

Cinnamon Oil Microcapsules for Antifungal Applications: Preparation Strategies, Characterization, Controlled Release, Self-Healing Coatings and Future Perspectives - A Review

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ABSTRACT

Cinnamon essential oil (CEO) has great potential as a plant-derived antifungal because its main components, especially cinnamaldehyde and eugenol, target multiple sites in microbial cells. Nonetheless, direct use of CEO is constrained by its volatility, oxidation, poor aqueous dispersibility, strong aroma, and rapid loss from exposed surfaces. Microencapsulation is a more realistic approach to protect the oil, improve handling, tune release, and embed it in coatings, foods, textiles, and topical delivery systems. In this context, the present review discusses the preparation of these CEO microcapsules, focusing on spray drying, complex coacervation, cyclodextrin inclusion complexes (CICs), ionic gelation, and emulsion-based techniques, as well as polymeric shell-forming strategies (e.g., melamine-formaldehyde systems for use in protective coatings). This work places special emphasis on wall-material selection, encapsulation efficiency, particle size, morphology characterization, chemical and thermal characterization, release kinetics, and antifungal assessment. Representative examples indicate that optimized spray-dried systems can achieve encapsulation

efficiencies above 90%, while coacervate, cyclodextrin, and stimulus-responsive systems can prolong retention and modulate release in the presence of humidity, temperature, or matrix-driven stimuli. Disrupting membrane integrity, energy metabolism, redox homeostasis, hyphal development, and other virulence-related processes can reduce fungal growth and biofilm-associated traits in *C. factitium*. Nonetheless, this should not be regarded as automatically self-healing; true self-healing includes damage-induced release plus quantifiable recovery of a property. Future advances rely on standardized oil characterization, validated release models, application-relevant fungal assays, assessment of formaldehyde remaining and migration over time, long-term coating tests, and sensory/toxicological evaluation at scale. In summary, although CEO microcapsules may be promising candidates for next-generation antifungal materials, claims about their relative stability in formulation should refer only to functions demonstrated in the experimental data rather than general attributes of capsule morphology.

Keywords: cinnamon essential oil; cinnamaldehyde; microencapsulation;

antifungal activity; biofilm; controlled release; self-healing coating; active packaging

INTRODUCTION

Fungal contamination adversely affects human health, food quality, stored products, indoor areas, and biomaterials. However, the need for resistance management, concerns about residue levels in food products, sensory restrictions, and increasing societal demand for bio-based materials have driven a search for antifungal agents from plants. Essential oils of cinnamon (*Cinnamomum* spp.) are particularly appealing because the bark- and leaf-derived essential oils contain chemically active phenylpropanoids with a wide antimicrobial spectrum [1-4]. The antifungal activity of CEO is related to its chemical composition. Bark oils may also be high in trans-cinnamaldehyde, while leaf oils may contain substantial levels of eugenol; concentrations of these and other terpenoid or phenylpropanoid compounds vary by species, plant part, geographic origin, harvest condition, and extraction method [5, 6]. This variability matters because cinnamon oil is not a single chemical entity. This implies that formulation studies must include botanical identification and, preferably, chromatographic profiling of the oil substrate. However, free CEO has many practical limitations despite its activity. It is volatile, hydrophobic, easily oxidized and rapidly lost during storage, heating or by long-term exposure on surfaces. However, the strong smell and taste can restrict dosage in food and consumer products. To overcome these limitations, microencapsulation techniques are employed because they produce multifunctional particles by entrapping the oil in a polymeric, protein, polysaccharide, lipid, or inclusion-complex matrix. The wall also mitigates direct contact with oxygen and light, minimizes evaporation, increases dispersibility, and can form a release barrier that prolongs biological activity [7-10].

Recent studies demonstrate diverse approaches. Protein-polysaccharide walls in spray-dried CEO powders have been shown to achieve high encapsulation efficiencies with good retention during storage [11]. Spherical capsules are made using complex-coacervate and chitosan/gum arabic systems with possible controlled release [12]. Inclusion complexes such as β -Cyclodextrins (β -CD) have been shown to stabilize volatile components and enhance delivery of antifungal material [13,14]. Aminoplast shells, such as melamine-formaldehyde, are commercially used for coatings because they provide a water-borne, mechanically resistant microencapsulated vehicle [15]. Recently, however, researchers have developed humidity- and temperature-responsive capsules based on natural polymers that burst to release oil when the conditions are right for mould growth [16].

This review integrates these developments with a critical focus on antifungal applications. It examines preparation routes, wall materials, characterization tools, release mechanisms, biological assays, coating integration and translation challenges. A central theme is the distinction between sustained or triggerable release and genuine self-healing. Microcapsules may be components of self-healing materials, but the label 'self-healing' is justified only when damage causes a functional response, and the material demonstrably recovers a relevant property.

SCOPE AND APPROACH OF THE REVIEW

This critical narrative review examines representative, peer-reviewed literature on cinnamon essential oil, encapsulation, and its application in antifungal microcapsules, focusing on key publications from the last decade and selected pioneering work. We reviewed recent studies through 2026 on delivery-design pathways, antifungal performance, active packaging and coating applications, and stimulus-responsive release. Encapsulation terminology varies

across disciplines, and we distinguish true core-shell microcapsules from matrix particles, inclusion complexes, and nano/micro-carriers where the original study allows such a distinction. Quantitative data are only provided when explicitly reported in the studies from which the comparison is made; otherwise, comparisons are qualitative

CINNAMON ESSENTIAL OIL: COMPOSITION AND ANTIFUNGAL BASIS

Botanical source and chemical composition

Commercial cinnamon oils are obtained from several *Cinnamomum* species, particularly *C. verum* (*C. zeylanicum*) and *C. cassia*. Bark oil is generally dominated by cinnamaldehyde, whereas leaf oil often contains a larger eugenol fraction. Minor constituents can include cinnamyl acetate, linalool, β -caryophyllene and related aromatic or terpenoid compounds. The biological response of a formulation therefore depends not only on total oil content but also on its chemotype. Gas chromatography coupled with mass spectrometry (GC-MS) is the preferred approach for defining the composition of the starting oil and tracking retention of volatile markers after encapsulation [4-6].

Physicochemical limitations of free oil

CEO is poorly miscible with water and readily partitions into hydrophobic phases. Volatile constituents may evaporate from open surfaces, and unsaturated or reactive compounds may oxidize during processing and storage. These properties complicate direct dosing, produce burst exposure and shorten residual activity. Encapsulation can reduce headspace loss, protect labile constituents and provide a more reproducible delivery format. In food and topical systems, it can also reduce immediate sensory impact by delaying oil release [7-11].

Multitarget antifungal action

Instead, Cinnamaldehyde and other CEO constituents act through multiple, partially overlapping mechanisms rather than a single fungicidal target. These include effects on membrane structure and permeability, changes in membrane potential and energy metabolism, ergosterol-related homeostasis, oxidative stress, mitochondrial dysfunction, and inhibition of adhesion, yeast-to-hypha transition, and biofilm development in *Candida* [17-19]. Efficacy depends on concentration, fungal species, growth phase, and the physical form of the oil (liquid, vapour, or in capsules). This multitarget behaviour provides broad, non-specific activity but makes mechanistic claims dependent on specification.

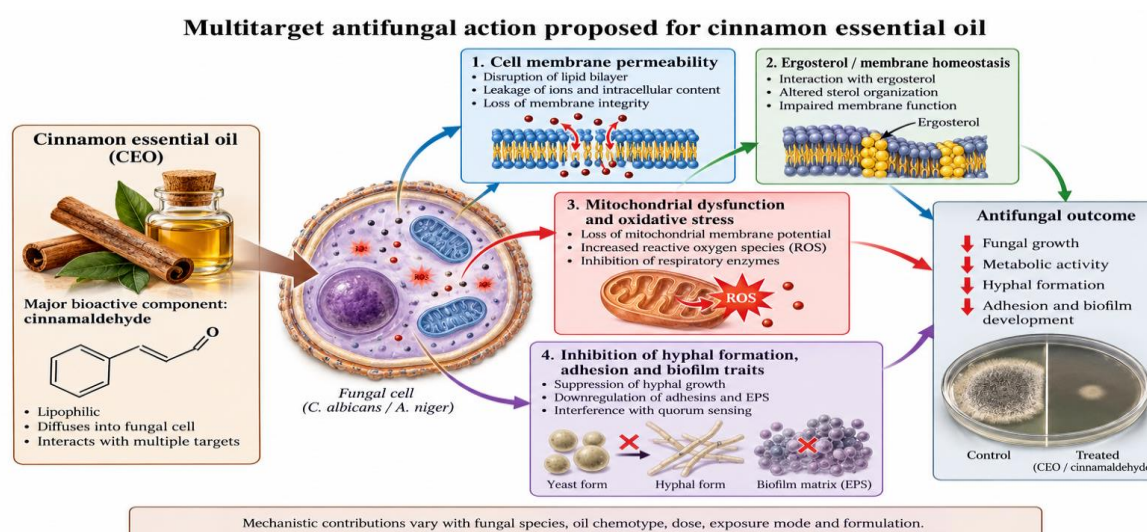


Figure 1. Conceptual summary of the major antifungal mechanisms reported for cinnamon essential oil and cinnamaldehyde.

MICROENCAPSULATION STRATEGIES FOR CINNAMON OIL

Spray drying

Spray drying is the most established industrial route for converting oil-in-water emulsions into dry powders. The feed emulsion is atomized into hot air, water evaporates rapidly, and the wall solidifies around dispersed oil droplets. Common wall materials include maltodextrin, modified starches, whey proteins, gum arabic, alginate, or other food-grade polymers. Hu et al. optimized a whey protein isolate-maltodextrin-sodium alginate wall for CEO and reported encapsulation efficiency above 93% together with high oil retention during accelerated storage [11]. The principal advantages are scalability, continuous operation and production of free-flowing powders. Limitations include possible loss of surface oil, thermal exposure and dependence on emulsion stability, inlet/outlet temperature and wall-to-core ratio [7, 8].

Complex coacervation

Complex coacervation uses attractive interactions between oppositely charged biopolymers to form a dense polymer-rich phase around oil droplets. Gelatin-gum arabic, chitosan derivatives-gum arabic and related pairs are frequently used. Coacervation can operate under comparatively mild thermal conditions and can produce distinct core-shell structures with high oil loading. Liu et al. prepared CEO microcapsules using quaternized chitosan and gum arabic and optimized the process using response-surface methodology, reporting an encapsulation rate of about 90.7% and an average particle size of about 6.3 μm [12]. Crosslinking, pH, polymer ratio, ionic strength and drying conditions strongly influence shell integrity and release [8,12].

Cyclodextrin inclusion complexes

β -Cyclodextrin has a hydrophobic cavity that can host volatile hydrophobic molecules while retaining a hydrophilic

outer surface. CEO/ β -cyclodextrin complexes can be produced by coprecipitation or kneading and are attractive for food and botanical preservation because they avoid a conventional polymer shell. Munhuweyi et al. showed that β -cyclodextrin effectively complexed cinnamon and oregano oils and that the resulting systems retained antifungal activity against *Botrytis* species [13]. More recent work has applied CEO/ β -cyclodextrin microcapsules to postharvest and medicinal-material preservation, including inhibition of storage-associated fungi [14,20]. Inclusion systems are simple and often stable, but cavity stoichiometry and competitive inclusion of different oil components constrain loading.

Ionic gelation, emulsification and nano/micro-carriers

Ionic gelation typically uses alginate, chitosan or related polyelectrolytes that crosslink in the presence of multivalent ions. The process is aqueous and mild, which is attractive for heat-sensitive oils, although particle size can be relatively large and encapsulation efficiency varies widely. Emulsification-based carriers, nanoemulsions, liposomes, solid-lipid systems and polymeric nanoparticles can improve dispersion and interfacial delivery but are not always 'microcapsules' in the strict core-shell sense. Their main benefit is high surface area and tunable interaction with packaging, biological or coating matrices [7,9,21].

Aminoplast and polymeric-shell microcapsules for coatings

For paints and self-responsive coatings, shell strength and binder compatibility become as important as food-grade status. Melamine-formaldehyde and related aminoplast systems can form robust shells around hydrophobic oils by in situ or interfacial polymerization. Revuelta et al. incorporated melamine-formaldehyde microcapsules containing essential oils into an acrylic waterborne paint and

demonstrated antifungal protection against *Aspergillus fumigatus* on coated surfaces [15]. Such shells are attractive for damage-triggered release, but residual formaldehyde, shell brittleness, storage stability and compatibility with the coating must be

evaluated. For applications involving skin, food or prolonged human exposure, safer natural-polymer alternatives may be preferable unless migration and toxicological limits are established.

Design logic for cinnamon-oil microcapsules

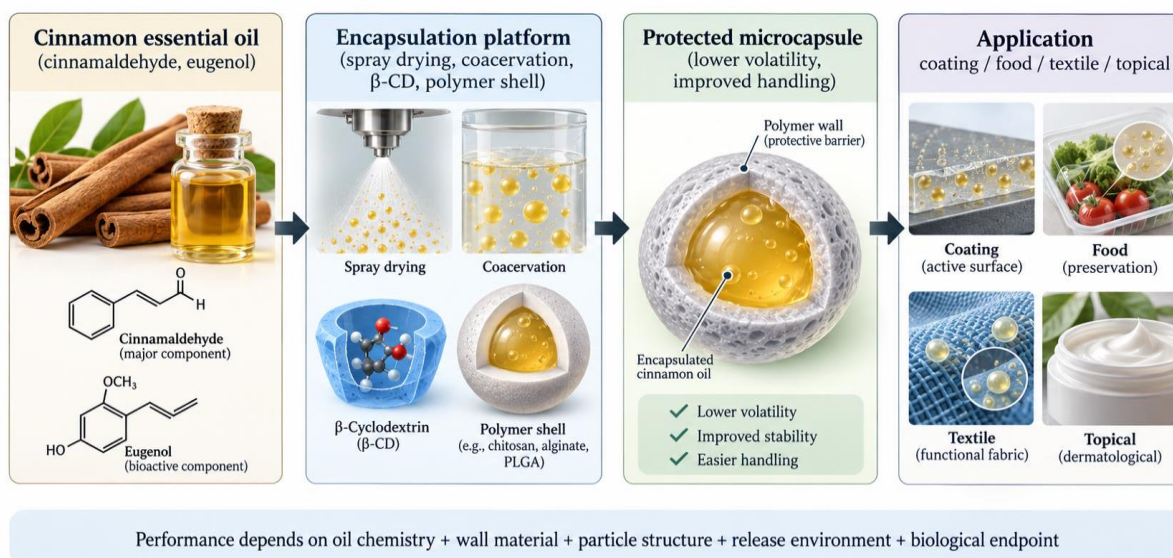


Figure 2. Design pathway from cinnamon essential oil to an application-specific antifungal microcapsule system.

Table 1. Comparison of major encapsulation approaches for cinnamon essential oil.

Method	Typical wall/carrier	Main strengths	Main limitations	Best-fit applications
Spray drying	Maltodextrin, proteins, gums, alginate	Scalable; dry powder; high throughput; often high EE	Thermal/atomization stress; surface oil; burst release	Food powders, packaging additives, dry formulations
Complex coacervation	Gelatin-gum arabic, chitosan-gum arabic	High loading; core-shell morphology; mild processing	Sensitive to pH/ionic strength; crosslinking and drying needed	Food, coatings, controlled release
β -Cyclodextrin inclusion	β -Cyclodextrin and derivatives	Simple; protects volatiles; water-dispersible exterior	Limited cavity loading; selective inclusion of components	Food, botanical preservation, films
Ionic gelation	Alginate, chitosan, Ca^{2+} systems	Aqueous; low temperature; biocompatible	Larger particles; variable EE; diffusion may be rapid	Foods, topical, agriculture
Polymeric shell / in situ polymerization	Melamine-formaldehyde or related resins	Strong shell; tunable rupture; coating compatibility	Residual monomer concern; not ideal for all exposure routes	Protective and self-responsive coatings
Nanoemulsion/nanocarrier	Lipids, surfactants, biopolymers	High dispersion; large interfacial area	Not always true capsules; stability and regulatory complexity	Active packaging, topical delivery

EE: encapsulation efficiency.

WALL MATERIAL SELECTION AND FORMULATION VARIABLES

The wall material determines oil retention, particle morphology, moisture sensitivity, mechanical strength and release behaviour. Protein-polysaccharide combinations are valuable because proteins stabilize the emulsion interface while carbohydrates contribute to glass formation and drying stability. Gum arabic provides emulsification and film formation; maltodextrin lowers viscosity and improves spray-drying performance but has limited emulsifying ability on its own. Chitosan adds intrinsic antimicrobial and cationic properties, whereas alginate offers mild ionic crosslinking. Cyclodextrins protect individual volatile molecules through host-guest interactions. Synthetic aminoplast shells offer high mechanical resistance but require careful control of residual monomers [7,8,11,12,15]. Core-to-wall ratio is a central design variable. A high oil fraction improves payload but can increase surface oil, shell defects and coalescence. Conversely, excessive wall material lowers loading and may slow release to sub-effective levels. Emulsifier concentration, stirring/shear rate, viscosity and interfacial tension control droplet size before shell formation. For coacervation, pH and charge density regulate polymer association. For aminoplast polymerization, temperature, acidification rate and prepolymer chemistry control shell deposition. Optimize these variables against a defined target profile rather than a single metric such as encapsulation efficiency.

CHARACTERIZATION OF CINNAMON-OIL MICROCAPSULES

Morphology and particle size

Scanning electron microscopy (SEM) is routinely used to visualize particle shape, surface roughness, cracks and agglomeration. Smooth spherical particles may indicate successful particle formation, but SEM of intact capsules does not by itself prove a liquid core or complete shell continuity. Cross-sectional imaging,

confocal microscopy or complementary chemical mapping is needed when core-shell architecture is a critical claim. Dynamic light scattering is useful for submicrometre dispersions, whereas laser diffraction and image analysis are often better suited to broad micrometre-scale populations. Report size distributions with the correct basis (intensity, volume, or number) and include replicate measurements.

Chemical confirmation and oil loading

FTIR spectroscopy can show functional groups from wall and oil and may demonstrate spectral changes after encapsulation. However, overlapping bands and physical mixing can produce similar spectra; therefore, interpret FTIR alongside direct oil-loading methods. GC-MS or GC-FID can quantify retained volatile markers, while extraction followed by gravimetry or chromatography can provide total oil content and encapsulation efficiency. Surface-oil measurements are especially important for spray-dried powders because externally exposed oil largely determines early volatilization and burst release [11].

Thermal analysis

Thermogravimetric analysis (TGA) measures mass loss and is well suited to comparing volatilization/decomposition of free and encapsulated oil. Differential scanning calorimetry (DSC) measures heat flow and can reveal glass transitions, melting, curing or other thermal events. These methods are complementary and should not be used interchangeably. Improved thermal stability is best demonstrated by a direct comparison among free oil, empty wall material and loaded microcapsules under the same program [12,13].

Release and stability testing

A credible controlled-release claim requires time-resolved quantification of oil release under defined conditions. Depending on the application, release can be followed by

headspace GC, solvent sampling, UV/visible or chromatographic assays, mass loss or marker-compound analysis. Kinetic models such as zero-order, first-order, Higuchi, Korsmeyer-Peppas and Avrami equations may be used, but model selection

should be based on fit quality and mechanistic plausibility. Control temperature, relative humidity, pH, mechanical damage, and matrix composition because they can alter wall swelling, diffusion, and partitioning [7,16].

Table 2. Core characterization tools and the conclusions they can legitimately support.

Technique	Primary information	Useful outputs	Common over-interpretation to avoid
SEM / optical microscopy	Particle morphology and size	Shape, surface defects, agglomeration	Assuming a hollow core from external morphology alone
DLS / laser diffraction	Particle-size distribution	Hydrodynamic size, PDI, volume/number distribution	Treating one intensity peak as proof of monodispersity
FTIR / Raman	Functional-group signatures	Wall-oil spectral features, interactions	Claiming encapsulation solely from overlapping bands
GC-MS / GC-FID	Oil composition and retention	Cinnamaldehyde/eugenol content, marker retention	Ignoring changes in chemotype during processing
TGA / DSC	Mass-loss and heat-flow behaviour	Volatilization/decomposition; thermal events	Calling DSC alone a TGA stability test
Release assay	Time-dependent oil transfer	Release %, rate, model parameters	Claiming sustained release from a single extraction point
Microbiological assays	Growth, biomass or metabolic response	MIC/MFC, OD, CV biomass, TTC/XTT metabolism	Treating all optical readouts as equivalent biofilm endpoints

RELEASE BEHAVIOUR AND STIMULUS-RESPONSIVE DELIVERY

The polymeric barrier-based mechanism can release from microcapsules via diffusion across the microcapsule wall, dissolution or swelling of the carrier, polymer degradation and partitioning into the surrounding matrix, or shell rupture. The significance of environmental conditions on transport, release and degradation of drug carriers is also evident from their Phase II usage; humidity and temperature generally dominate in food powders and films [14, 21, 22]; mechanical damage can expose or fracture coatings [15]; pH, hydration, and biological fluids can alter the kinetics in topical systems [16]. When some oil is close to the particle surface, diffusion is initially fast, followed by a slower rate. Thus, the release profile reflects both microcapsule architecture and the final product in which the capsules are embedded [7,9]. Recent work indicates a movement towards ecological responsiveness. Tang et al. developed gelatine-acacia gum CEO microcapsules for wood protection and found temperature- and humidity-dependent swelling, enhanced release in mould-

favouring conditions, and Avrami-type release behaviour [16]. Coupling release to environmental risk, rather than the constant passive diffusion on which most currently employed systems are based, makes such systems conceptually appealing. Yet, 'responsive' must be differentiated from self-healing: a stimulus-responsive capsule could also merely release an antifungal agent without repairing a crack (i.e., restoring adhesion or recovering barrier resistance).

ANTIFUNGAL PERFORMANCE OF ENCAPSULATED CINNAMON OIL Candida and biofilm-associated endpoints

Candida albicans is a useful model because pathogenicity depends on adhesion, morphogenesis, biofilm formation and stress adaptation. Cinnamon leaf oil and related phenylpropanoids can inhibit growth and virulence-related traits, including hyphal development [3,17,18]. In encapsulated systems, interpretation requires separating planktonic growth, adherent biomass, and metabolic activity. Crystal violet primarily estimates retained biomass, whereas tetrazolium dyes report metabolic reduction;

OD measurements may reflect planktonic turbidity. A well-designed study therefore includes matched blank particles, free oil, vehicle controls, and, where possible, MIC/MFC data alongside biofilm-specific endpoints.

Filamentous fungi and postharvest preservation

Aspergillus, *Penicillium*, *Botrytis* and related genera are important targets in food, botanical and building applications. β -Cyclodextrin-CEO systems have shown antifungal activity against *Botrytis* species [13]. Cinnamon-Litsea cubeba compound-oil microcapsules have been used for peanut storage, where the encapsulated system reduced fungal burden and aflatoxin B1 while preserving product quality [22]. Gao et al. applied CEO microcapsules to preservation of *Spatholobi caulis* and demonstrated the practical relevance of encapsulated cinnamon oil for storage-associated fungal control [20]. These examples show that antifungal performance can be retained after encapsulation, but application-specific dose, headspace volume, humidity and contact mode strongly affect outcome.

Coatings and surfaces

Coatings are especially suited to microcapsule delivery because the particles

can be distributed through a continuous matrix and protected until release. In waterborne antifungal paint, essential-oil microcapsules have reduced fungal colonization compared with unprotected controls [15]. The coating matrix influences capsule integrity, oil diffusion and surface availability; therefore, antimicrobial tests on extracted aliquots cannot substitute for direct testing of the cured coating. Standardized surface-fungal tests, ageing, abrasion, wet-dry cycling and repeated challenge experiments are valuable for demonstrating durability.

Food packaging, films and paper

CEO is increasingly incorporated into active packaging as free oil, emulsions, inclusion complexes or microcapsules. Reviews of cinnamon-based active packaging emphasize improved antimicrobial functionality but also note the need to balance retention and release to achieve microbial inhibition without unacceptable flavour or aroma [23,24]. Microcapsule-loaded bioactive paper has been reported to prolong CEO release and improve preservation of edible fungi [25]. Film systems can also benefit from CEO, although the oil may plasticize polymers and alter tensile, optical and barrier properties [26].

Table 3. Representative studies illustrating cinnamon-oil encapsulation and antifungal/antimicrobial application.

Study	System	Key reported outcome	Application relevance
Hu et al., 2020 [11]	Spray-dried CEO; WPI/maltodextrin/alginate	>93% encapsulation efficiency; high accelerated-storage retention	Scalable dry powder and food use
Munhuweyi et al., 2018 [13]	β -Cyclodextrin complexes; nanofibre films	EO inclusion confirmed; antifungal activity against <i>Botrytis</i> sp.	Active packaging
Revueita et al., 2021 [15]	MF microcapsules with essential oils in waterborne paint	Reduced <i>Aspergillus fumigatus</i> growth on coated surface	Indoor antifungal coatings
Liu et al., 2023 [12]	HACC/gum arabic CEO microcapsules	~90.7% encapsulation; ~6.3 μ m; sustained release	Food/cosmetic/medicine potential
Lv et al., 2023 [22]	Cinnamon-Litsea cubeba oil/ β -CD microcapsules	Antifungal activity, lower fungal burden and aflatoxin B1 in peanuts	Postharvest storage
Gao et al., 2026 [20]	CEO/ β -CD microcapsules	Storage-preservation antifungal application	Medicinal botanical preservation
Tang et al., 2026 [16]	Gelatin-acacia CEO microcapsules	Humidity/temperature-responsive release; antifungal wood protection	Responsive protective materials

SELF-HEALING: WHAT SHOULD THE TERM MEAN?

In materials science, microcapsules filled with a healing agent are often termed self-healing microcapsules (SHM), but this term should apply only to capsules that undergo functional release and healing, not merely to the presence of a liquid-filled capsule. Traditional microcapsule-based self-healing polymers rely on a damage event that ruptures the capsule, releasing the healing agent to flow into the crack, followed by a chemical or physical process that restores structural integrity. Thus, for demonstration rather than experimentation, there should be a specific damage event in addition to quantitative repair of a property (e.g., fracture toughness, adhesion, corrosion resistance, permeability or electrical performance) [27]. In antifungal coatings, for instance, both reliable biocidal function and the ability to physically heal may be present simultaneously in response to damage. These are not identical. It is possible to provide localized biocidal protection via CEO release from a capsule that ruptures at the scratch. On the other hand, a healing resin may heal a crack but give no antifungal protection. A high-performing 'bioactive self-healing' coating will ideally exhibit both (i) damage-dependent delivery or otherwise exposure of CEO with a subsequent inhibition of fungal colonization and (ii) restoration of a coating property relative to its damaged state. This differentiation increases scientific rigor while avoiding overinterpretation of capsule morphology or extraction assays.

SAFETY, REGULATORY AND SCALE-UP CONSIDERATIONS

Just because a compound is derived from its natural origin does not mean it has inherent safety at any dose or method of exposure. CEO is persistent and irritating; formulation can change local dose and residence time. Food-contact testing (migration, sensory thresholds and legal authorisation for both the oil and carrier). However, reviews of existing active cinnamon packaging show

that while advances have been made, regulatory and standardization gaps remain before industrial adoption [23,24]. For topical or pharmaceutical applications, cytotoxicity, skin irritancy, contact allergy, drug-release uniformity, and in vivo efficacy require special assessment. Shell chemistry also matters. Protein and polysaccharide walls may be more suitable for food and biomedical applications, while melamine-formaldehyde shells are commonly used in industrial coatings. Otherwise, where applicable, residual formaldehyde or other unreacted species should be quantified. Test not just the capsules but the final product, as the latter may alter migration and biological activity by interference with binder, plasticizer, surfactant, and curing process. Droplet size, mixing energy, heat transfer, and mass transfer need to be controlled for scale-up, as do emulsion stability and drying. High wall-to-core ratios or costly biopolymers used in laboratory batches may not be economically scalable. Coacervation and stimulus-responsive systems allow for controlled release but involve additional unit operations, while spray drying has higher throughput. In fact, studies on industrialization of methods should have indicated those properties resulting in yield, process reproducibility, energy use, as well as storage stability and the cost per functional dose and not only encapsulation efficiency [9,24].

FUTURE RESEARCH PRIORITIES

- Standardize CEO identity: report Cinnamomum species, plant part, extraction method, batch and GC-MS composition, with cinnamaldehyde/eugenol content quantified.
- Use application-driven design targets: optimize not only encapsulation efficiency but also surface oil, release rate, shell strength, sensory threshold and effective antifungal dose.
- Strengthen release evidence: generate time-resolved release profiles under

- realistic temperature, humidity, pH and mechanical-damage conditions and compare kinetic models.
- Separate biological endpoints: distinguish planktonic growth, attached biomass, metabolic activity, viability and true eradication of established biofilm; include blank capsules and free-oil controls.
 - Validate self-healing claims: quantify damage-triggered release and recovery of a material property, not simply capsule rupture or oil extraction.
 - Expand durability testing: assess repeated fungal challenge, ageing, abrasion, light exposure, wet-dry cycling and storage.
 - Address safety and migration: determine residual monomers, oil migration, cytotoxicity, irritation and application-specific regulatory compliance.
 - Improve manufacturability: evaluate batch-to-batch reproducibility, continuous processing, energy demand, raw-material cost and end-of-life impact.
 - Explore smart hybrid systems: combine natural-polymer shells with humidity-, pH-, enzyme- or damage-responsive features, while keeping the formulation simple enough for scale-up.

Table 4. Translational gaps and recommended evidence for future cinnamon-oil microcapsule studies.

Claim	Minimum evidence required	Preferred controls
Successful encapsulation	Oil-loading/retention data + morphology + chemical confirmation	Free oil; blank wall material
Improved thermal stability	Direct free-oil vs loaded-capsule TGA/DSC under same program	Empty shell
Sustained release	Time-resolved release profile and model fit	Free oil or non-encapsulated formulation
Antifungal efficacy	Defined fungal endpoint and dose-response; replicate statistics	Vehicle, blank capsule, free oil, positive antifungal
Biofilm inhibition/eradication	Biomass plus metabolic/viability endpoint; preformed-biofilm design for eradication	Sterility and growth controls
Self-healing	Defined damage + trigger + quantified property recovery	Undamaged, damaged-unhealed, blank capsule coating
Safe application	Migration/residuals/toxicity relevant to route	Carrier-only and dose-matched controls

CONCLUSION

This review summarizes the progress of cinnamon essential oil microencapsulation from simple stabilization of a volatile oil to application-tailored delivery systems in food preservation, coatings, cultivation and anticipated topical applications. Spray drying is the path of least resistance for scalable powder production; coacervation and cyclodextrin inclusion are mild, broadly applicable methods; and polymeric or stimulus-responsive shells are crucial if coatings or triggered-delivery applications are envisioned. The best systems emerge from combining chemical characterization of the oil, quantitative loading, particle morphology, thermal behaviour, release kinetics, and biologically meaningful

antifungal assays. Microcapsules containing encapsulated oleoresins can reduce fungal growth and biofilm-associated responses while limiting rapid oil loss; however, efficacy depends on oleoresin chemotype, matrix, dosage, and the release environment. Future studies should shift from descriptive particle characterization to validated function in the final product. For example, sustained release, antifungal performance and self-healing should be considered as separate claims supported by subcases. Standardized formulation, safety assessment and scale-up underline the promise of cinnamon-oil microcapsules as bio-based antifungal components in advanced materials or preservation systems.

Declaration by Authors

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