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Review Paper

Comprehensive Review on Cinnamon Essential Oil-Loaded Microcapsules and Their Antifungal Efficacy

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ABSTRACT

Cinnamon essential oil (CEO), primarily composed of cinnamaldehyde, is a potent natural antimicrobial agent with significant efficacy against a wide range of phytopathogenic and clinical fungi. However, its high volatility, susceptibility to oxidative degradation, and intense aroma limit its direct application in food, agriculture, and pharmaceuticals. Microencapsulation has emerged as a robust strategy to protect CEO, ensure controlled release, and enhance its biological stability. This review provides a comprehensive analysis of the various preparation techniques for CEO-loaded microcapsules, including spray drying, complex coacervation, and ionotropic gelation. Furthermore, it explores the optimization parameters using Response Surface Methodology (RSM) and Artificial Neural Networks (ANN) to maximize encapsulation efficiency and loading capacity. The mechanism of antifungal action, primarily through membrane disruption and inhibition of ergosterol synthesis, is discussed in detail. Finally, the review summarizes current challenges and future perspectives regarding the commercial scalability and regulatory aspects of CEO-based microencapsulated products..

INTRODUCTION

Fungal infections and contaminations are a serious threat to global food security and public health. Phytopathogenic fungi like *Aspergillus flavus*, Penicillium expansum, and Botrytis cinerea cause significant post-harvest losses. Clinical fungi such as Candida albicans also pose growing challenges because of antifungal resistance [1]. For a long time, synthetic fungicides were used to tackle these problems. However, concerns about environmental harm, leftover effects in the food chain, and the rise of resistant strains have shifted the focus to natural alternatives [2]. Essential oils (EOs) from aromatic plants contain active volatile compounds with antimicrobial properties. Cinnamon Essential Oil (CEO), derived from the

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bark or leaves of Cinnamomum species, is particularly recognized for its high levels of trans-cinnamaldehyde [3]. Despite its effectiveness, CEO faces several challenges. It is very sensitive to light, heat, and oxygen, is not very soluble in water, and has a strong sensory profile that can change the taste and smell of food products [4]. Microencapsulation is a method where bioactive compounds (the core) are enclosed in a protective shell (the wall material), creating particles in the micrometer range. This technique not only protects CEO from environmental damage but also allows for a steady, controlled release of antifungal agents, extending their effectiveness [5]. In the past ten years, research has focused on improving the preparation conditions to achieve the best encapsulation efficiency (EE) and the highest antifungal performance. This review aims to bring together current knowledge on the preparation methods, wall material choices, and optimization strategies for CEO-loaded microcapsules, with a specific focus on their use as antifungal agents.

CINNAMON ESSENTIAL OIL: COMPOSITION AND ANTIFUNGAL POTENTIAL

A. Chemical Composition

The bioactivity of CEO is primarily attributed to its major component, *trans*-cinnamaldehyde (65–90%), followed by eugenol, cinnamyl acetate, and caryophyllene [6]. The specific composition varies depending on the species (*Cinnamomum zeylanicum* vs. *Cinnamomum cassia*), the part of the plant used, and the extraction method (hydrodistillation, steam distillation, or supercritical CO2 extraction) [7]

B. Mechanism of Antifungal Action

The antifungal mechanism of CEO is multi-target. Cinnamaldehyde, being lipophilic, easily penetrates the fungal cell wall and interacts with the lipid bilayer of the cytoplasmic membrane. This interaction leads to:

1. **Membrane Disruption:** Increased permeability, causing leakage of essential ions (K+) and cytoplasmic contents [8].
2. **Inhibition of Ergosterol Synthesis:** Ergosterol is vital for fungal membrane integrity. CEO inhibits the enzymes involved in the ergosterol biosynthetic pathway [9].
3. **Mitochondrial Dysfunction:** Interference with mitochondrial electron transport, leading to reactive oxygen species (ROS) accumulation and programmed cell death (apoptosis) [10].
4. **Cell Wall Damage:** Inhibition of chitin and glucan synthesis, resulting in morphological deformities such as hyphal shriveling and reduced conidial germination [11].

PREPARATION TECHNIQUES FOR MICROENCAPSULATION

The choice of encapsulation technique depends on the physical properties of the wall material and the intended application of the microcapsules.

A. Spray Drying

Spray drying is the most common industrial method due to its cost-effectiveness and scalability. It involves atomizing an emulsion of CEO and wall material into a hot air chamber, causing rapid evaporation of water and the formation of solid particles [12].

1. Advantages*:* High production rate, low moisture content, and long shelf-life.
2. Disadvantages*:* High temperatures (typically 140°C–180°C) can lead to the loss of volatile CEO components [13].

B. Complex Coacervation

This method relies on the electrostatic attraction between two oppositely charged polymers (e.g., gelatin and gum Arabic) at specific pH levels. The interaction forms a coacervate phase that deposits around the CEO droplets [14].

1. Advantages*:* High core loading (up to 90%) and excellent thermal protection.
2. Disadvantages*:* Requires precise pH and temperature control; can be sensitive to ionic strength.

C. Ionotropic Gelation

In this "dripping" method, an emulsion of CEO and a polymer (usually sodium alginate) is dropped into a cross-linking solution (calcium chloride). This creates hydrogel beads [15].

1. Advantages*:* Mild conditions (no heat or organic solvents), suitable for maintainng the bioactivity of CEO.
2. Disadvantages*:* Beads are often large (mm range) and have a porous structure that might lead to rapid release.

D. Emulsification and Solvent Evaporation

This involves dissolving the wall material (like PLGA or ethyl cellulose) in an organic solvent, emulsifying it with the CEO and water, and then evaporating the solvent to precipitate the polymer around the oil [16].

1. Advantages*:* Very small particle sizes (sub-micron possible).
2. Disadvantages*:* Use of toxic organic solvents.

WALL MATERIALS AND THEIR ROLE

The wall material serves as the barrier between the CEO and the external environment.

1. **Polysaccharides:** Maltodextrin, gum Arabic, and modified starches are popular for spray drying due to their low viscosity and good film-forming properties [17]. Chitosan is favored for antifungal applications because it possesses inherent antifungal activity, creating a synergistic effect with CEO [18].
2. **Proteins:** Whey protein isolate, soy protein, and gelatin offer high emulsifying capacity and are biodegradable. They often provide better protection against oxidation compared to carbohydrates [19].
3. **Lipids:** Solid lipid nanoparticles (SLN) or nanostructured lipid carriers (NLC) utilize waxes or fatty acids. These provide an excellent moisture barrier but may have lower loading capacity for CEO [20].

OPTIMIZATION OF ENCAPSULATION PARAMETERS

Optimization is critical to balance the Encapsulation Efficiency (EE) and the release rate. EE is defined as the percentage of the initial oil that is successfully trapped within the microcapsules.

A. Key Variables

1. **Core-to-Coat Ratio:** A higher ratio increases loading capacity but may lead to thinner walls and higher surface oil, reducing stability [21].
2. **Homogenization Speed:** Higher speeds result in smaller emulsion droplets, which generally leads to smaller, more stable microcapsules [22].
3. **Surfactant Concentration:** Essential for stabilizing the initial emulsion; however, excess surfactant can interfere with wall formation.
4. **Inlet Temperature (for Spray Drying):** High temperatures increase drying rates but can cause "ballooning" or cracking of the particles, leading to oil loss [23].

B. Statistical Optimization Tools

1. **Response Surface Methodology (RSM):** Most researchers use Box-Behnken or Central Composite Designs (CCD) to find the mathematical relationship between variables and responses (EE, particle size, antifungal activity).
2. **Artificial Neural Networks (ANN):** Recent studies show ANN can predict encapsulation

behavior more accurately than linear models in complex non-linear systems [24].

ANTIFUNGAL EFFICACY OF CEO MICROCAPSULES

Microencapsulated CEO has shown superior performance compared to free oil in various studies.

1. **Extended Inhibition:** While free CEO may inhibit fungal growth for 48–72 hours, encapsulated CEO can maintain inhibitory concentrations for over 15–30 days through controlled release [25].
2. **Vapor Phase Activity:** Many microcapsules are designed to release CEO in the vapor phase, which is highly effective for controlling mold in packaged breads or fruits without direct contact [26].
3. **Specific Studies:** *Aspergillus niger:* CEO-loaded chitosan microcapsules showed a 95% reduction in colony formation compared to control [27].
4. *Botrytis cinerea:* In post-harvest grapes, CEO microcapsules reduced the decay index by 60% compared to untreated samples [28].

CHARACTERIZATION TECHNIQUES

To ensure the quality of CEO microcapsules, several characterization steps are standard:

1. **Scanning Electron Microscopy (SEM):** To observe surface morphology, cracks, and particle size distribution [29].
2. **Fourier Transform Infrared Spectroscopy (FTIR):** To confirm the presence of CEO within the wall material and check for any chemical interactions [30].
3. **Thermogravimetric Analysis (TGA):** To evaluate the thermal stability and determine the degradation temperature of the encapsulated oil [31].
4. **Release Kinetics:** Often described using models like the Higuchi or Korsmeyer-Peppas equations to understand whether release is governed by diffusion, erosion, or swelling [32].

CHALLENGES AND FUTURE PERSPECTIVES

Despite the promising laboratory results, several challenges remain:

1. **Scale-up:** Transitioning from lab-scale (grams) to industrial-scale (tons) while maintaining uniformity in particle size and EE.
2. **Cost:** Complex coacervation and specialized polymers can be expensive.
3. **Regulatory Hurdles:** Ensuring all wall materials and surfactants used are "Generally Recognized as Safe" (GRAS) for food and pharmaceutical applications [33].
4. **Sensory Impact:** Even when encapsulated, the strong odor of cinnamon can sometimes permeate through packaging, which might be undesirable in certain food products [34].

Future research is trending toward "Smart Microcapsules"—particles that release CEO only in response to specific triggers like increased humidity (which correlates with fungal growth) or changes in pH caused by fungal metabolites [35].

CONCLUSION

Microencapsulation is an effective solution to the limitations of Cinnamon Essential Oil, transforming it into a stable, potent, and long-lasting antifungal agent. Through the careful selection of wall materials like chitosan or maltodextrin and the optimization of process parameters via RSM, researchers have achieved high encapsulation efficiencies and sustained release profiles. The resulting microcapsules show immense potential in replacing synthetic fungicides in food preservation and agriculture. As encapsulation technologies continue to evolve, the integration of stimuli-responsive release mechanisms will likely pave the way for the next generation of natural antimicrobial packaging and treatments.

CONFLICT OF INTEREST

The authors have no conflicts of interest.

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