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Electrostatic Interaction Based Fabrication of Calcium Alginate-Zein Core-Shell Microcapsules of Regulable Shapes and Sizes

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KEYWORDS: hydrophilic-hydrophobic core-shell microcapsules, electrostatic interaction, two-step extrusion, one-step extrusion, controlled digestion and release

ABSTRACT

The core-shell microcapsules with combined features of hydrophilicity and hydrophobicity have become much popular. However, the assembly of biocompatible and edible materials in hydrophilic-hydrophobic core-shell microcapsules is not easy. In this work, based on the electrostatic interaction, we prepared the controllable calcium alginate (ALG)-zein core-shell particles of different shapes and sizes using hydrophilic ALG and hydrophobic zein by a two-step extrusion method. The negatively charged hydrogel beads of spherical, ellipsoidal, or fibrous shape were added into the positively charged zein solution (dissolved in 70% (v/v) aqueous ethanol solution) to achieve different shaped core-shell particles. Interestingly, the size, shape, and shell thickness of the particles can be regulated by needle diameter, stirring speed, and zein concentration. Moreover, for simplification, the core-shell particles were also formed by a one-step extrusion method, in which ALG solution was dropwise added into 70% (v/v) aqueous ethanol solution containing zein and $CaCl_2$. The particles synthesized in this work showed controlled digestion of the encapsulated medium-chain triglyceride (MCT) and sustained release of encapsulated thiamine and ethyl maltol. Our preparation method is simplistic and can be extended to fabricate a variety of hydrophilic and hydrophobic core-shell structures to encapsulate a broad spectrum of materials.

INTRODUCTION

In recent years, microcapsules have attracted great attention for their wide applications in food,[1,2] biomedicine,[3,4] and cosmetic industries.[5,6] In general, their functions depend on structural[7] and material properties[8] such as particle size and shape.[9] The wall materials of microcapsules have been studied extensively, mainly adopting a single hydrophilic, hydrophobic, or amphiphilic material for microencapsulation. Relatively, the hydrophilic-hydrophobic core-shell structure has been ignored. Practically, microcapsules with hydrophilic-hydrophobic core-shell structure achieve complementary performance and synergy by integrating both core and surface materials.[10] Also, It can significantly improve the functional properties of microcapsules by combining different substances and directional modifications. In particular, the size and shape of microcapsules remarkably impact the biological functions, including cell endocytosis,[11] drug release,[12] and intracellular transport.[13] Therefore, by varying the sizes and shapes of hydrophilic-hydrophobic core-shell particles, different biological functions can be facilitated.

Currently, there are multiple approaches to prepare core-shell particles. Mohammed *et al.* prepared zein-casein and zein-lactoferrin core-shell nanoparticles by phase separation method utilizing the differential solubility of zein and milk protein.[14] Liu *et al*. prepared mechanically controlled spherical core-shell alginate beads through reverse spherification using the reaction-diffusion mechanism.[15] Sun *et al*. synthesized pullulan-gelatin core-shell nanofibers with improved drug-loading capacity using the electrospinning technology.[16] Chen *et al.* fabricated an oxidized sodium alginate/chitosan core-shell microgel by emulsification.[17] Yang *et al.* combined electrostatic droplets and microfluidic droplets to obtain a core-shell structure having dual pH-responsive drug release.[18]

However, the above-mentioned methods have certain limitations, such as complex preparation procedures, high production cost, and low biocompatibility. Furthermore, the preparation methods requiring synthetic materials greatly limit their applications in food, drug, and cosmetics. Previously, using the emulsion templating method, we prepared size-controllable hydrophilic-hydrophobic core-shell microcapsules on a microcosmic scale using zein and a variety of polysaccharides as the wall and core material respectively.[19] However, that process failed to scale up for industrial production and the shapes of prepared microcapsules were also not controllable. Therefore, we wanted to develop a versatile approach to fabricate the hydrophilic-hydrophobic core-shell microcapsules of regulated shapes.

Here, using electrostatic interaction, we prepared calcium alginate (ALG)-zein microcapsules composed of ALG and zein as the core and shell materials, respectively. ALG, a natural anionic polysaccharide,[20] is widely utilized in the food industry[21] and medicine.[22] It can form hydrogels by cross-linking with most divalent ions such as Ca^{2+}.[21,23,24] Also, due to its stability, viscosity, and edibility, ALG can be used in wound dressing and as a microcapsule core material to transport small drug molecules, proteins, and functional foods.[25] The solubility of zein, an alcohol-soluble protein,[26] can be varied based on ethanol concentration. Due to this unique dissolution property, it is often used as an antioxidant,[27−29] coating agent,[30] and sustained-release drug matrix.[31−33] Here, using the anionic ALG hydrogel beads and amphoteric zein, we successfully formed the microcapsules of controlled shape and sizes. These were examined for microstructures using different microscopy techniques. Furthermore, these were used to encapsulate emulsions of thiamine and ethyl maltol and evaluated for *in vitro* digestions and release, respectively.

MATERIALS AND METHODS

Materials. Sodium type alginate (G3909401), a gift from FMC BioPolymer (Norway), was employed without further purification. Absolute ethanol (≥99.7%), Tween 80, and calcium chloride were purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). Zein, mucin from porcine stomach, pepsin from porcine gastric mucosa, lipase from porcine pancreas pancreatin were purchased from Sigma-Aldrich. Medium-chain triglyceride (MCT) was obtained from KLK Oleo, Ltd. (Malaysia). Thiamine and ethyl maltol were provided by Macklin Reagent Co., Ltd. (Shanghai, China). All chemical reagents were of analytical grade and the water source was Ultrapure Milli-Q.

Zeta Potential. The zeta (ζ) potentials of ALG and zein, within the pH range of 3-8, were measured by Zetasizer Nano-ZS apparatus (Malvern Instruments, UK) according to Henry's equation[34] at sample concentration 1 mg mL^{-1} and temperature 25.0±0.2℃. The final values were the average of three measurements.

Optimization of pH. The effect of different pH values (unadjusted, 3, 4, 5, 6, 7) in the preparation of ALG-zein core-shell particles was analyzed. The microcapsules, stained with 1 mg mL^{-1} Nile Blue, were observed under the inverted confocal scanning laser microscope (CLSM) (Leica TCS-SP8) at 10x using excitation and emission at 631 and 660 nm probing the Nile Blue local environment of the protein. The staining proportion on the particles was used to optimize the final pH conditions for sample preparation. The thickness of the zein-formed shell was determined by analyzing CLSM images using the Nano Measurer (version 1.2.5) software.

Preparation of Spherical Hydrogel Beads. Spherical hydrogel beads were fabricated by introducing Ca^{2+} to the ALG solution. Stock solutions of 1% (w/w) ALG and 5% (w/w) calcium chloride were prepared. Firstly, depending on the targeted particle size, ALG solutions were

extruded by hand at a uniform speed drop by drop using syringes with various needle dimensions (purchased from SUNGSHIM and KDL, 0.19×3 mm, 0.3×13 mm, 0.45×16 mm, 0.6×25 mm, and 1.2×38 mm), to produce spherical droplets. Then, these were hardened/ maturated by dropping them into the calcium chloride solution and incubated for 30 minutes.

Preparation of Ellipsoidal Hydrogel Beads. Ellipsoidal hydrogel beads were produced in a similar way to the spherical ones. Briefly, 1% (w/w) ALG was added dropwise, with continuous stirring (Eurostar 20 Digital, IKA, German) at 400 rpm for 20 minutes, into 0.2% (w/w) calcium chloride solution using syringes with various needle dimensions (0.19×3 mm, 0.3×13 mm, 0.45×16 mm, 0.6×25 mm, and 1.2×38 mm). It should be noted that the ALG droplets fell near the wall of the beaker containing the calcium chloride solution, so that the spherical beads could be better stretched into ellipsoidal beads. The formed ellipsoidal beads were hardened in 5% (w/w) calcium chloride solution for 30 minutes. Also, different stirring speeds (200-1000 rpm) were tested to optimize the aspect ratio of ellipsoidal beads.

Preparation of Fibrous Hydrogel Beads. Fibrous hydrogel beads were prepared also in a similar manner. Briefly, 1% (w/w) ALG solution was immersed and fast injected into 5% (w/w) calcium chloride solution using syringes with different needle dimensions (0.6×25 mm, 0.7×32 mm, 0.8×38 mm, 0.9×38 mm, and 1.2×38 mm). The formed fibrous hydrogel beads were matured by incubation in calcium chloride solution for 30 minutes.

Fabrication of ALG-Zein Core-Shell Particles of Different Shapes Using Two-Step Extrusion Method. The shape of core-shell microcapsules is influenced by the shape of the internal hydrophilic core template. Therefore, a two-step extrusion method was employed to prepare spherical (**Figure 1a**), ellipsoidal (**Figure 1b**) and fibrous (**Figure 1c**) ALG-zein core-shell particles. Briefly, a certain number of previously prepared hydrogel beads of different shapes were

added to the oppositely charged zein solution (dissolved in 70% (v/v) aqueous ethanol solution) with stirring at 200 rpm for 2 hours to reduce the ethanol concentration to 45% (v/v). This is because the osmotic pressure of the water inside the hydrogel is lower than that of the external absolute ethanol, causing the water inside the hydrogel to gradually permeate out and reduce the concentration of the absolute ethanol. A decrease in system ethanol concentration led to gradual precipitation of zein nanoparticles on the surface of ALG hydrogel beads and formed core-shell microcapsules by electrostatic interactions. The shell thickness of particles was adjusted by varying the concentrations of zein solution (0.5, 1, 2, 3, 4, and 5% (w/v)).

Fabrication of Spherical Core-Shell Particles Using One-Step Extrusion Method. The spherical core-shell particles were also fabricated using the one-step extrusion method (**Figure 1d**). Briefly, a mixture of zein (2%, w/v) and calcium chloride (5%, w/w) was prepared using 70% (v/v) aqueous ethanol. To this, 1% (w/w) ALG solution was added dropwise using syringes with different needle dimensions (0.19×3 mm, 0.3×13 mm, 0.45×16 mm, 0.6×25 mm, and 1.2×38 mm) while stirring at 200 rpm for 2 hours to reduce ethanol concentration and subsequently form the core-shell particles.

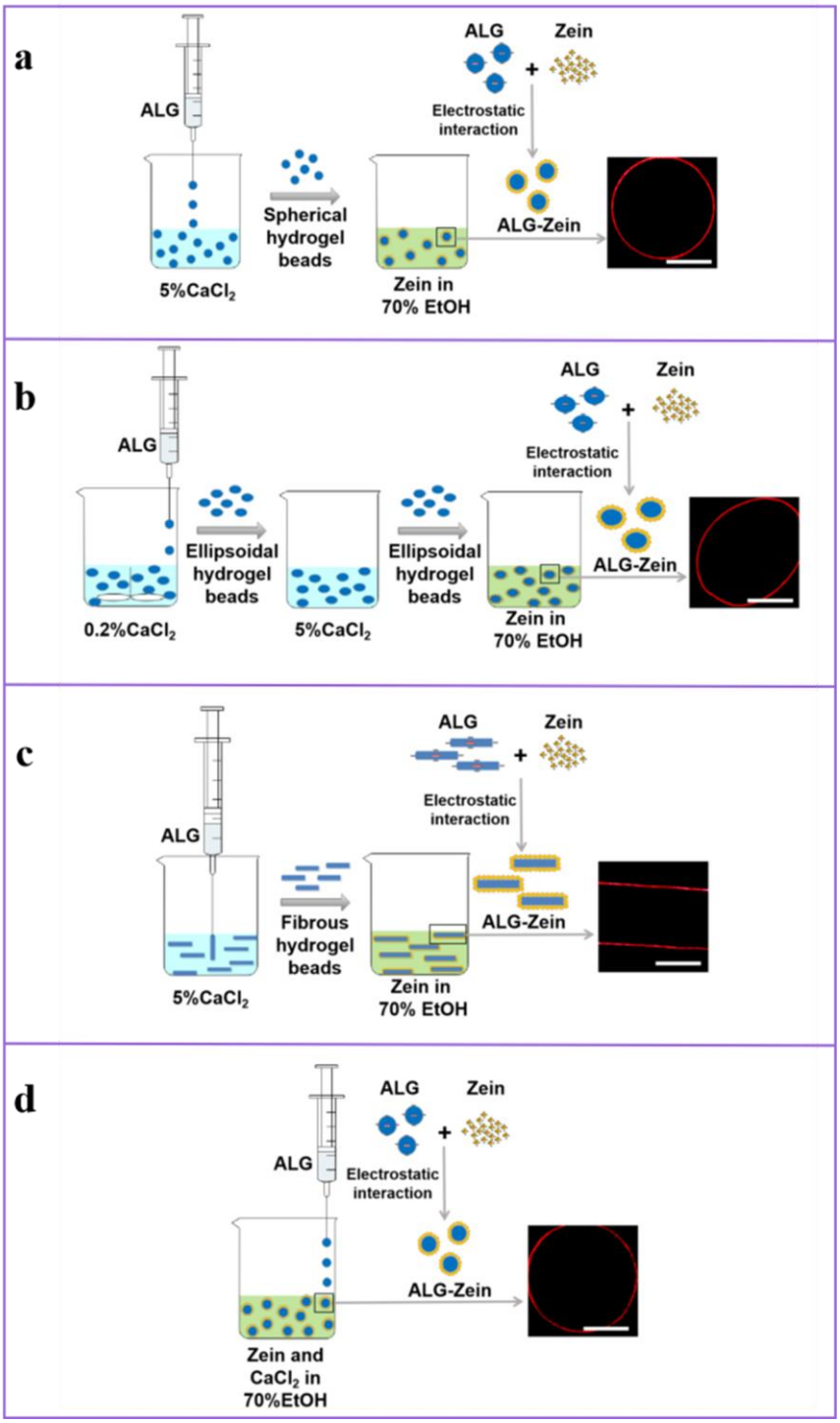


Figure 1. Schematic diagram of fabrication of spherical (a), ellipsoidal (b), and fibrous (c) core-shell particles using two-step extrusion method. (d) Preparation of spherical core-shell particles

using the one-step extrusion method. The CLSM images reveal the microstructure of core-shell particles with different shapes (Scale bars, 500 μm).

Optical Microscopy. The microstructures of ALG hydrogel beads and ALG-zein core-shell particles with different sizes and shapes were examined using the Olympus optical microscope (BX50, Olympus, Tokyo, Japan) at 4x.

Fluorescence Microscopy. The fluorescent images of particles were obtained using an inverted fluorescence microscope (IX73, Olympus, Tokyo, Japan). The particles, stained with 1 mg mL^{-1} Nile Blue, were observed at 4x and excitation wavelength of 530-550 nm.

Scanning Electron Microscopy (SEM). The particle surface morphology was examined by field-emission SEM (Sirion 200, FEI, United States). Briefly, ALG hydrogel beads and ALG-zein core-shell particles were quickly frozen in liquid nitrogen and then freeze-dried. The internal structure of a particle was observed by preparing the ultra-thin cross-sections, dispersed on the conductive glue. The particles were treated with Turbomolecular Pumped Sputter Coater (Q 150T ES plus, Quorum, United Kingdom) and photographed with SEM at 15 kV.

Encapsulation and Digestion of Emulsion Containing MCT. The 1% (w/w) ALG solution was prepared in phosphate buffer (5 mM, pH 6.5). Then, the emulsifier solution was prepared by dissolving 1% (w/w) Tween 80 into ALG solution with overnight continuous stirring at 200 rpm ensuring complete dissolution. The weight fraction of MCT, as oil phase, was 10% (w/w). The oil-in-water (O/W) emulsion was prepared using a high-speed disperser (T18 Digital ULTRA TURRAX®, IKA, Germany) at 20000 rpm for 2 minutes. ALG and ALG-zein core-shell spherical particles containing MCT were prepared according to the previously detailed methods. The *in vitro* digestion of particles was performed as described by Chen *et al.*[35] 1 g emulsion, ALG gel beads, or ALG-zein core-shell particles were mixed with phosphate buffer (15 g) at 37℃ for 15 minutes.

Then, the mixture was blended with oral simulation fluid (15 g) containing 3% mucin at pH 6.8. This was heated at 37°C for 10 minutes to simulate the mouth phase. After that, the samples from the mouth phase were added to stomach simulant (30 g) containing 0.32% pepsin at pH 2.5. The resulting mixture was heated at 37°C for 2 hours to stimulate digestion in the stomach phase. Finally, to simulate digestion in the small intestine phase, the samples collected from the stomach phase were added to small intestine simulation fluid (1.5 g) and bile salt (3.5 g), which were mixed in a beaker and the pH was adjusted to 7. The small intestine phase was produced by adding lipase solution (2.5 g). Simulations of digestion in the small intestine phase were conducted at 37°C for 2 hours. Moreover, the sample pH was automatically controlled to maintain pH 7 using an automatic titration unit (Metrohm, Inc., Riverview, FL, USA).

Encapsulation and Release of Thiamine. 1% (w/w) ALG solution containing 1% (w/v) thiamine was used to prepare thiamine-loaded ALG beads or ALG-zein core-shell particles as described in the section regarding to preparation of spherical hydrogel beads and ALG-zein core-shell particles. These particles were harvested by filtration and stored in 1% (w/v) thiamine solution to maintain thiamine concentration. To evaluate thiamine release from the particles, ALG beads (1 g) with or without zein shell were mixed with water (10 g), respectively. Then, thiamine absorbance was measured in the water phase at 246 nm using a UV-Vis spectrophotometer (TU-1901, Beijing, China) at a specified time. Ultrapure water was used as control and the thiamine release from the particles was quantified using a standard curve. The thiamine release was calculated by the following Equation (1):

$$\textit{R}\text{elaease }(\%) = 100 \times \frac{A_t}{A_o} \quad (1)$$

where A_t and A_o are the concentrations of thiamine released at different time points t and the initial encapsulated concentration of thiamine, respectively.

Encapsulation and Release of Ethyl Maltol. 0.1% (w/v) ethyl maltol-loaded particles with or without zein shell were prepared like thiamine-loaded particles. The final particles were collected through filtration and stored in 0.1% (w/v) ethyl maltol solution to prevent loss before measurement. The release of ethyl maltol was measured by dynamic headspace analysis. Briefly, ethyl maltol-loaded ALG particles (1 g) with or without shell were added into an airtight bottle (100 mL) at 40°C. Then, to measure the ethyl maltol release amount and release rate, the gas sample (1 mL) was collected from the bottle every 1.5 minutes and injected into a gas chromatography (GC) system (Agilent 7890B).

RESULTS AND DISCUSSION

pH Optimization for the Formation of Core-Shell Particles. The ζ-potential reflects the electrification of a substance. **Figure 2** indicates the ζ-potential of ALG and zein as a function of pH. Consistent with the previous literature, the isoelectric point (IEP) of the zein solution is 6.12.[36] In pH 2-8, the ALG solution remains negatively charged with the saturation ζ value of about -60 mV. At the largest absolute value of the product of ζ values of the negatively charged ALG and the positively charged zein, the electrostatic attraction is the strongest. In our case, the electrostatic interaction between ALG and zein is the strongest at pH 4.

To find the optimal pH for the preparation, the core-shell particles were evaluated by CLSM (**Figure 2I-VI**). At pHs 6 and 7, zein either remained neutral or turned negatively charged offering zero electrostatic interaction for adsorption on the surface of ALG hydrogel beads, therefore no zein shell was formed (**Figure 2V-VI**). Also, the pH of the untreated sample was close to the IEP (about 5.5), therefore it also failed to create the shell (**Figure 2IV**). Notably, with a decrease in pH, a fuzzy shell contour began to emerge at pH 5 due to some electrostatic attraction (**Figure 2III**). However, a uniform and well-defined shell was formed only at pH 4 (**Figure 2II**), which is

consistent with the ζ-potential tests. Although zein could adsorbed on the ALG hydrogel at pH 3 (**Figure 2I**), the ALG solution was in a partial gel form under this condition. This was due to protonation of carboxyl matrix that caused weak gelation of ALG solution which was not conducive for preparing regulable shaped ALG hydrogel beads. Therefore, all the sample preparations were carried out at pH 4.

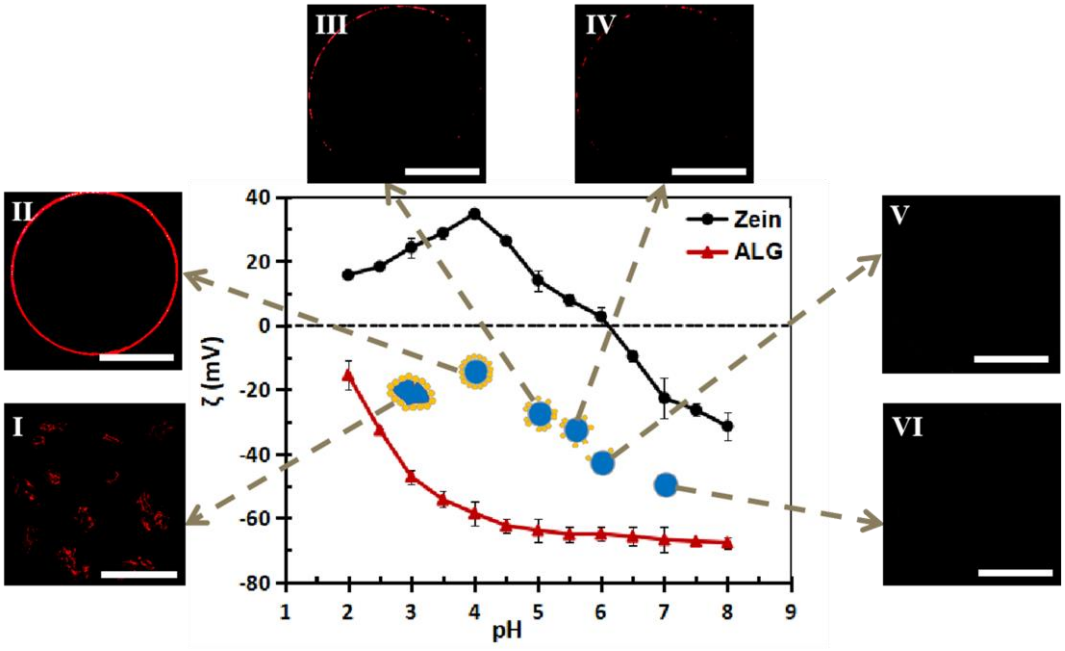


Figure 2. Effect of pH on ζ-potential of ALG and zein; the insert shows the CLSM images of ALG-zein particles prepared under different pH conditions (I: pH 3, II: pH 4, III: pH 5, IV: unadjusted, V: pH 6, VI: pH 7). Scale bars are 500 μm.

Fabrication of Core-Shell Particles by Two-Step Extrusion Method

Preparation of Core-Shell Particles of Different Shapes. Various methods, such as the mold method, have been used to prepare seeding hydrogel beads of different shapes.[37] In this study, ALG gel beads of different shapes (spherical, ellipsoidal, fibrous) were successfully prepared by changing the extrusion pressure of the syringe and providing additional shearing force (**Figure 3**). Initially, ALG hydrogel beads of different shapes were transparent and then turned milky after

adsorbing zein (**Figure 3a**). Importantly, the shape of ALG gel beads covered with or without the zein shell was almost the same (**Figure 3b**). This is consistent with a previous study, in which the middle part of ALG gel beads was initially transparent (column I)[38] and then turned opaque upon mixing with 70% (v/v) ethanol aqueous solution containing zein (column II) when observed under an optical microscope. This phenomenon suggests the formation of a zein shell layer on the surface of ALG gel beads, which blocks the transmission of light. Additionally, fluorescence microscopy (column III) and laser confocal microscopy (column IV) suggest that ALG gel beads were uniformly and densely covered in zein particles. Also, SEM revealed that the surface of particles having different shapes was rougher (column VI) than the ALG hydrogel beads (column V) which again suggests the accumulation of several zein nanoparticles on ALG gel beads. A similar morphology was observed in zein nanoparticles coated core-shell particles prepared by water-in-oil emulsion *via* hydrophobic interactions.[19]

The core-shell particle fabrication methods used in this work are simple and versatile and can be applied to any material capable of forming a hydrogel. Also, in addition to the shapes generated in this work, the principle of electrostatic interaction could be used to obtain more shapes, such as cylinders, discs, and cuboids, depending on the inner hydrogel beads.

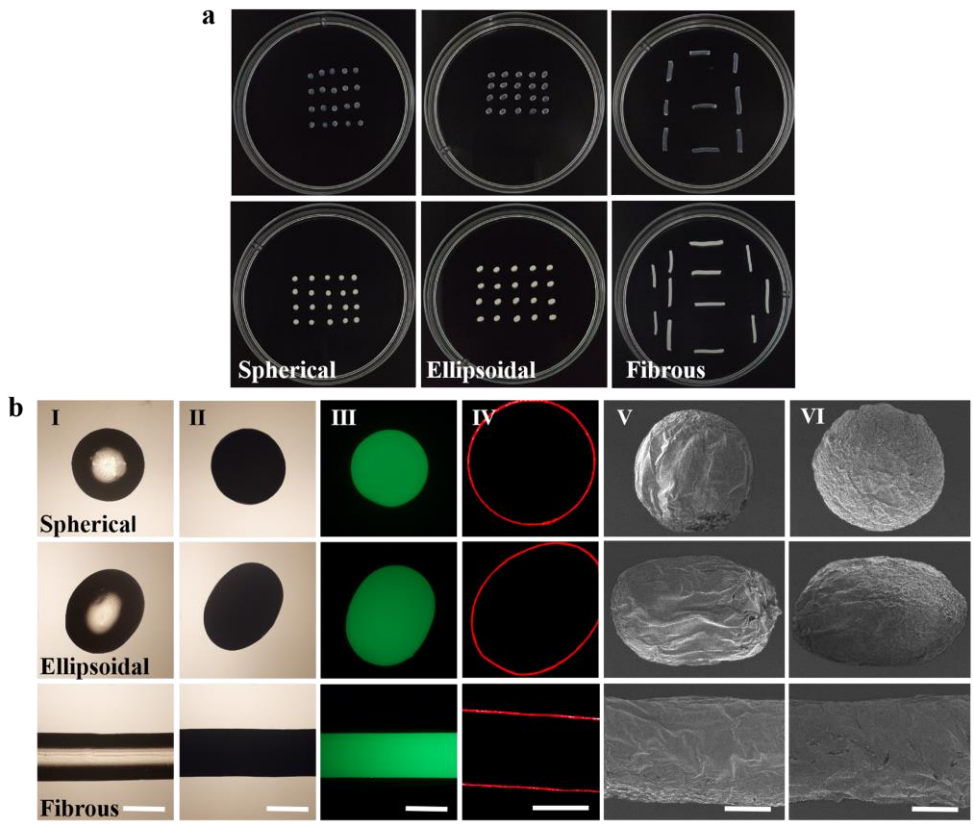
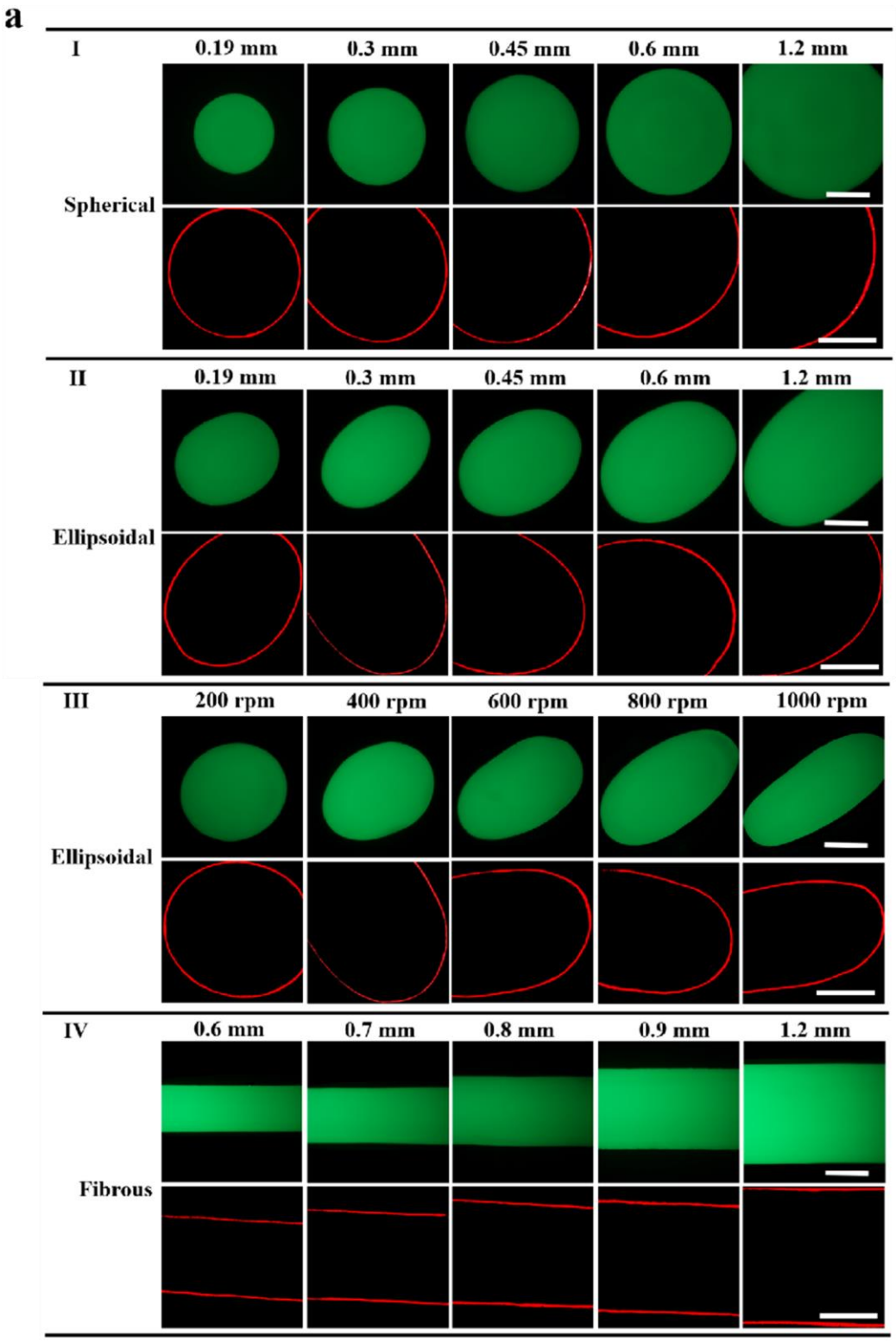


Figure 3. (a) Images of spherical, ellipsoidal, and fibrous ALG hydrogel beads and ALG-zein core-shell particles. (b) Optical microscope (column I) and SEM (column V) images of respective ALG hydrogel beads. Optical microscope (column II), fluorescence microscope (column III), CLSM (column IV), and SEM (column VI) images of respective ALG-zein core-shell particles. Scale bars, 500 μm.

Regulating the Size and Shell Thickness of Core-Shell Particles. The size of core-shell particles depends on ALG hydrogel beads. Practically, core-shell particles ranging from microns to millimeters can be produced by adjusting either needle diameter or stirring speed. For instance, to produce the spherical system, ALG hydrogel beads of different sizes were prepared by adjusting the needle diameter (**Figure 4a-I**). Likewise, for the ellipsoidal system, the size of ALG hydrogel beads was adjusted by varying needle diameter or stirring speed (**Figure 4a-II** and **-III**). For the

fibrous system, the fibrous core-shell particles with different cross-sectional areas were fabricated by adjusting the needle diameter (**Figure 4a-IV**). The needle diameter limits the size of the particles while required electrostatic interactions are maintained.

Next, we studied the effect of zein concentration on the amount and thickness of the particles protein shell layer by using spherical core-shell structure particles as the test material. We observed that with an increase in zein concentration, the color of core-shell particles changed from white to yellow (**Figure 4b**) with increased fluorescence intensity (**Figure 4c**). To measure the weight of zein particles and the thickness of the zein shell, the CLSM images of freeze-dried ALG-zein core-shell particles were analyzed (**Figure 4d**). The zein adsorption amount and the thickness of the shell increased with an increase in zein concentration up to 4% (w/v) and then became stable, suggesting a tight correlation between the two. The reason is that with the increase of zein concentration, more zein nanoparticles gathered at the core surface through hydrophobic interaction, resulting in the increase of zein adsorption amount and shell thickness.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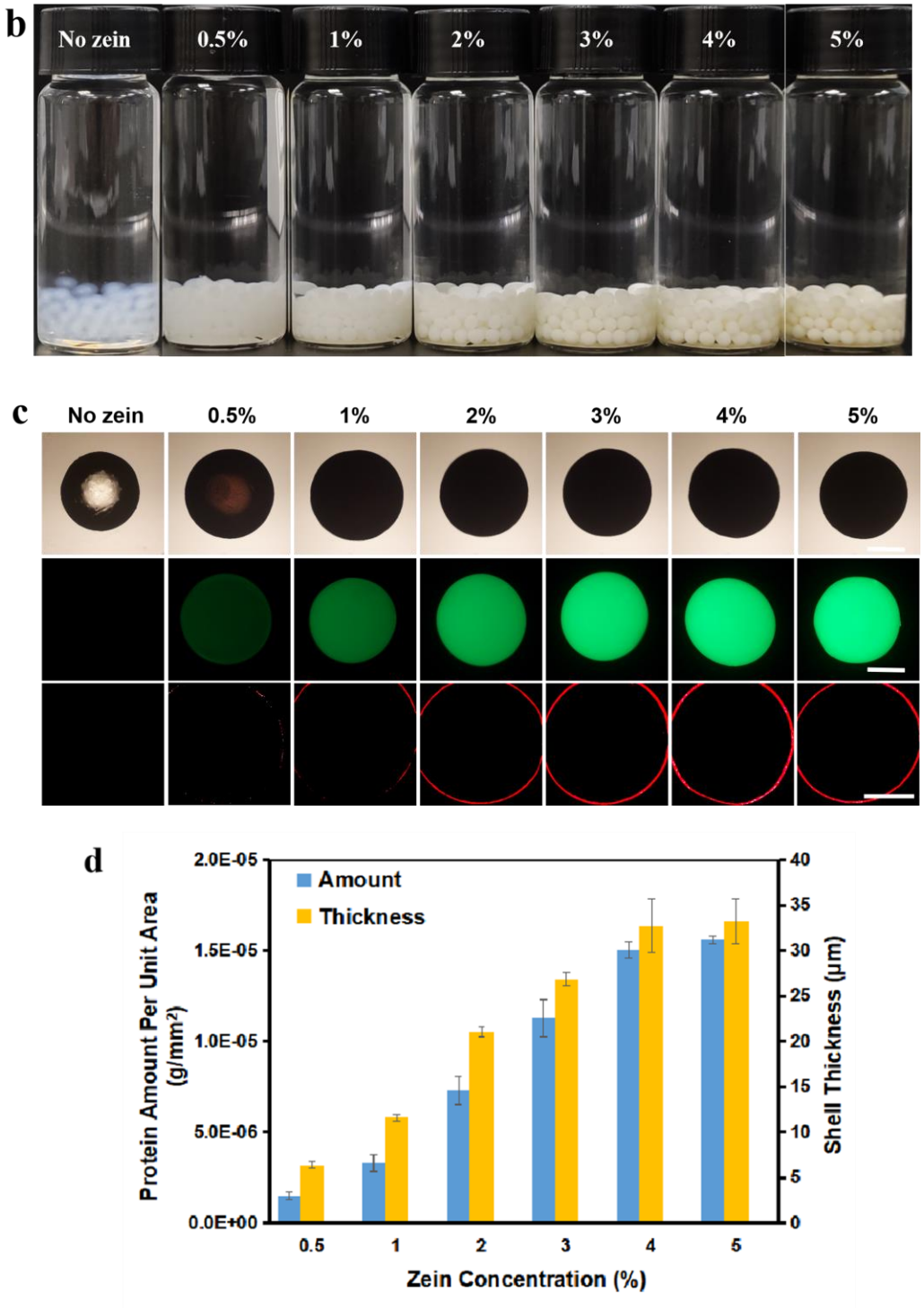

Figure 4. (a) Regulation of the size of spherical (I), ellipsoidal (II), and fibrous (IV) core-shell particles by adjusting the needle diameter to 0.19, 0.3, 0.45, 0.6, 0.7, 0.8, 0.9, and 1.2 mm. Regulation of the aspect ratio of ellipsoidal core-shell particles (III) by adjusting the stirring speed

to 200, 400, 600, 800, and 1000 rpm (In Figure a-I-IV, the first and second rows correspond to fluorescence and CLSM images, respectively). Physical appearance (b), microscope images (c), zein adsorption amount and shell thickness (d) of the core-shell particles at different zein concentrations (0.5, 1, 2, 3, 4 and 5%, w/v). Scale bars, 500 μm.

Fabrication of Core-Shell Particles by One-Step Extrusion Method. To simplify the formulation process, spherical core-shell particles were prepared using the one-step extrusion method (**Figure 5**). Optical microscopy, fluorescence microscopy, and CLSM indicate that the surface of ALG hydrogel beads was uniformly and densely covered with zein shell (**Figure 5a**). Also, the particles maintained good spherical properties (**Figure 5b-c**) having rough surfaces (**Figure 5c-II**). The cross-section image of the particles reveals that the inner phase was a honeycomb-like structure (**Figure 5c-III**). This may be due to the specific combination of ALG and Ca^{2+} to form a three-dimensional network structure, and the water inside the ALG hydrogel formed ice crystals during the freezing process, and the ice crystals sublimated to form a honeycomb structure during the freeze-drying process. The outer shell layer was dense and compact (**Figure 5c-IV**) which is different from a porous shell usually formed by conventional anti-solvents. A dense shell layer also signifies better electrostatic interactions (**Figure 5c-V**). In conclusion, the one-step extrusion method is efficient to prepare quality core-shell particles.

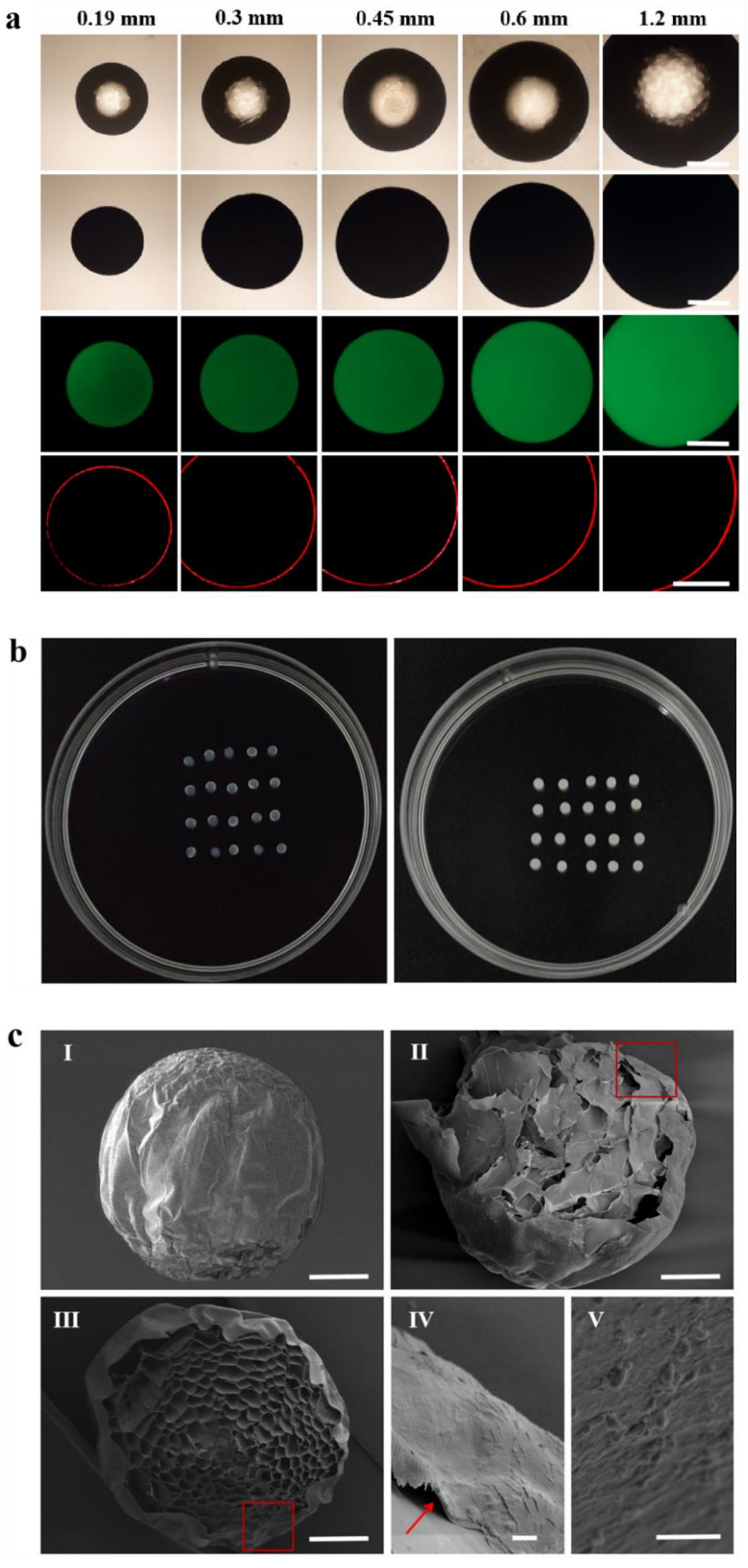
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Figure 5. Microscopy images (a) and appearance (b) of ALG hydrogel beads and core-shell particles. Typical SEM images of a freeze-dried ALG hydrogel particle (c-I) and core-shell particles (c-II). A cross-sectional picture of a core-shell particle (c-III). Images in (c-IV) and (c-V) are the enlarged sections from (c-II) and (c-III), respectively. (Scale bars, 500 μm for a, c-I, c-II, c-III, 20 μm for c-IV and 1 μm for c-V.)

***In vitro* Digestion of Encapsulated Emulsion in Core-Shell Particles.** The emulsion containing medium-chain triglyceride (MCT), encapsulated in core-shell particles, was evaluated for digestion. After simulating the mouth and stomach stages, the release of free fatty acid (FFA) was measured for NaOH volume in the simulated small intestine stage (**Figure 6**). For the three different delivery systems, emulsion, particles with or without covering zein, the FFA release was significantly higher in the first 10 minutes and then reached a plateau. Notably, the FFA release rate from core-shell particles was much slower than the ALG gel beads and O/W emulsions. Previous studies showed that the FFA release from encapsulated oil varies with different delivery systems. One of the critical reasons is the altered reach of pancreatic lipase.[39] In O/W emulsions, the lipase quickly reaches the surface of oil while in the ALG gel bead system, it must first pass the ALG gel network to digest the oil.[40] In the core-shell structured particle system, the pepsin (stomach stage) and pancreatic lipase (small intestine stage) only partially digest the zein shell which delays the lipase reach to the oil surface.[41] Therefore, the various delivery systems studied in this work can more effectively control the speed and degree of fat digestion and have significant practical applications.

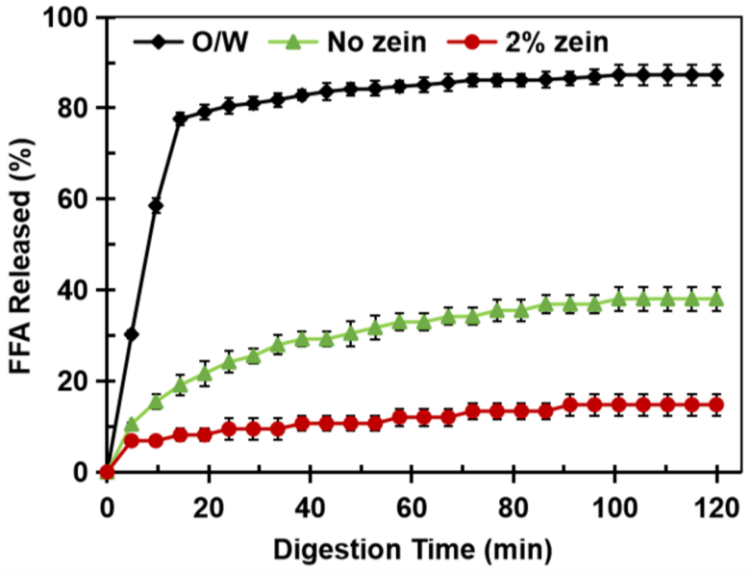

Figure 6. FFA release rates during small intestine digestion from MCT-loaded oil-in-water emulsion, ALG gel beads, and core-shell particles.

Release of Thiamine and Ethyl Maltol Encapsulated in Core-Shell Particles. A previous study showed the nature of the delivery system affected the release of encapsulated curcumin.[42] Along those lines, we also investigated the release of food functional ingredients and flavor substances from core-shell particles by selecting thiamine and ethyl maltol as representative encapsulants. A comparison of release rates of thiamine-loaded particles with or without shell in water is shown in **Figure 7a**. For particles without zein, complete thiamine release occurs within the first 15 minutes. However, particles with zein took about 60 minutes to reach the plateau, suggesting a much slower release rate. The dense and compact structure of the zein shell greatly controlled the thiamine release. The release profiles of ethyl maltol-loaded particles with or without shell are shown in **Figure 7b**. Similarly, the release rate in core-shell systems was much lower than the shell-free systems. Notably, the release rate of ethyl maltol decreased after 15 minutes which could be due to continuous extraction of gas from the sealed bottle.

These results indicate that core-shell particles, having dense zein shell on AGL beads, can achieve an efficient controlled release effect. Concisely, the ALG-zein core-shell particles produced by electrostatic interactions can be used to encapsulate functional agents and volatile substances and have great potential in food or medicine applications.

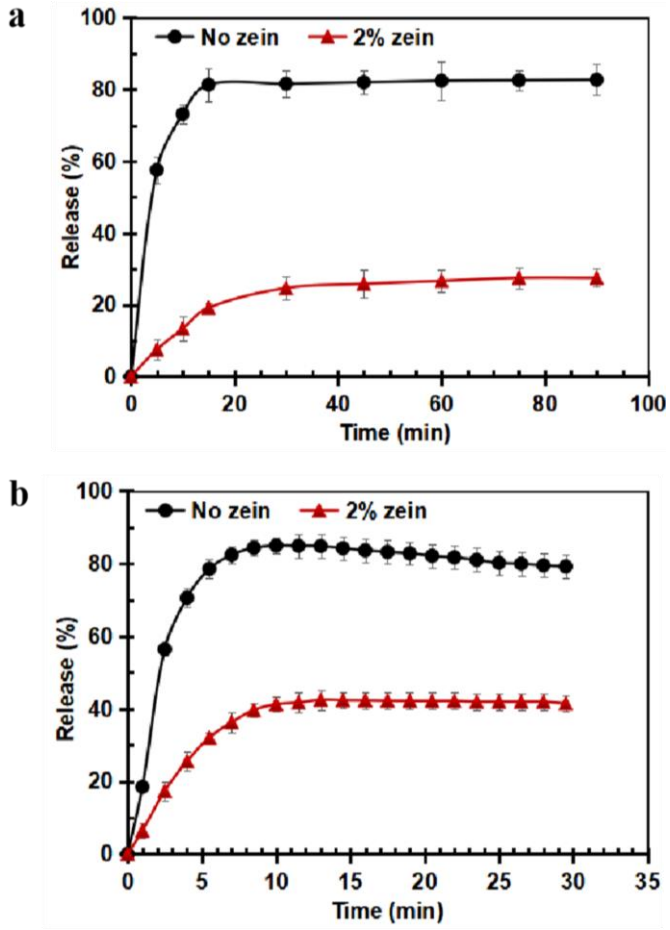

Figure 7. The release profiles of thiamine-loaded (a) and ethyl maltol-loaded (b) particles with or without shell.

CONCLUSION

Based on electrostatic interaction, the ALG-zein core-shell particles were successfully prepared using hydrophilic polysaccharide ALG and hydrophobic protein zein by one-step or two-step extrusion methods. The core-shell particles of different shapes, sizes, and shell thicknesses were

fabricated by regulating the syringe size, stirring rate, and zein concentration. The surface of core-shell particles, densely and uniformly covered with zein nanoparticles, played a key role in delaying the digestion of emulsion and the sustained release of thiamine and ethyl maltol. Overall, the ALG-zein core-shell particles have great potential in the fields of food, cosmetics, and biomedicine due to their simple formulation process and special structure.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENT

This work was sponsored by the Shanghai Sailing Program (No. 20YF1421800), Shanghai Science and Technology Committee (No. 18JC1410801), the Start-up Program of Shanghai Jiao Tong University (No. 19X100040087).

ABBREVIATIONS

ALG, Sodium alginate; MCT, Medium-chain triglyceride; CLSM, Confocal scanning laser microscope; SEM, Scanning electron microscopy; GC, Gas chromatograph; IEP, Isoelectric point; FFA, Free fatty acid.

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The negatively charged hydrogel beads of spherical, ellipsoidal, or fibrous shape were added into the positively charged zein solution to achieve different shaped ALG-zein core-shell particles.The core-shell particles show great advantages in controlling the digestion of the oil gets and the release of functional factors.

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