Improvement in texture and color of soy protein isolate gel containing capsorubin and carotenoid emulsions following microwave heating

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Research Article

Keywords: Soy protein isolate, Capsorubin, Carotenoid, Emulsion, Color, Texture

Posted Date: April 21st, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1561701/v1

Abstract

The effects of capsorubin and carotenoid emulsions on the properties of soybean protein isolate (SPI) gels were studied following microwave heating. The data confirmed that emulsions have a protective effect on the capsorubin and carotenoid. Rheological properties and the texture of SPI gels were investigated. All SPI gels showed shear–thinning behavior, and the viscosity, G' and G'' of SPI gels containing capsorubin and carotenoid emulsions was significantly higher than gels with added pigment aqueous solution. These results illustrate that the SPI gels containing emulsions tend to form a gel–like structure and were in a state of elastic dominance. In addition, differential scanning calorimetry (DSC), fourier transform infrared (FTIR) spectroscopy and scanning electron microscope (SEM) methods were used to investigate the interaction between SPI and soybean soluble polysaccharide (SSPS) in the gels structure, confirming that the SPI gels have a more continuous, folded and uniformly dense three–dimensional network structure. Most importantly, the chain entanglements between proteins and polysaccharides became even tighter due to microwave heating. The overall results suggested that the emulsion had an excellent protective effect on the capsorubin and carotenoid and was beneficial to the application of pigments in food and supplements.

1. Introduction

Soybean protein isolate (SPI) is considered to be the main plant–based protein raw materials of plant meat (Ang et al. 2016; Alexeev, et al. 2020). SPI has good emulsification and gel properties (Bhattacharya & Jena 2007; Shan et al. 2015), after heat treatment, such as microwave or steam heating, it can form a gel that can be used to make plant protein products. However, the natural color of plant protein products is a problem, product coloring plays an important role in changing or imparting color for food to increase its appeal to consumers (You 2002), so adding pigments is a common solution.

Capsorubin and carotenoids are two of the most common natural pigments that are often added to foods to change the color of food (Guo 2008; Hassan et al. 2019). Carotenoids are lipophilic natural pigments that are usually incorporated into fats and oils to obtain a better–sustained release effect in the human body. They have potential health benefits, such as provitamin activity (Perucka & Materskac 2003), enhancing the immune system (Liu et al. 2011) and cognitive function (Liu et al. 2016). The carotenoids contained in capsorubin are not only the precursor compounds of vitamin A but also have important physiological functions such as antioxidant activity (Nishino et al. 2016), prevention and treatment of cardiovascular diseases (Riccioni 2012), and regulation of immune system activity (Honda 2021). They are often used in foods such as condiments, frozen sandwiches, cakes, aquatic products processing and beverage coloring (Li et al. 2009). These two pigments have poor water solubility, low bioavailability and stability, are vulnerable to ultraviolet light, temperature, oxygen and other environmental factors. Pre–emulsification can be used to protect the pigments from environmental factors, and improve their homogeneity in products.

As a type of thermodynamic system, emulsions have poor stability. To avoid the natural separation of oil and water phases, it is necessary to add emulsifiers to stabilize oil droplets physically (Herceg et al. 2000). Proteins and polysaccharide complexes can adsorb and diffuse in the oil–water interface, and improve the stability of the emulsion (Perugini et al. 2018). Kharat et al. (2017) investigated the physical and chemical stability of pure curcumin in aqueous solution and in oil–in–water emulsions, and the results showed that the emulsion improved the water dispersibility and chemical stability of curcumin. Wei et al. (2019) improved the bioavailability of curcumin using emulsion stabilized by ovotransferrin fibrils. Lu's et al. (2019) study found that compared to curcumin encapsulated in free oil, the weight bioavailability of emulsion embedding was improved. Sharma et al. (2021) studied the in vitro release of curcumin–loaded emulsion, and the results showed that the release amount of curcumin was slow and the bioavailability increased.

In this study, SPI and soybean soluble polysaccharide (SSPS) were used to prepare emulsions. Fat–soluble capsorubin and carotenoids were encapsulated in emulsion, and the final mixture was added to SPI to make a paste. The color change of paste induced by microwaves' slow–release process was explored. Primarily, the microstructure and particle size of the emulsions were characterized and analyzed. Then, the state, color, texture and rheological characteristics of the microwave–induced SPI gels were determined. Furthermore, changes in the internal structure of the SPI gels were analyzed using FTIR, DSC and SEM. The slow release of pigment in an emulsion of SPI gels during microwave preparation is expected to render food attractive.

2. Materials And Methods

2.1 Materials

SPI (95% protein) was obtained from Shandong Yuwang Ecological Food Industry Co. Ltd (Yucheng, 251200 China). SSPS was purchased from Shandong Juyuan Ecological Food Industry Co. Ltd., (Yucheng, 251200, China). Soy oil was purchased from Jiu San Grain and Oil Industry Group Co., Ltd (Harbin, China). Capsorubin and carotenoid were obtained from Luqi Biological Products Co., Ltd (Shandong, China).

2.2 Methods

2.2.1 Preparation of capsorubin emulsions

SPI powders (1 g) were dissolved in 100 mL deionized water with magnetic stirring at 25°C for 12 h overnight in order to hydration. SSPS powders (1 g) were dissolved in 80 mL deionized water with magnetic stirring at 25°C for 12 h overnight hydration. Capsorubin (0.1 g) was dissolved in 19.9 mL soy oil. Then the capsorubin (0.05 wt%) based on the weight of emulsion was mixed with 9.95 wt% soy oil in a beaker. Finally, SPI solution, SSPS solution and capsorubin solution were sheared by a high–speed homogenizer (FJ–200, Specimen model factory, Shanghai, China) at 10000 r/min for 2 min, and then emulsified by high pressure homogenizer (FB–110S, LiTu Machinery Equipment Engineering Co., Ltd.,

Shanghai, China) at 30 MPa for 3 min to prepare capsorubin emulsions. Carotenoid emulsions were prepared in the same method.

2.2.2 Preparation of capsorubin and carotenoid aqueous solution

Capsorubin (0.1 g) and carotenoid (0.1 g) were dissolved respectively in deionized water (199.9 mL) with magnetic stirring at 25°C for 12 h overnight in order to hydration.

2.2.3 Preparation of SPI gel

SPI powder (2.5 g) and capsorubin or carotenoid emulsions or aqueous solution (15 g) were stirred for 5 min. SPI/capsorubin and SPI/carotenoid paste was poured into a heart–shaped mold, then all the samples were heated by a microwave oven with a 200–W microwave (HC–83202FB, Galanz, China) enerator. The samples with different levels of added emulsions or aqueous solution were heated for 0, 30, 60, 90, 120, 150, 180 s (Cool for 30 s after each heating).

2.3 Characterization of emulsions

2.3.1 Particle size

The average volume diameter ($d_{4,3}$) and the area mean diameter ($d_{3,2}$) of emulsions were detected by a laser particle size distribution analyzer (BT–9300ST, Baite Instrument Co., Ltd., Dandong, China). The shading rate was 5%, and the refractive indexes of the droplets and deionized water were 1.520 and 1.333, respectively. The droplet size of all emulsions was measured in duplicate (Sun et al. 2019).

2.3.2 Microscopy

The microscopic emulsions images were measured with a vertical microscope (Nikon 80i, Japan) at 25°C according to the method of Xiong et al. (2018). Emulsion (6 μL) was dropped on the glass slide, then covered a coverslip on to remove air in emulsion. The images were collected using elementary imaging analysis software (Nikon, Melville, NY).

2.4 Characterization of SPI gel

2.4.1 Surface appearance and color measurement before and after microwave

The color of the SPI gels was assessed using a chroma meter (Konica–Minolta, CR–400, Osaka, Japan). Prior to each measurement, the colorimeter was calibrated using a white ceramic standard. The luminosities (L^*), redness/greenness (a^*), yellowness/blueness (b^*) and total color difference (ΔE) of the SPI gels were determined at 0, 30, 60, 90, 120, 150 and 180 s after microwave heating, respectively. The average value of three random points on each gel surface was used to illustrate the color change of the gels.

2.4.2 Rheological properties measurement

The rheological properties of SPI gels that containing emulsions and aqueous solution of pigments were measured using a Discovery HR–1 rheometer (TA Instruments Ltd., USA) according to the method of Chang and Min with slight modifications (Chang et al. 2020). A 40 mm diameter steel plate and a 1000 μm gap at 25°C were applied. The SPI gel was first equilibrated for 2 min before measurement. The viscosity was determined at a shear rate of 0.01–1 s^{-1}. The frequency sweep test was performed at 0.1% strain of constant deformation (in the linear viscoelastic region) from 1 to 100 rad/s. The elastic modulus G' (storage modulus) and the viscous modulus G" (loss modulus) were recorded as a function of the oscillation frequency. Experiments were repeated three times for each sample.

2.4.3 Texture properties measurement

The SPI gels were kept at room temperature for 1 h, then the hardness, adhesiveness, springiness, cohesiveness and resilience values were determined using a TA–XT plus Physical Property Tester (TA–XT plus, Instruments Ltd., USA) following the method of with slight modifications (Chen et al. 2019). The P/50 cylindrical probe (diameter 50 mm) was used for double–cycle compression test to obtain force–time curves. Prior to testing, various parameters were calibrated, then the heart–shaped gels were stably fixed on the platform. The test parameters were as follows: the speed before the test was 1.0 mm/s, the speed after the test and the test was 1.0 mm/s, and the compressive strain was 45%. All tests were conducted at 25°C and were repeated at least three times.

2.4.4 Fourier transform infrared (FTIR)

The FTIR of SPI gels were determined by a Scimitar 2000 Near FT–IR Spectrometer (Agilent Technologies, Santa Clara, USA) at 25°C (Li et al. 2019). Lyophilized samples were ground and uniformly mixed with dried KBr powder (1:100, w/w), and pressed into a pellet. The spectra were acquired in the range of 400–4000 cm^{-1} at a resolution of 1 cm^{-1}.

2.4.5 Differential scanning calorimeter (DSC)

The thermodynamic properties of different samples were investigated using Discovery series DSC (Q2000, TA instruments, USA) according to Shand et al. (2007). The SPI gels (6 mg) were placed into the DSC pan, sealed and weighed to an accuracy of ± 0.01 mg. The gels were cooled to 0°C, then heated to 180°C at a heating rate of 10°C /min under nitrogen at a rate of 50 mL/min.

2.4.6 Scanning electron microscope (SEM) analysis

The microstructures of freeze–dried SPI gels were sputtered with gold and observed by SEM (SEM, S–4800, Hitachi, Japan) at an accelerating voltage of 1.0 kV with a magnification 8000 ×.

2.5 Statistical analysis

All samples were performed in triplicate, and all experimental data were expressed as the mean and standard deviations. The significance of the means was established by using IBM SPSS Statistics

version 26 (Chicago, IL, USA). The Origin 9.0 software (Origin Lab, Northampton, MA) was used to map and further analyze the data.

3. Results And Discussion

3.1 Particle size and microstructure of emulsions

The distribution of particle size, $d_{4,3}$ and $d_{3,2}$, and microscopy of the two emulsions are shown in Fig. 1. As can be seen from Fig. 1A, the $d_{4,3}$ of capsorubin and carotenoid emulsions were 1.937 and 2.021 μm, respectively. The $d_{3,2}$ of capsorubin and carotenoid emulsions were 1.551 and 1.620 μm, respectively. The particle size distributions of capsorubin and carotenoid emulsions were dominated by a single peak at 1–10 μm, suggesting emulsion is stable (Wang et al. 2020). It also can be seen from Fig. 1B and 1C that the droplets of the two emulsions were uniform without obvious aggregation, which is consistent with the results of the particle size distribution.

3.2 Characterization of SPI gels

3.2.1 Surface appearance and color of the SPI gels

Surface changes of SPI gels after microwave heating from 0 to 3 min are depicted in Fig. 2. As can be seen from Fig. 2, the surface appearances of SPI gels after microwave heating for different times were different. The surface of the SPI gels containing emulsions was smooth, and become smoother as the time increased. However, the surface of SPI gels containing aqueous solution was coarse with many small undissolved SPI particles and small pigment particles scattered. It was also found that when the heating time was extended to 120 s, the surface of the SPI gels expanded slightly and the bottom collapsed slightly. In addition, when the heating time increased to 180 s, the bottom of the gels almost collapsed and lost its original heart–shape. This collapse may due to the expansion caused by internal steam formation and excessive moisture. The obvious difference is that the emulsion gels still maintain a three–dimensional structure after being heated for 180 s, the reason may be related to the reacting between proteins and polysaccharides in the emulsion during microwave heating.

As shown in Table 2, the colors of SPI gels containing capsorubin and carotenoids were different. The SPI gels containing capsorubin and carotenoid emulsions were slightly darker than aqueous solution SPI gels, with small decreases in L^* values, which may be related to the decomposed fat globules induced by microwave heating were released on the surface of the gels, causing a reduction in adhesion. Camille et al. (2020) reported a similar phenomenon for cheese products. In addition, the gels containing capsorubin and carotenoid emulsions were redder and yellower, respectively, than aqueous solution gels. Specifically, with the increase of heating time, the a^* values of gels containing capsorubin and carotenoid emulsions significantly increased from 3.06 to 5.08 and from 10.01 to 14.67, respectively. The b^* gels values of containing capsorubin and carotenoid emulsions significantly increased from 42.73 to 52.22 and from 39.70 to 51.24, respectively. Furthermore, the trend is flat for gels of capsorubin and carotenoid aqueous

solution. However, the overall difference of capsorubin and carotenoid emulsions gels shows a linear upward trend, and the ΔE^* values increased from 40.39 to 51.29 and from 42.38 to 55.36, respectively. This was attributed to emulsions inhibiting oxidative degradation of the capsorubin and carotenoids wrapped in fat globules, and gradually releasing the capsorubin and carotenoids during heating.

3.2.2 Rheological properties

The rheological properties of SPI gels containing capsorubin and carotenoid emulsions and aqueous solutions are shown in Fig. 3. The changes of apparent viscosity with shear rate were measured at 25°C (Fig. 3A). As the shear rate increases from 0.01 to 100 s^{-1}, a decrease in apparent viscosity was observed, which indicates that all SPI gels exhibit shear–thinning behaviors (Lipton & Jeffrey 2017). It can be seen that the viscosity of SPI gels containing capsorubin and carotenoid emulsions was significantly higher than that of aqueous solutions, which may be due to the interaction between soybean oil and polysaccharides and breaking the intermolecular and intramolecular hydrogen bonds, making the polymer more adhesive (Mali et al. 2005). This result might also be attributed to the SPI gels containing emulsion forming a dense three–dimensional network structure, caused by polysaccharides and proteins.

G' is a representative index defined by the behavior of elastic solids and predicts mechanical strength, and G'' is a viscous response index (Liu et al. 2017). $G'$and G'' of SPI gels containing capsorubin and carotenoid emulsions or aqueous solutions are shown in Fig. 3B. Both G' and G'' increased as the oscillation frequency increased, indicating their frequency–dependent behavior. The G' values of all SPI gels were higher than G'' in the linear region, and the G' and G'' values of SPI gels containing capsorubin and carotenoid emulsions were significantly higher than those of the aqueous solutions. These results indicate that the SPI gels containing emulsions tend to form a gel–like structure and were in the state of elastic dominance that represents solid–like behaviors (Karunaratne & Nedra 2012), the reason may be attributed to the interaction of polysaccharides and proteins in the emulsions improving the strength and stability of the binding in the gel network.

3.2.3 Texture properties

The texture profile of SPI gels such as hardness, adhesiveness, chewiness, resilience, cohesiveness and springiness are provided in Table 1. As shown in the result of this analysis, the hardness, adhesiveness, chewiness and springiness of SPI gels containing capsorubin and carotenoid emulsions are lower than those of aqueous solutions. The hardness of SPI gels containing capsorubin emulsions decreased from 4407.19 to 2670.31, and the adhesiveness of SPI gels containing carotenoid emulsions decreased from 4961.79 to 1840.12. The key reason for this result is that the interaction between soybean oil and SPI reduces the binding rate between protein molecules, forming a protein–oil composite gel structure, resulting in a decrease in gel hardness. However, it can be seen that adhesiveness, chewiness and springiness increase with increasing hardness. In contrast, for resilience and cohesiveness, there was no significant difference among the four gels.

3.2.4 Fourier transform infrared (FTIR) spectroscopy

The structural features of polysaccharides and proteins in the capsorubin and carotenoid emulsions and aqueous solution SPI gels were characterized by FTIR, as shown in Fig. 4. As expected, emulsion gels containing capsorubin and carotenoids exhibited an FTIR spectral profile of a polysaccharide, showing a broad peak at around 3100–3700 cm^{-1} and a minor peak at around 2930 cm^{-1}, which corresponds to the O–H stretching of hydrogen bonds and the C–H group stretching, respectively (Coimbra et al. 1998; Mateos–Aparicio et al. 2010) (Fig. 4A, B). The reason that the peak shapes of the capsorubin and carotenoid emulsion gels are not sharp may be that more hydrogen bonds are formed between O–H at around 3100–3700 cm^{-1}. In addition, capsorubin and carotenoid emulsion gels show a peak at around 2930 cm^{-1}, which is the characteristic absorption peak of hydroxyl–hydrogen (OH) and carbon–hydrogen (C–H) bonds in polysaccharide molecules. The absorption peaks at around 1747 cm^{-1} and a relatively minor peak at around 1160 cm^{-1} observed in Fig. 4A, B, were largely contributed by the stretching vibrations of saturated fatty acid esters (C = O) and aliphatic primary amines (C–N), respectively. Obviously, the appearance of these two peaks was due to the presence of soybean oil in capsorubin and carotenoid emulsion gels.

The amide I, II and III bands were observed in the FTIR profiles of all the test gels at around 1654, 1550 and 1240 cm^{-1} (Fig. 4A, B), respectively, confirming the presence of a large fraction of proteins. Compared with capsorubin and carotenoid aqueous solution gels, the absorption peaks of amide II of capsorubin and carotenoid emulsions gels had a blue shift (shifted from 1452 cm^{-1} to 1458 cm^{-1}). These observations suggested that hydrogen bonds and hydrophobic interactions were the main binding forces in capsorubin and carotenoid emulsion gels.

3.2.5 Differential scanning calorimetry (DSC)

The DSC profiles showed the presence of a single broad endothermic peak in each SPI gel heated for different times (Fig. 5). The calorimetric curve (Fig. 5A) of SPI gels containing capsorubin emulsions not heated by microwaves showed an endothermic peak from 112.83℃ to 131.28℃, corresponding to an enthalpy value of 35.38 kJ/mol at this stage. The DSC curve of the SPI gels containing capsorubin emulsions heated by microwaves for 180 s showed an endothermic peak from 111.68℃ to 118.03℃, corresponding to an enthalpy value of 1.177 kJ/mol. Meanwhile, the calorimetric curve of SPI gels containing capsorubin aqueous solution not heated by microwaves showed an endothermic peak from 114.9℃ to138.5℃, corresponding to 58.1 kJ/mol. The endothermic peak (at 41.13 kJ/mol) of capsorubin aqueous solution heated for 180 s ranged from 113.52℃ to 134.2℃. The above results suggest that the endothermic peak can be attributed to loss of water associated with bound water and the glass transition of SPI gels. The above enthalpy value of the SPI gels containing capsorubin emulsions heated for 180 s is the lowest, corresponding to 1.177 kJ/mol. The changing trend of enthalpy values of SPI gels containing carotenoid emulsions and aqueous solutions is similar to that of SPI gels containing capsorubin emulsions and aqueous solutions. The enthalpy value of the SPI gels containing carotenoid emulsions heated for 180 s is the lowest, corresponding to 2.586 kJ/mol (Fig. 5B), which is mainly due to the SPI gels with more continuous, folded and uniformly dense three–dimensional network

structure owing to the addition of emulsion and chain entanglements between proteins and polysaccharides.

3.2.6 Scanning electron microscope (SEM)

The SEM micrographs exhibited microstructural differences between all the gels after microwave heating for 0 s and 180 s (Fig. 6). As can be seen in Fig. 6b, d, a loose and heterogeneous inner network with large porosity was found in capsorubin and carotenoid aqueous solution SPI gels heated for 0 s. However, the surface area of the SPI gels containing capsorubin and carotenoid aqueous solution heated for 180 s clearly increased and the cavity decreased (Fig. 6B, D). This was mainly due to the evaporation of water and the binding of protein molecules after microwave heating. Folded, continuous and uniform macromolecular structures were observed in capsorubin and carotenoid emulsion gels heated for 0 s (Fig. 6a, c). This might be attributed to the formation of hydrogen bonds between polysaccharides and proteins, and the presence of soybean oil. Furthermore, after microwaving for 180 s (Fig. 6A, C), a more consistent and firm structure was formed, which is attributed to enhancement of the interaction between polysaccharides and protein molecules by microwave heating; this phenomenon was consistent with the surface appearance of the SPI gels.

4. Conclusion

In this study, SPI gels containing capsorubin and carotenoid emulsions were successfully prepared. The results of microstructure and particle size show that the two emulsions have similar volume average diameters and good stability. Surface appearance and color methods were used to characterize slow release of pigments after microwave heating from 0 to 180 s, confirming that emulsions have a protective effect on the capsorubin and carotenoids. In addition, the texture and rheological results show that the SPI gels containing emulsions tend to form a gel–like structure and were in a state of elastic dominance. Meanwhile, DSC, FTIR and SEM results confirm that incorporation of an emulsion into a SPI gel had some effect on their internal structure, a more continuous, folded and uniformly dense three–dimensional network structure was observed owing to the addition of emulsion. Furthermore, the chain entanglements between proteins and polysaccharides become even tighter due to microwave heating. It is worth mentioning that capsorubin and carotenoids are extremely unstable, and this work is expected to use emulsions to protect pigments and could provide us with a new concept for the development of colorful foods.

5. Practical Application

The emulsion containing pigment is added to SPI powder to prepare a gel, which is heated to give the gel an attractive color. Meanwhile, the protein gel has good rheological properties and is expected to be used in 3D printing of food.

Declarations

Funding

This work was supported by the National Natural Science Foundation of China (No.32102005).

Author Contributions

Shengnan Wang: Conceptualization, Methodology, Data curation, Writing – original draft. Yangyang Li: Conceptualization, Methodology, Data curation, Writing – original draft. Xiulin Liu: Software, Data curation, Visualization. Guilan Zhao: Data curation, Investigation. Lina Yang: Validation, Project administration. Lijie Zhu: Methodology, Conceptualization, Writing – review & editing. He Liu: Supervision, Project administration.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of interest

The authors declare no competing financial interests.

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Tables

Table 1 Texture properties of gel samples heating for 180 s.

Texture properties	Capsorubin emulsions	Capsorubin solutions	Carotenoid emulsions	Carotenoid solutions
Hardness (g)	2670.31 ± 200.60^{a}	4407.19 ± 438.29^{b}	2853.97 ± 243.92^{a}	7017.84 ± 980.50^{c}
Adhesiveness (g.s)	1612.36 ± 155.72^{a}	2644.84 ± 173.19^{b}	1840.12 ± 223.41^{a}	4961.79 ± 722.56^{c}
Chewiness	1122.22 ± 177.89^{a}	1909.35 ± 151.36^{b}	1289.29 ± 199.95^{a}	3912.85 ± 537.95^{c}
Resilience (%)	0.69 ± 0.05^{a}	0.72 ± 0.02^{a}	0.69 ± 0.04^{a}	0.70 ± 0.01^{a}
Cohesiveness	0.61 ± 0.04^{a}	0.60 ± 0.02^{a}	0.59 ± 0.05^{a}	0.65 ± 0.03^{a}
Springiness (%)	0.24 ± 0.01^{a}	0.32 ± 0.04^{b}	0.25 ± 0.02^{a}	0.39 ± 0.03^{c}

Data are expressed by means ± standard deviation, values with different letters (a–c) in a row are significantly different ($p < 0.05$).

Table 2 L^*, a^*, b^* and ΔE^* of the gel samples heating for 0–180 s at an interval of 30 s.

Time (s)	Color value	Samples			
		Capsorubin emulsion	Capsorubin solution	Carotenoid emulsion	Carotenoid solution
0	*L**	75.79 ± 1.23^{a}	64.28 ± 1.12^{a}	71.16 ± 0.70^{a}	51.58 ± 1.21^{a}
	*a**	3.06 ± 0.08^{b}	7.88 ± 0.58^{ab}	10.01 ± 0.13^{a}	12.91 ± 0.16^{a}
	*b**	42.73 ± 0.39^{a}	40.25 ± 0.70^{a}	39.70 ± 0.81^{a}	23.08 ± 0.31^{a}
	*ΔE**	40.39 ± 0.57^{a}	46.29 ± 1.18^{a}	42.38 ± 0.70^{a}	49.10 ± 1.08^{a}
30	*L**	75.49 ± 0.56^{ab}	61.72 ± 0.34^{b}	70.66 ± 0.79^{ab}	53.90 ± 2.04^{a}
	*a**	2.30 ± 0.07^{a}	8.00 ± 0.48^{a}	10.62 ± 0.17^{a}	13.44 ± 0.21^{ab}
	*b**	44.78 ± 0.37^{b}	39.77 ± 0.69^{a}	44.52 ± 0.32^{b}	24.24 ± 0.65^{abc}
	*ΔE**	42.29 ± 0.26^{ab}	47.72 ± 0.26^{ab}	46.57 ± 0.34^{b}	47.69 ± 1.47^{a}
60	*L**	74.31 ± 1.58^{ab}	61.40±0.54^{bc}	68.92 ± 0.55^{bc}	52.79 ± 2.19^{a}
	*a**	2.88 ± 0.58^{ab}	7.10 ± 0.10^{b}	11.61 ± 0.18^{b}	12.80 ± 0.61^{a}
	*b**	46.19 ± 1.85^{bc}	39.69 ± 0.67^{a}	46.27 ± 0.80^{bc}	22.92 ± 0.44^{a}
	*ΔE**	44.18 ± 2.15^{bc}	47.65 ± 0.78^{ab}	49.18 ± 0.85^{bc}	47.97 ± 1.66^{a}
90	*L**	74.68 ± 1.57^{ab}	60.88 ± 0.80^{bc}	67.88 ± 0.86^{cd}	51.08 ± 2.10^{a}
	*a**	2.99 ± 0.24^{b}	7.18 ± 0.35^{ab}	12.50 ± 0.42^{c}	13.10 ± 0.18^{a}
	*b**	47.66 ± 0.52^{c}	40.35 ± 0.44^{a}	47.37 ± 1.84^{bc}	23.28 ± 0.48^{ab}
	*ΔE**	45.32 ± 1.15^{c}	48.48 ± 0.92^{b}	50.89 ± 1.94^{cd}	49.68 ± 1.81^{a}
120	*L**	73.20 ± 0.50^{bc}	58.75 ± 1.43^{d}	67.05 ± 1.35^{cd}	52.72 ± 1.00^{a}
	*a**	4.04 ± 0.31^{c}	7.74 ± 0.50^{ab}	13.63 ± 0.55^{d}	14.09 ± 0.54^{b}
	*b**	50.32 ± 0.95^{d}	40.35 ± 0.22^{a}	49.45 ± 2.40^{cd}	24.92 ± 0.78^{bc}
	*ΔE**	48.49 ± 1.10^{d}	50.13 ± 1.27^{c}	53.34 ± 2.75^{de}	49.17 ± 1.33^{a}
150	*L**	71.82 ± 0.85^{c}	60.66 ± 0.06^{bc}	66.83 ± 1.50^{cd}	52.32 ± 2.67^{a}
	*a**	4.89 ± 0.40^{d}	7.44 ± 0.44^{ab}	14.34 ± 0.59^{de}	14.15 ± 0.47^{b}
	*b**	51.67 ± 0.66^{de}	39.50 ± 0.38^{a}	49.36 ± 1.62^{cd}	25.08 ± 1.56^{c}

	*ΔE**	50.45 ± 1.01^{de}	48.14 ± 0.25^{b}	53.63 ± 2.23^{de}	49.63 ± 1.92^{a}
180	*L**	71.17 ± 2.21^{c}	59.97 ± 0.50^{d}	66.56 ± 1.63^{d}	51.83 ± 0.85^{a}
	*a**	5.08 ± 0.42^{d}	7.29 ± 0.45^{ab}	14.67 ± 0.82^{e}	13.46 ± 0.72^{ab}
	*b**	52.22 ± 0.39^{e}	39.24 ± 0.72^{a}	51.24 ± 3.15^{d}	23.26 ± 1.48^{ab}
	*ΔE**	51.29 ± 1.02^{e}	48.42 ± 0.83^{b}	55.36 ± 3.40^{e}	48.83 ± 0.59^{a}

Values with different superscript letters (a–e) for same color index of same sample at different times are significantly different ($P < 0.05$).

Figures

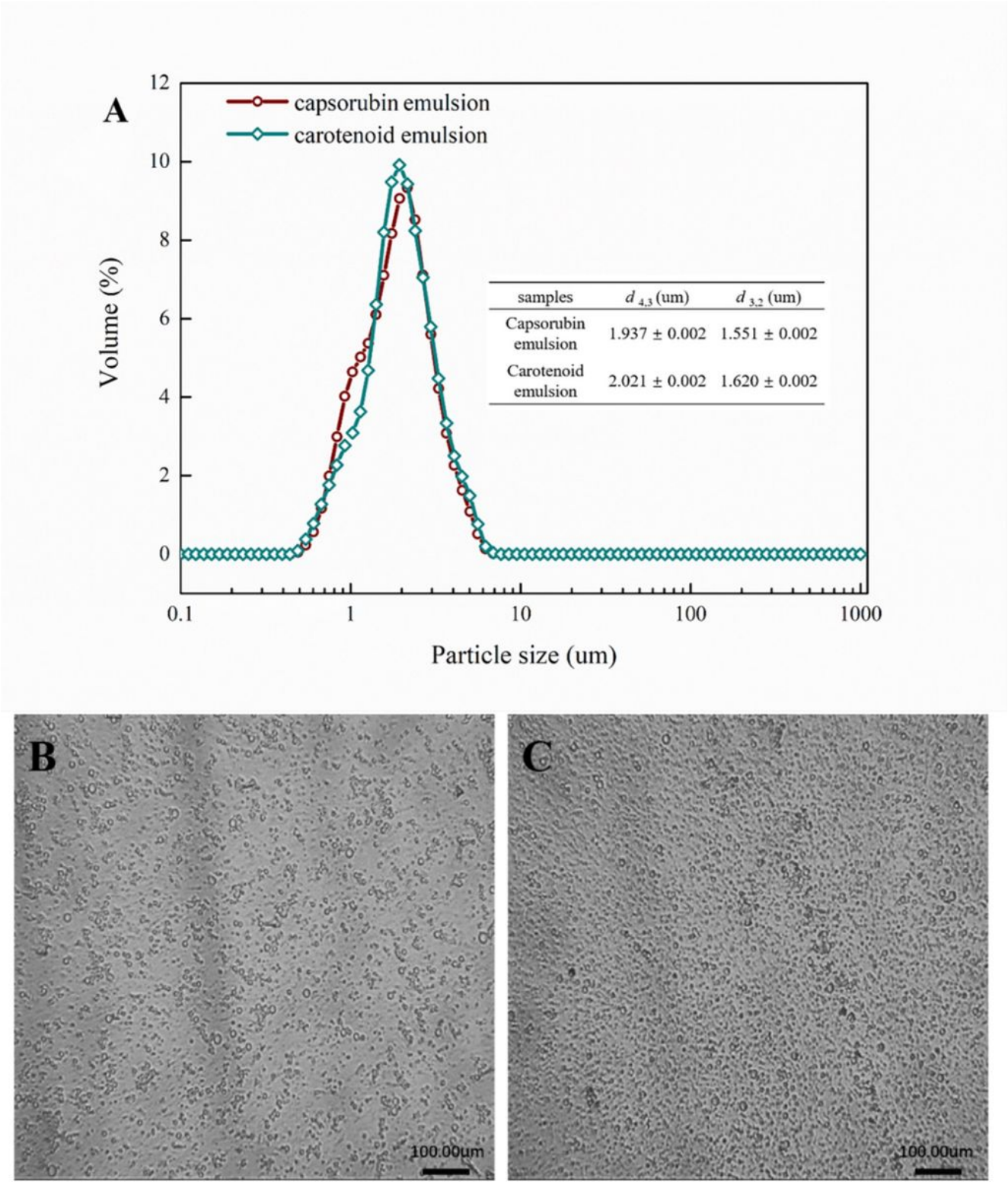

Figure 1

The distribution of particle size, $d_{4,3}$ and $d_{3,2}$ (A) and microscopy of capsorubin (B) and carotenoid (C) emulsions.

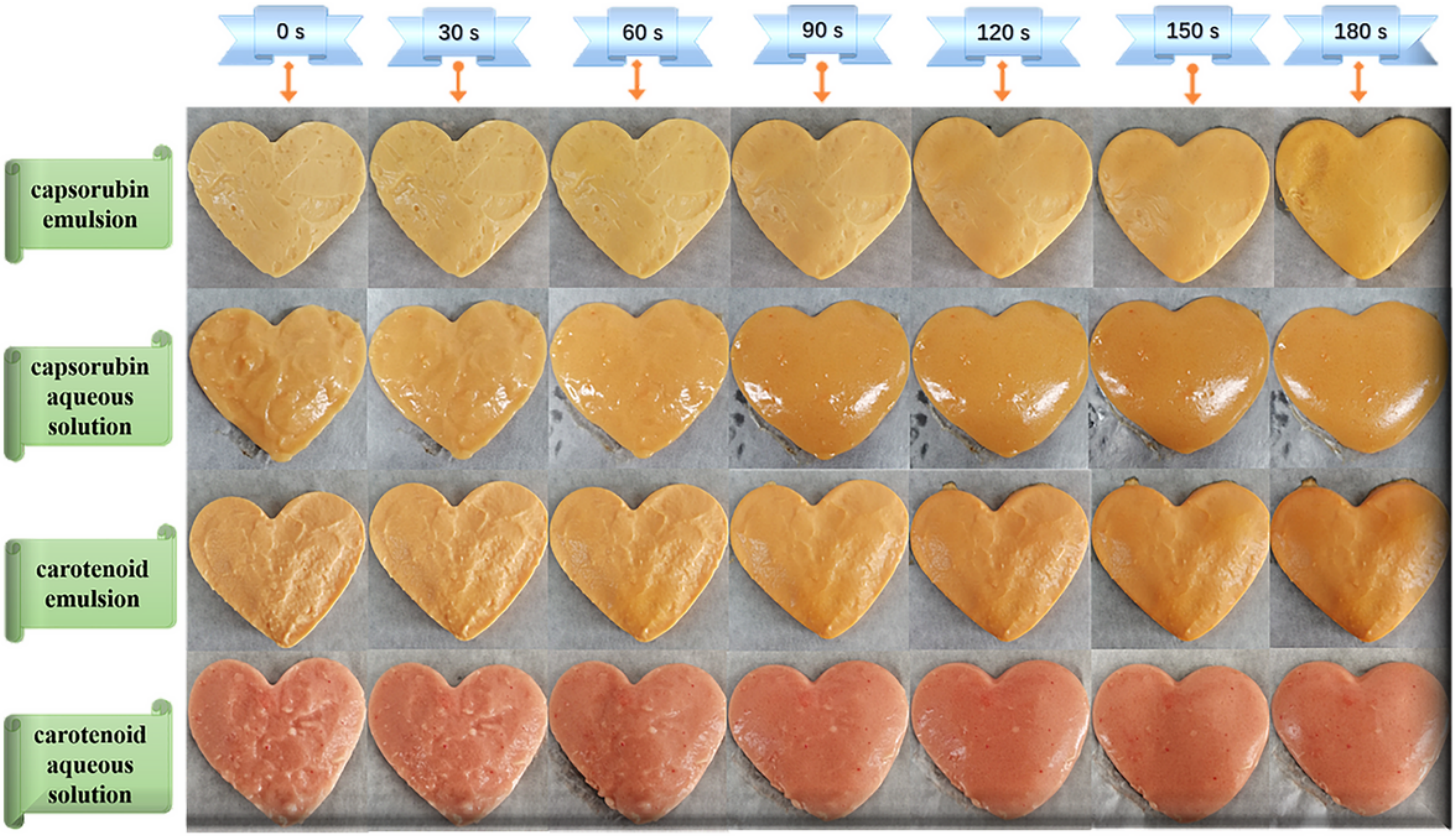

Figure 2

Surface appearance of the gel samples heating for 0–180 s at an interval of 30 s.

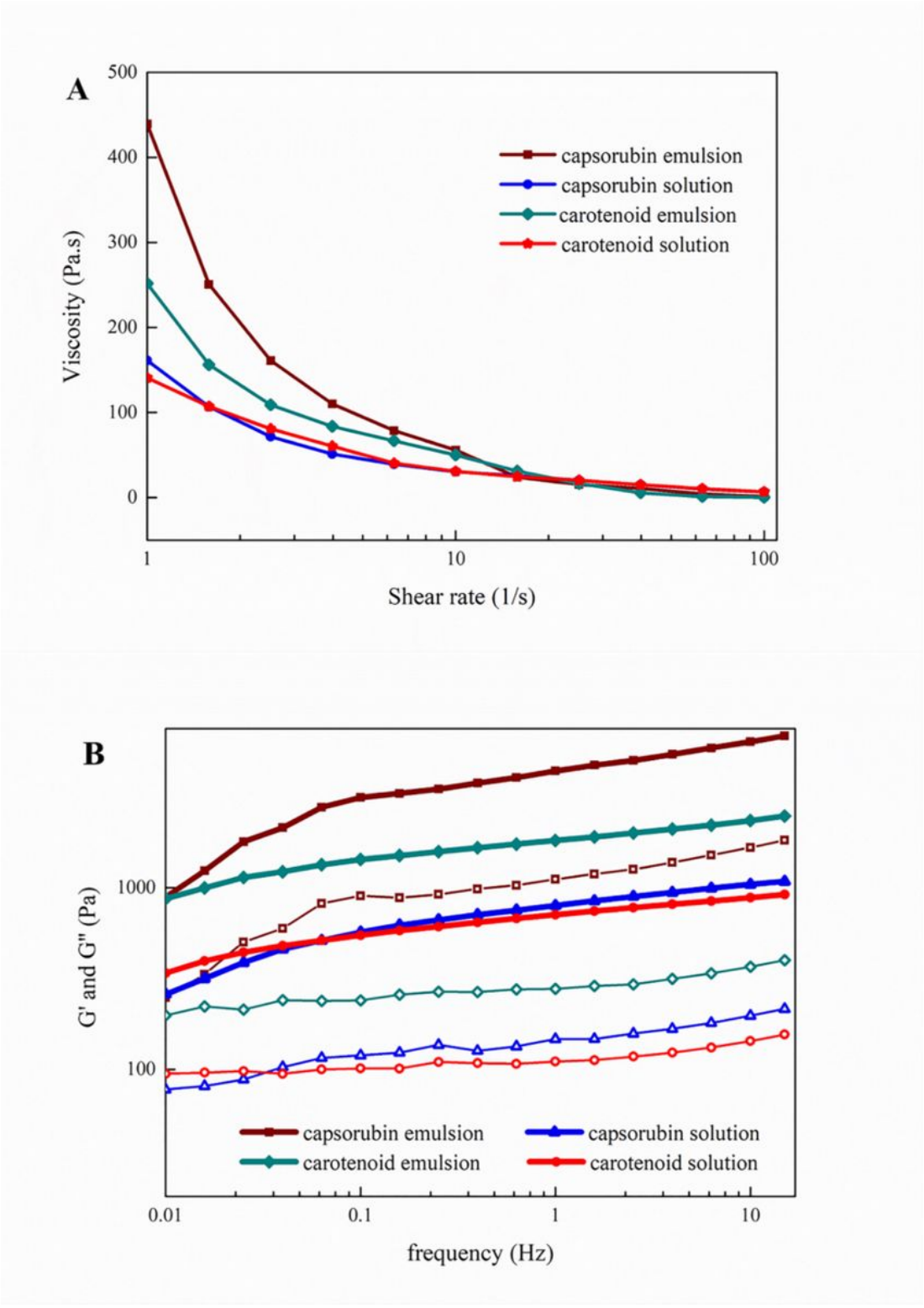

Figure 3

Viscosity (A), storage modulus (B, solid squares) and loss modulus (B, hollow squares) of gel samples containing capsorubin and carotenoid emulsions or aqueous solution.

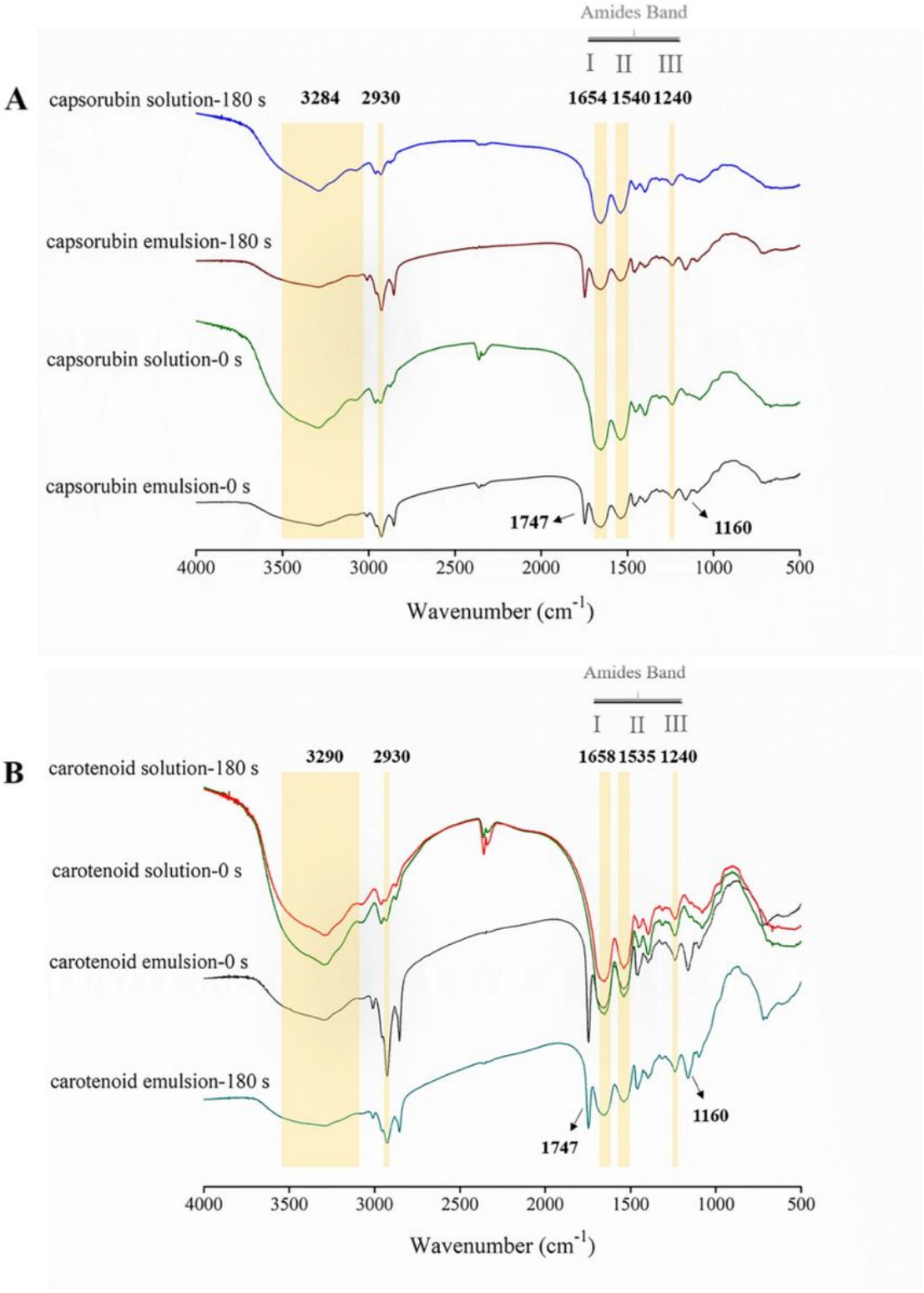

Figure 4

FTIR spectra of gel samples containing capsorubin (A) and carotenoid (B) solutions or emulsions heating for 0 s and 180 s.

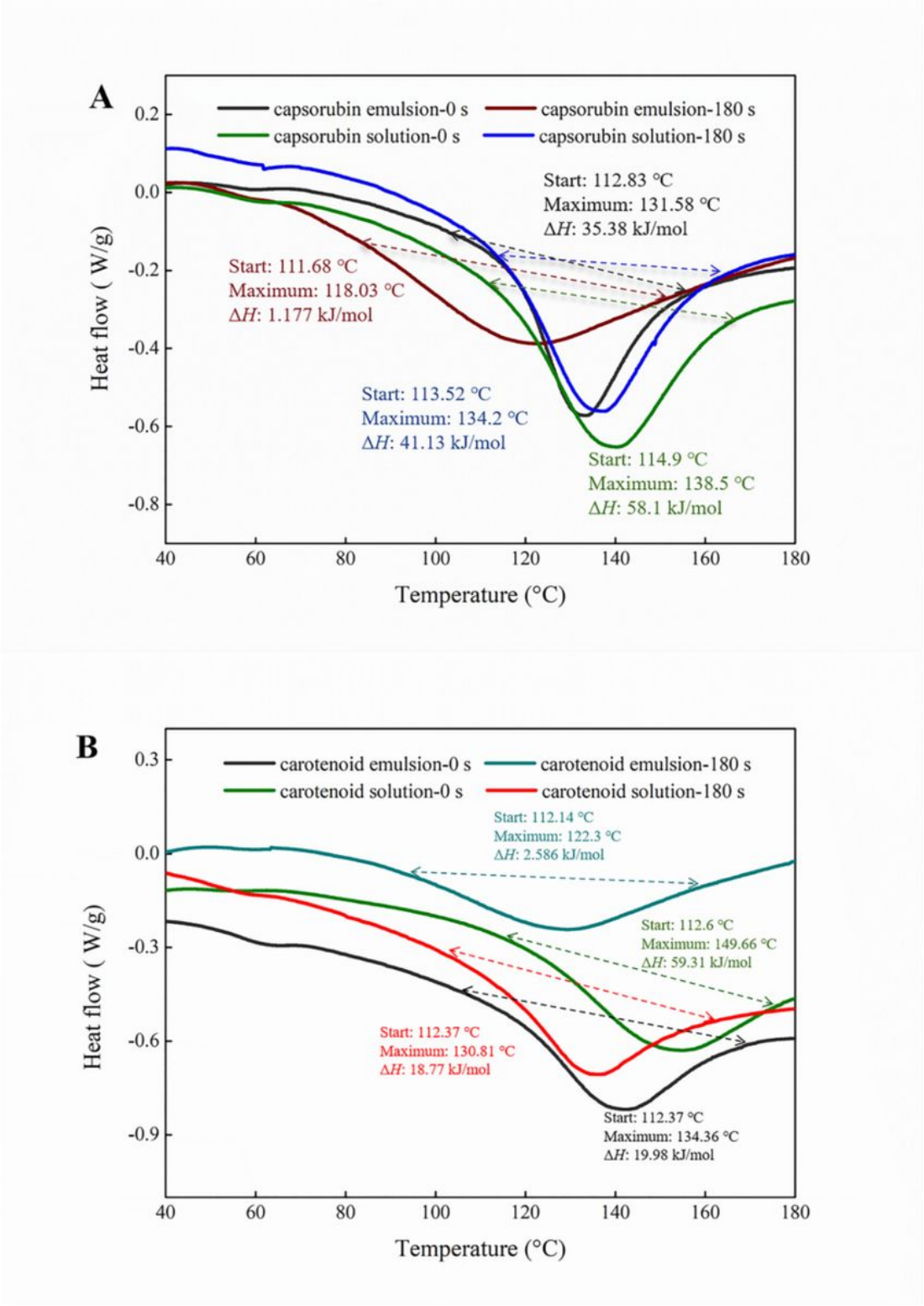

Figure 5

DSC thermograms of the emulsions and aqueous solution samples containing capsorubin (A) and carotenoid (B) with different heating times.

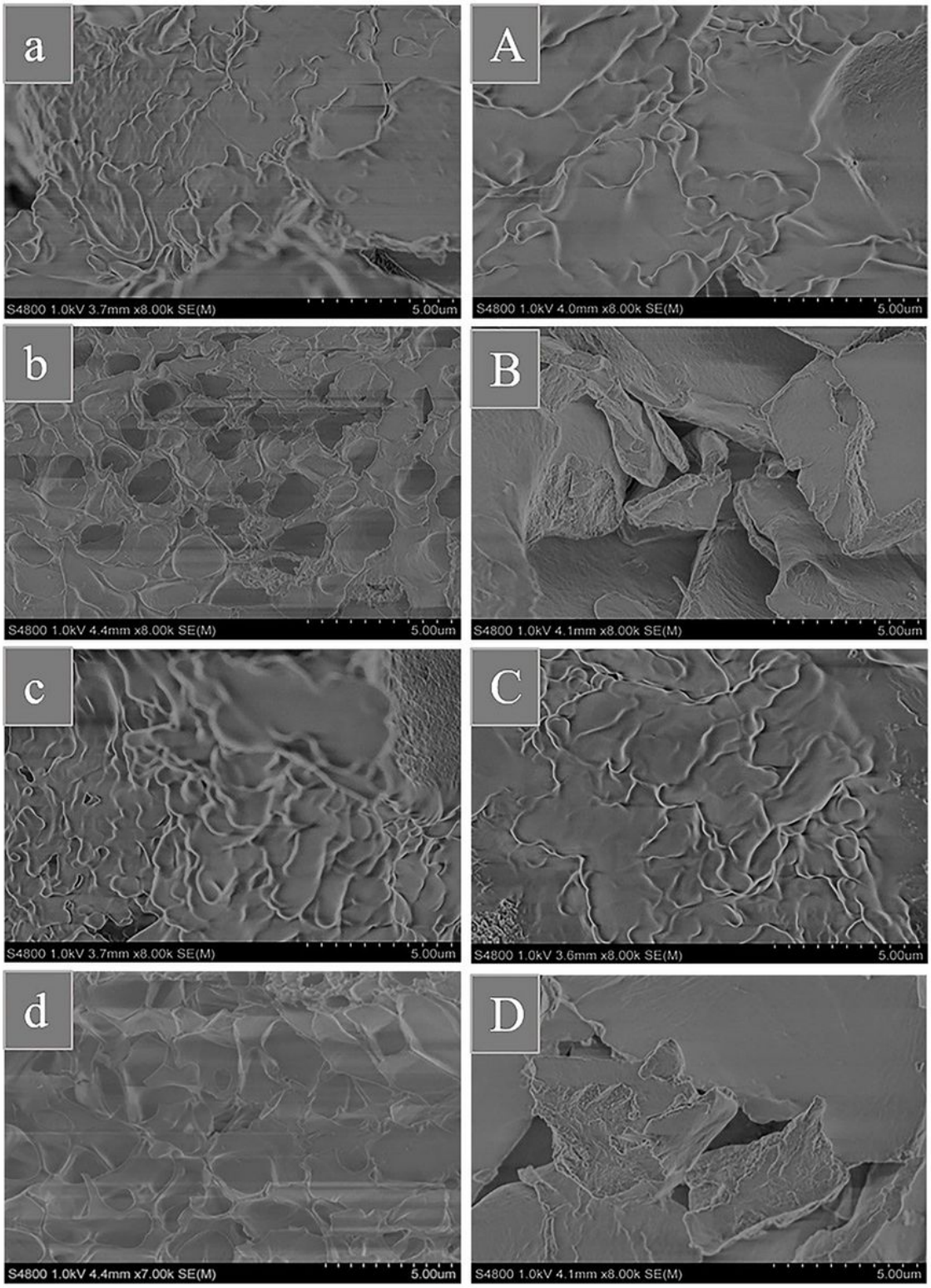

Figure 6

SEM images of gel samples containing capsorubin and carotenoid emulsions heating for 0 s (a, c) and 180 s (A, C) and containing capsorubin and carotenoid aqueous solution heating for 0 s (b, d) and 180 s (B, D).