety and benefits [23].

From a research perspective, long-term validation in real food systems remains limited. Much of the current literature demonstrates enhanced activity under controlled or accelerated conditions. Future research should focus on conducting extended storage trials and comparative studies with conventional preservatives to validate the practical benefits of cyclodextrin-based systems. In parallel, efforts should aim at simplifying CD modification strategies, improving cost-effectiveness, and developing hybrid delivery platforms that combine CDs with biodegradable polymers or edible coatings. Refining specifically designed CD derivatives and engineered delivery matrices could further improve controlled release and the overall functional performance of essential oils. Additionally, sustainability evaluations and life-cycle analyses will be crucial to confirm the environmental advantages of CD-based preservation technologies compared to conventional packaging solutions [22, 35].

7. Conclusion

This paper focused on the potential of cyclodextrin-based nanoencapsulation systems to improve the practical use of essential oils in food applications. Essential oils are well known for their strong antimicrobial and antioxidant properties, which make them attractive natural alternatives to synthetic food preservatives. However, their direct application in food systems is often limited by several challenges, including high volatility, low water solubility, chemical instability, and an intense aroma that can negatively affect sensory acceptance. These limitations significantly reduce their effectiveness in real food matrices compared to laboratory conditions.

The reviewed literature clearly shows that cyclodextrins represent an effective strategy to overcome many of these challenges. Due to their unique molecular structure, cyclodextrins can form inclusion complexes with hydrophobic bioactive compounds, such as essential oil components. This encapsulation improves the stability of essential oils, protects them from degradation caused by light, oxygen, or heat, and reduces their volatility.

Various cyclodextrin-based systems were discussed, including simple inclusion complexes, cyclodextrin nanosponges, polymeric systems, and cyclodextrin-biopolymer composites used in active food packaging. These approaches demonstrate that cyclodextrins can be successfully applied not only directly in food products, but also in food-contact materials, edible coatings, and antimicrobial packaging films. In particular, the combination of cyclodextrins with natural biopolymers such as chitosan, starch, or proteins offers promising solutions for developing sustainable and biodegradable active packaging with controlled release properties.

Overall, cyclodextrin-based nanoencapsulation represents a versatile and technologically mature approach that transforms essential oils from challenging ingredients into reliable, food-compatible preservatives. The journey from simple inclusion complexes to sophisticated active packaging composites illustrates a field moving steadily toward application. While challenges in scale-up, regulation, and consumer trust require focused interdisciplinary efforts, the scientific foundation is robust. Successfully navigating these final hurdles will position CD-EO systems not merely as novel additives, but as cornerstone technologies for building safer, more natural, and truly sustainable food systems for the future.

Conflicts of interest

The authors declare no conflicts of interest.

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