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Construction and Physicochemical Characterization of 6-Gingerol Microcapsules Based on Gelatin–Gum Arabic Composite Wall Materials

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Abstract: 6-Gingerol microcapsules were prepared by complex coacervation using gelatin–gum arabic as composite wall materials and medium-chain triglycerides as the oil-phase carrier. The particle size, microscopic morphology, intermolecular interactions and thermal properties of microcapsules were investigated. The results showed that the obtained microcapsules possessed relatively concentrated particle size distribution, and the volume-weighted mean diameter $D_{[1,2]}$ was 98.197 μm. Microscopic and scanning electron microscope observations revealed that most particles were spherical or nearly spherical with clear outlines and relatively intact capsule walls. FTIR spectra indicated that the microcapsules exhibited characteristic absorption signals of both core and wall materials, and no obvious new chemical bonds were formed. Thermal analysis suggested that the wall materials could slow down the thermal volatilization and degradation of 6-gingerol. This study can provide a basis for the research on microencapsulation of lipophilic natural bioactive compounds.

Keywords: 6-Gingerol; gelatin; gum arabic; complex coacervation; microcapsules; physicochemical properties

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1. Introduction

6-Gingerol is one of the representative phenolic bioactive compounds in ginger. Owing to its characteristic pungent flavor and potential functional value, it has attracted increasing attention in the development of natural functional ingredients [1], food additives, and nutrition-related products. However, the molecular structure of 6-gingerol contains active groups such as phenolic hydroxyl groups, which makes it susceptible

to oxidation, degradation, or structural transformation under environmental conditions such as heat, oxygen, and light. These changes may lead to the loss of active components and a decline in quality stability [2-3, 4-5]. In addition, 6-gingerol is highly hydrophobic, and its dispersibility, compatibility, and long-term stability in aqueous food systems are limited [6-8]. These drawbacks restrict its processing adaptability and practical utilization efficiency. Therefore, constructing a suitable protective carrier to improve the environmental stability and system dispersibility of 6-gingerol is an important strategy for promoting its further application.

This article is developed from and based on part of the author's master's thesis, *Preparation and Application of Ginger-Derived 6-Gingerol Microcapsules Based on Complex Coacervation* (2026) [9]. The present study further condenses and deepens the relevant content, focusing on the influence of gelatin–gum arabic composite wall materials on the structural characteristics and thermal stability of 6-gingerol microcapsules. Different from the thesis framework, which included process optimization and application evaluation, this article mainly focuses on the physicochemical characterization and stability changes of the microcapsules, with the aim of further clarifying the structural protective effect of the composite wall materials on 6-gingerol.

Microencapsulation is a widely used technique for improving the stability of active compounds. By coating the core material with appropriate wall materials, a relatively stable physical barrier can be formed around the active ingredient, thereby reducing the adverse effects of the external environment on the core material and improving its processing stability, storage stability [10-13], and system compatibility. Complex coacervation is a common method for preparing microcapsules. Its basic principle involves electrostatic interactions between oppositely charged polymers under suitable conditions, resulting in the formation of a polymer-rich phase that deposits on the surface of the core material. Compared with some high-temperature drying methods or strong-solvent systems, complex coacervation is relatively mild and offers a broad selection of wall materials. Therefore, it is particularly suitable for encapsulating and protecting easily oxidized, heat-sensitive, or lipophilic active substances.

Gelatin and gum arabic are natural wall materials commonly used in complex coacervation systems. Under appropriate pH conditions, they form capsule walls on oil droplet surfaces via electrostatic interaction. Gelatin exhibits favorable film-forming and gelling properties, while gum arabic possesses emulsifying and stabilizing capacity. Medium-chain triglycerides serve as an oil carrier for 6-gingerol and promote the uniform distribution of active ingredients in emulsions. Accordingly, this study prepared 6-gingerol microcapsules using gelatin–gum arabic as composite wall materials. The particle size distribution, microscopic morphology, FTIR spectrum, and thermal stability of microcapsules were characterized to provide a reference for the microencapsulation of lipophilic natural active substances.

2. Materials and Methods

2.1. Materials and reagents

6-Gingerol, gelatin, gum arabic and medium-chain triglycerides (MCT) served as primary experimental materials. 6-Gingerol was adopted as active core material, MCT as oil-phase carrier, and gelatin together with gum arabic as composite wall materials. The auxiliary reagents included absolute ethanol, methanol, glacial acetic acid, sodium hydroxide and transglutaminase. Methanol and other organic solvents for analysis were chromatographic grade, and other chemicals were analytical grade.

2.2. Instruments and equipment

The main instruments used in this study included a laser particle size analyzer, an optical microscope, a scanning electron microscope, a Fourier-transform infrared spectrometer, a simultaneous thermal analyzer, a vacuum freeze dryer, a high-speed centrifuge, a pH meter, an electronic analytical balance, and a thermostatic magnetic stirrer.

2.3. Preparation of 6-gingerol microcapsules

6-Gingerol microcapsules were prepared via gelatin–gum arabic complex coacervation. Preparation parameters were optimized using single-factor experiments combined with response surface methodology. The optimal conditions were pH 4.11, total wall material concentration of 1.04%, and core-to-wall ratio of 0.77:1. Microcapsules fabricated under these conditions exhibited good formation and encapsulation performance, and all samples for subsequent physicochemical and thermal stability tests were prepared accordingly.

Briefly, gelatin and gum arabic were separately dissolved in deionized water and fully hydrated at 45 °C to prepare wall material solutions. 6-Gingerol was dispersed in MCT to form the oil core phase.

The oil phase was mixed with gum arabic solution and dispersed to form primary emulsion. Gelatin solution was slowly added under constant-temperature stirring. Glacial acetic acid was used to adjust pH to induce complex coacervation, generating microcapsule precursors on oil droplet surfaces. The system was cooled for gelation, followed by the addition of transglutaminase to crosslink and stabilize capsule walls. After standing, centrifugation, washing, pre-freezing and vacuum freeze-drying, 6-gingerol microcapsule powder was obtained and characterized for particle size, morphology, chemical structure and thermal stability.

2.4. Determination of particle size distribution

6-gingerol microcapsule powder was dispersed in deionized water and homogenized via shaking or brief ultrasonication. Particle size distribution was measured by a laser particle size analyzer. The volume-weighted mean diameter $D^{[1,2]}$ and related parameters were recorded to evaluate the particle size and distribution uniformity of microcapsules.

2.5. Morphological observation

The microcapsule morphology was characterized by optical microscopy (OM) and scanning electron microscopy (SEM). OM observed particle dispersion, contour and aggregation, while SEM analyzed the surface morphology, wall structure and particle integrity of microcapsules. Freeze-dried microcapsule powder was fixed on a sample stage and gold-sputtered prior to SEM observation. Representative images were captured for morphological analysis.

2.6. Fourier-transform infrared spectroscopy analysis

Pure 6-gingerol, wall materials, blank microcapsules and 6-gingerol-loaded microcapsules were analyzed by FTIR. All samples were scanned in the mid-infrared region to record characteristic absorption peaks. Peak differences in position, intensity and shape were compared to explore intermolecular interactions between 6-gingerol and wall materials and assess structural changes of 6-gingerol after microencapsulation.

2.7. Thermal stability analysis

Thermal stability was analyzed using a simultaneous thermal analyzer. 6-gingerol microcapsules were placed in test crucibles and measured under a programmed heating procedure. By analyzing the mass changes, weight-loss stages, and thermal effects of the sample during heating, the thermal stability of the microcapsules was evaluated.

2.8. Data processing

All experiments were conducted in triplicate, with data expressed as mean ± standard deviation and analyzed and plotted using statistical software.

3. Results and Analysis

3.1. Particle size distribution of 6-gingerol microcapsules

The particle size distribution of 6-gingerol microcapsules is shown in **Figure 1**. The results indicated that the prepared microcapsules had a relatively concentrated particle size distribution, with a volume-weighted mean diameter D [1, 2] of 98.197 μm. This result suggests that, in the gelatin–gum arabic composite wall material system, the oil-phase core material could form relatively uniform microcapsule particles after emulsification, complex coacervation, and solidification.

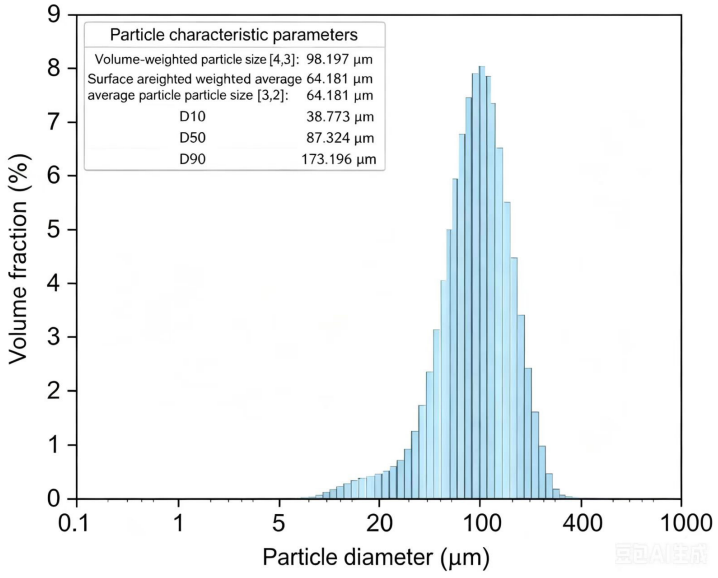

Figure 1. Particle size distribution of 6-gingerol microcapsules.

Particle size distribution is an important indicator for evaluating the stability and formation uniformity of microcapsule systems. The particle size of microcapsules is closely related to the emulsification and dispersion of the oil phase, the deposition behavior of wall materials at the oil droplet interface, the formation rate of the coacervate phase, and the subsequent solidification process. The relatively concentrated particle size distribution observed in this study indicates that the oil phase was well dispersed during the emulsification stage, and the composite wall materials could deposit relatively uniformly on the surface of the oil droplets to form an encapsulating structure. In addition, uniform particle size distribution can help reduce batch-to-batch variation and provide a basis for subsequent processing, dispersion, and application.

These results suggest that the gelatin–gum arabic composite wall material system has good encapsulation adaptability for the 6-gingerol oil phase and can form microcapsule particles with a certain degree of structural stability.

3.2. Morphological characteristics of 6-gingerol microcapsules

The microscopic and scanning electron microscopy images of 6-gingerol microcapsules are shown in **Figure 2**. Optical microscopy showed that the microcapsule particles exhibited relatively good dispersion and clear particle contours. Scanning electron microscopy further revealed that the microcapsules were mostly spherical or quasi-spherical, with relatively continuous particle surfaces and no obvious large-scale rupture or collapse. These observations indicate that the composite wall materials formed a relatively complete coating layer around the oil-phase core.

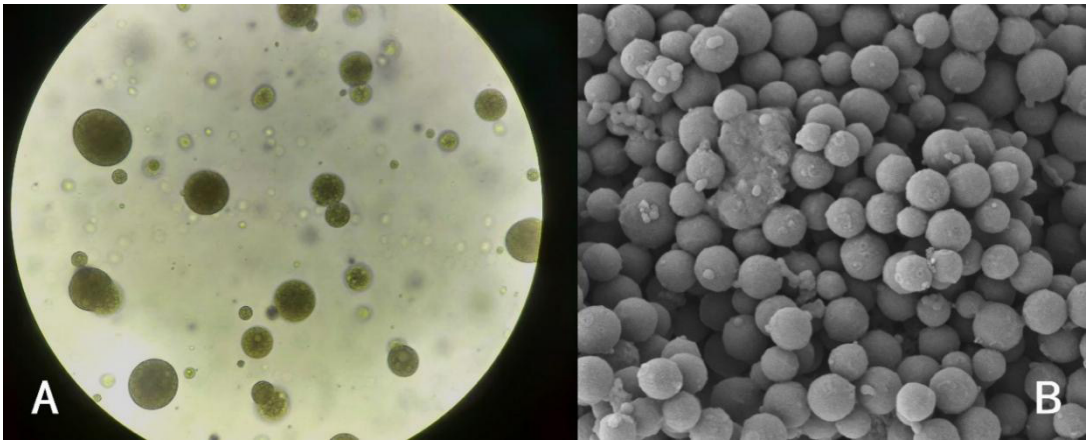

Figure 2. Microscopic and scanning electron microscopy images of 6-gingerol microcapsules.

Note: (a) Optical microscopy image; (b) scanning electron microscopy image.

Microcapsule morphology directly reflects the effects of wall material deposition, capsule wall formation and drying treatment on particle structure. The quasi-spherical morphology confirmed that gelatin and gum arabic could deposit uniformly around the core during complex coacervation, forming a well-constructed capsule wall. Slight surface shrinkage and irregular shapes of individual microcapsules were mainly attributed to water sublimation and wall material contraction during freeze-drying. Overall, the prepared microcapsules exhibited favorable structural integrity.

3.3. FTIR analysis of 6-gingerol microcapsules

The Fourier-transform infrared spectra of 6-gingerol, wall materials, blank microcapsules, and 6-gingerol-loaded microcapsules are shown in **Figure 3**. As shown in **Figure 3**, the 6-gingerol microcapsule sample retained the characteristic absorption information of both the wall materials and the core material. Meanwhile, changes in the position or intensity of some absorption peaks were observed, suggesting that certain intermolecular interactions may exist between the core material and the wall materials during microcapsule formation.

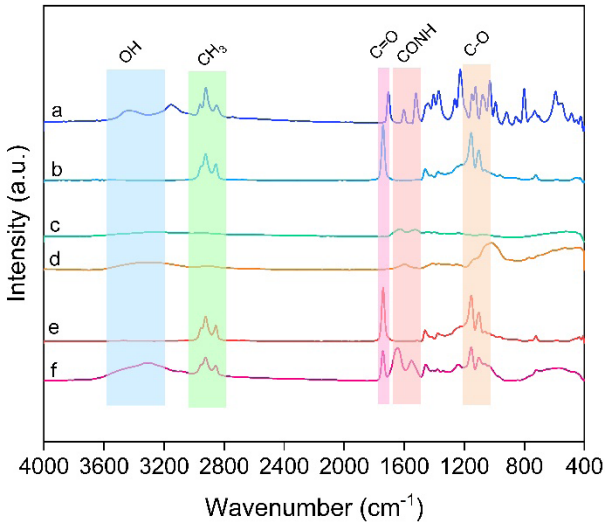

Figure 3. FTIR spectra of 6-gingerol, wall materials, blank microcapsules, and 6-gingerol microcapsules.

Compared with free 6-gingerol, the 6-gingerol microcapsules did not show obvious new characteristic peaks corresponding to newly formed chemical bonds, indicating that the encapsulation process did not significantly change the main chemical structure of 6-gingerol. Based on the changes in peak positions among different samples, it can be inferred that the microcapsule system was mainly maintained by physical encapsulation of the oil-phase core by the composite wall materials, together with non-covalent interactions such as hydrogen bonding, electrostatic interactions, and hydrophobic interactions. Among them, electrostatic interactions between gelatin and gum arabic contributed to the formation of the complex coacervate phase, while possible hydrogen bonding or hydrophobic interactions between 6-gingerol and wall material molecules may further enhance the binding stability of the core material within the microcapsule system. These results indicate that the complex coacervation process was relatively mild and could achieve stable encapsulation without destroying the main structure of 6-gingerol.

3.4. Thermal stability of 6-gingerol microcapsules

Thermal stability results of 6-gingerol microcapsules are presented in **Figure 4**. The microcapsules exhibited staged weight loss during heating. Low-temperature mass loss originated primarily from residual water volatilization. Weight loss proceeded moderately in the medium-temperature region, while remarkable mass loss occurred at higher temperatures due to thermal degradation of polymeric wall materials together with the release and decomposition of encapsulated core material.

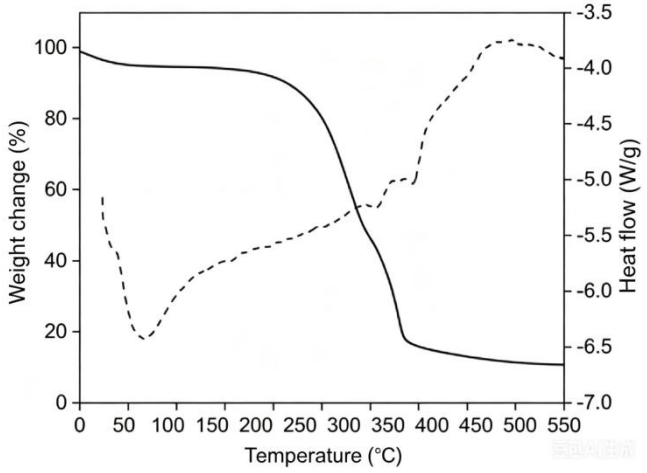

Figure 4. Thermal stability analysis of 6-gingerol microcapsules

The microcapsule sample presented specific thermal weight-loss characteristics. The shell constructed by gelatin and gum arabic forms a certain physical barrier layer, mitigating thermal effects on encapsulated 6-gingerol and relatively retarding its thermal volatilization and degradation. Microencapsulation alters the medium environment of 6-gingerol, which is embedded inside the polymer matrix. This microcapsule system can provide fundamental data for exploring the variation of 6-gingerol during processing and storage.

4. Conclusion

In this study, 6-gingerol microcapsules were prepared using gelatin–gum arabic composite walls and medium-chain triglycerides as oil carrier, and their physicochemical and thermal properties were characterized. The microcapsules exhibited narrow particle size distribution with $D^{[1, 2]}$ of 98.197 μm and mostly spherical morphology with intact shells, capable of encapsulating the oily core to a certain extent. FTIR spectra suggested no obvious structural variation of 6-gingerol; core-wall assembly mainly relied on physical entrapment and non-covalent interactions. Thermal analysis indicated the composite walls could delay the thermal decomposition of microcapsule core materials.

In summary, under the experimental conditions of this study, gelatin–gum arabic matrix exhibited certain encapsulation effect on 6-gingerol, and the relevant experimental data could supply basic evidence for the exploration of similar systems.

Disclosure statement

The author declares no conflict of interest.

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