Effect of ultrasound on the structural characteristics and oxidative stability of walnut oil oleogel coated with soy protein isolate-phosphatidylserine

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ABSTRACT

In this study, the three-dimensional network system formed by rice bran wax (RBW) was used as the internal structure, and the external structure formed by soybean protein isolate (SPI) and phosphatidylserine (PS) was added on the basis of the internal structure to prepare walnut oil oleogel (SPI-PS-WOG). Ultrasonic treatment was applied to the mixed solution to make SPI-PS-WOG, on the basis, the effects of ultrasonic treatment on SPI-PS-WOG were investigated. The results showed that both \( \beta \) and \( \beta' \) crystalline forms were present in all SPI-PS-WOG samples. When the ultrasonic power was 450 W, the first weight loss peak in the thermogravimetric (TGA) curve appeared at 326 °C, which was shifted to the right compared to the peak that occurred when the ultrasonic power was 0 W, indicating that the thermal stability of the SPI-PS-WOG was improved by the ultrasonic treatment. Moreover, when the ultrasonic power was 450 W, the oil holding capacity (OHC) reached 95.3 %, which was the best compared with other groups. Both confocal laser scanning microscopy (CLSM) and scanning electron microscopy (SEM) showed that the ultrasonic treatment of appropriate power succeeded in making the SPI-PS-WOG samples more evenly dispersed in the internal structure and denser in the external structure. In terms of oxidative stability, it was found that the peroxide value of SPI-PS-WOG remained at 9.8 mmol/kg oil for 50 days under 450 W ultrasonic power treatment, which was significantly improved compared with liquid walnut oil (WO). These results provide a new idea for the preparation of oleogels, and also lay a theoretical foundation for the application of ultrasonic treatment in oleogels.

1. Introduction

Walnut oil (WO) is a type of vegetable oil with a high content of unsaturated fatty acids. It is also rich in monounsaturated polyunsaturated fatty acids such as linoleic acid and \( \alpha \)-linolenic acids [1]. Moreover, WO contains many functional ingredients, such as vitamins, squalene, phenols, and trace elements [2]. However, WO is prone to suffer from oxidation problems during storage due to its high content of unsaturated fatty acids [3].

Under the action of a gelling agent, liquid vegetable oil is trapped in the three-dimensional gel network and gels to form a semi-solid substance [4], which is called oleogel. Nowadays, consumer demand for nutritional and healthy foods is increasing. Oleogel is gradually attracting attention as a semi-solid substance form with low saturated fatty acid content and no trans fatty acids. It prevents health problems caused by the high content of saturated fatty acids in traditional plastic fat [5]. Additionally, oleogel can make food have great color, flavor, texture, and stability [6], and can be used to replace traditional plastic fat in foods. Currently, oleogels have been studied in the preparation of chocolate [7], frankfurter-type sausages [8], cookies [9] and other products, and they have good application prospects. In addition, oleogel can retain the properties of the liquid oil itself [10]. Choosing a high-quality liquid oil has a positive effect on improving the quality of oleogel. Using WO to prepare oleogel rich in unsaturated fatty acids and many functional components will become one of the sources of high-quality oleogel.

During oleogel preparation, the three-dimensional gel network formed by the gelling agent serves as the internal structure, which can limit the flow of the liquid oil and protect it. For the selection of gelling agents forming the internal structure, hydroxypropyl methylcellulose, plant sterols, and plant waxes are now commonly used [9]. Rice bran wax (RBW) is a type of plant-derived low molecular weight gelling...
agent. RBW being a by-product of rice bran processing, has the advantages of wide sources, low cost, and strong oil binding ability [11]. The long hydrocarbon chain structure contained in RBW can produce strong intermolecular interactions [12], thereby promoting the formation of oleogel, and improving the gelation rate. In addition, in the preparation process of oleogel, RBW can form long acicular crystals with high crystallinity [13], which can effectively reduce the fluidity of liquid oil. The preparation of oleogels using RBW can play a positive role in the formation of the three-dimensional gel structure, and it is also beneficial to improve the utilization rate of by-products of rice bran processing.

To increase this protective effect, an additional layer of external structure can be constructed on the basis of the internal structure [14]. Phospholipids contain hydrophilic and lipophilic groups, have the property of self-sealing, and can participate in the formation of colloidal structures [15]. Phospholipids are often used to protect the biological activity of hydrophobic bioactive substances in liposomes [16] and have good physical stability in products with high water activity [15]. Based on the characteristics of phospholipids, they can be selected as one of the materials forming the external structure of the oleogel. The affinity between phospholipids and oil can be used to form a protective layer on the surface of oleogels. However, a single phospholipid layer as an external structure may have degradation, aggregation, fusion and leakage of core materials problems, which will adversely affect the oleogels [17].

Soy protein isolate (SPI) is often used to protect biologically active components [18] and as the wall material of oil microcapsules [19]. To make up for the deficiency of a single phospholipid layer, a dense SPI layer can be added to the phospholipid layer to form a complete external structure. The interaction between the phospholipid and SPI can be achieved in a variety of ways, including hydrophobic and electrostatic interactions [20]. Phosphatidylserine (PS) is a natural phospholipid with an irreplaceable role in biological cell membranes, showing great physicochemical properties and biological activity, and has been used in the preparation of mixed micelles [21], nanodispersions [22], and liposomes [23]. PS has a negatively charged head. The SPI has a positive charge below the isoelectric point. The combination of PS and SPI formed an external structure to provide a protective barrier for walnut oil oleogel (SPI-PS-WOG), which can delay the occurrence of oxidation and improve storage stability.

Ultrasound is a new type of technology. Recently, extensive studies on the ultrasound applied in the preparation of emulsions [24], and microcapsules [25], and great results have been achieved. For the double-layer structure oleogel, the effect of ultrasonic treatment on the internal structure is manifold, including the reduction of the crystal size distribution (CSD), the change of crystal habits, and the increase of crystal purity [26]. As for the external structure, under the action of thermal, mechanical, super mixing, and cavitation effects by ultrasonic treatment, the chemical bonds will be broken, the mechanical and barrier properties of the membrane will increase, and the membrane surface will be denser and smoother [27]. Furthermore, da Silva and Danthine proved that high-intensity ultrasonic treatment increased the hardness and oil holding capacity of oleogel [28]. Valoppi et al. used ultrasonic standing waves to control oleogel crystallization, which can improve oleogel performance and induce the formation of an external physical barrier [29]. The above studies have shown that ultrasonic treatment can optimize internal and external structures, and can be used in more in-depth applications in the preparation of oleogels.

In this study, a double-layer structure SPI-PS-WOG was prepared. Based on the three-dimensional network system formed by RBW as the internal structure, SPI and PS were added together as the external structure. The effects of ultrasonic power on SPI-PS-WOG were investigated to improve the functional characteristics and oxidation stability. This study is expected to apply ultrasonic treatment to improve the physicochemical properties of oleogels, improve their stability and oil holding capacity, provide a new idea for the preparation of oleogels, and lay a theoretical foundation for the application of ultrasonic treatment in oleogels.

2. Materials and methods

2.1. Materials

WO was purchased from Harbin Purun Oil Co., Ltd. RBW was purchased from Huzhou Shengtao Biotechnology Co., Ltd. PS was purchased from Shanghai Kaiyang Biotechnology Co., Ltd. SPI (90 %) was purchased from Harbin High-tech Co., Ltd. All other chemical reagents were of analytical grade.

2.2. Preparation of SPI-PS-WOG

PS and SPI were dissolved in distilled water to prepare an 8 wt% PS solution and an 8 wt% SPI solution, respectively. The pH of the SPI solution was adjusted to 3.5 and allowed to stand overnight for later use.

Next, 10 wt% RBW was added to 10 g WO. The mixture was stirred at 80 °C for 30 min. After the RBX was completely dissolved, the mixture was placed in an oven at 80 °C for 30 min to eliminate historical crystallization.

The PS solution was preheated to 80 °C and then added to the mixed system of WO and RBW at a ratio of 1:20 (v/v). To form a complete external structure, the SPI solution was added to the mixed system at a ratio of 1:1 (v/v). The obtained mixed system was homogenized for 10 min at 17500 rpm by an IKA homogenizer (Qingdao Jiaxing Analytical Instrument Co., Ltd.). After homogenization, ultrasonic treatment was performed with an ultrasonic generator (Shanghai Shengxi Ultrasonic Instrument Co., Ltd.). A titanium probe with a diameter of 6 mm was immersed in the mixed system and placed approximately 1 cm from the bottom. The ultrasonic treatment time remained unchanged at 15 min. The ultrasonic power was set to 0, 150, 300, 450 and 600 W to study the influence of different ultrasonic power settings on SPI-PS-WOG. Finally, the obtained sample was heated at 80 °C for 15 min and immediately placed at 4 °C to cool for 24 h to obtain SPI-PS-WOG.

2.3. Thermogravimetric analysis (TGA)

The TGA analyzer TGA 5500 (TA instrument, USA) was used to measure the thermodynamic properties of the SPI-PS-WOG sample. Three to five milligram SPI-PS-WOG samples were placed in an Al2O3 crucible. The initial temperature was set to 25 °C, and increased to 700 °C at a rate of 10 °C/min. The TGA curve was measured under an environment with a nitrogen flow rate of 50 mL/min.

2.4. Oil holding capacity (OHC)

The SPI-PS-WOG samples were centrifuged at 5000 × g for 30 min in the Centrifuge 5430/5430R multifunctional centrifuge (Eppendorf, China). Centrifugation was performed at 25 °C to separate the oil that was not fixed in the gel network. The centrifuge tube was inverted for 15 min, and the separated liquid oil was absorbed by filter paper. The OHC of the samples was calculated as follows:

\[ \text{OHC} (%) = \frac{W_2}{W_1} \times 100\% \]

where \( W_1 \) is the total mass of SPI-PS-WOG, and \( W_2 \) is the remaining mass of SPI-PS-WOG after separating the liquid oil.

2.5. Fourier transform infrared spectroscopy analysis (FT-IR)

All samples were placed in a freeze dryer and then lyophilized. The powdered samples, PS, SPI, and RBW (ground into powder) were measured separately. FT-IR was performed by the pellet method and the parameters set by Fourier infrared spectrometer (Nicolet AntarisII, USA)
were: wavelength range 4000–400 cm\(^{-1}\), resolution 4 cm\(^{-1}\), and each sample was scanned 32 times.

2.6. X-ray diffraction (XRD)

The SPI-PS-WOG crystal form analysis was performed using the Bruker D8 Advance X-ray diffractometer (Bruker, Germany), according to the method of Yang [30]. All samples were filled in the holes of the sample holder. The glass plate was adjusted so that the surrounding glass slides were level, and the XRD was fitted by copper potassium alpha rays (current 30 mA, voltage 40 kV). The 2θ angle was calibrated with copper, the reflection gap was 1.0 mm, the acceptance gap was 0.1 mm, the scanning angle was 5.0–80.0\(^{\circ}\) (2θ), the scanning rate was 8°/min, and the temperature condition was 25 °C. The obtained XRD pattern was analyzed with Jade software.

2.7. Confocal laser scanning microscopy (CLSM)

Isopropanol was used to prepare 0.1 % Nile red as a staining agent (needs to be protected from light). Moreover, 20 μL of Nile red was added to 0.5 mL of emulsion and then gelled according to the method described in Section 2.2. The stained SPI-PS-WOG samples were successively placed on a glass slide, and the CLSM (Leica Microsystems, Heidelberg GmbH, Germany) was used to observe the microstructure morphology of SPI-PS-WOG.

2.8. Scanning electron microscopy (SEM)

After the SPI-PS-WOG samples were cut into small pieces, they were fixed with glutaraldehyde and refrigerated for 1.5 h. Then, the samples were washed with phosphate buffer, dehydrated with different concentrations of ethanol, and replaced with tert-Butanol, and then the processed samples were freeze-dried. Dried samples were glued on the sample stage with conductive tape with the observation side facing up, and the surface of those samples was coated with an ion sputtering sample holder. The glass plate was adjusted so that the surrounding glass slides were level, and the XRD was fitted by copper potassium alpha rays and the surface of those samples was coated with an ion sputtering sample holder. The glass plate was adjusted so that the surrounding glass slides were level, and the XRD was fitted by copper potassium alpha rays (current 30 mA, voltage 40 kV). The 2θ angle was calibrated with copper, the reflection gap was 1.0 mm, the acceptance gap was 0.1 mm, the scanning angle was 5.0–80.0\(^{\circ}\) (2θ), the scanning rate was 8°/min, and the temperature condition was 25 °C. The obtained XRD pattern was analyzed with Jade software.

2.9. Oxidation stability

WO is prone to oxidation during storage. The effects of ultrasonic treatment on the oxidation stability of SPI-PS-WOG were evaluated according to the method of Zhuang et al. [31] with some changes. The peroxide value was used as an evaluation index. The WO and SPI-PS-WOG samples were placed in an oven at 20 °C, and their peroxide values were measured every ten days for a total of 50 days. The determination of the peroxide value refers to the AOCS Cd 8b–90 method [32].

2.10. Statistical analysis

The analysis indicators involved in this study were all repeated at least three times. SPSS 22.0 software was used to analyze the average and significance of the results, and Duncan’s test was performed to compare the significance of data in one-way ANOVA, where different letters indicate significant differences (P < 0.05). Finally, Origin 2021 was used for basic data processing and graph drawing.

3. Results and discussion

3.1. TGA analysis

The thermodynamic properties of SPI-PS-WOG were measured by a TGA analyzer. The results of the weight loss of SPI-PS-WOG with time and the weight loss derivative with time are shown in Fig. 1. In the process of gradually increasing the temperature from 25 °C to 700 °C at a rate of 10 °C/min, the weight loss curves of all SPI-PS-WOG samples had similar changing trends. All samples started to show weight loss at 50–150 °C, which may be caused by the evaporation of water on the surface or inside the SPI-PS-WOG [33]. Over the entire temperature range, the minimum and maximum weight losses occurred in the samples with ultrasonic powers of 450 W and 600 W, respectively. The differences in weight loss between samples were mainly reflected in the rate of weight change, which can be observed in the weight loss derivative figure. As the ultrasonic power increased, the first weight loss peak gradually shifted to the right. The first weight loss peak of the SPI-PS-WOG sample without ultrasonic treatment appeared at 319 °C, and when the power was 450 W, the first weight loss peak was located at 326 °C. The first weight loss peak shifted to the right, indicating that the thermal stability of SPI-PS-WOG improved. A special case appeared in the SPI-PS-WOG sample when the ultrasonic power was 600 W. Although the ultrasonic power was the highest at this time, the corresponding temperature of the first weight loss peak was 323 °C. It was shown that excessive ultrasound power showed negative effects on the thermal stability of SPI-PS-WOG. In terms of weight loss, there was more weight loss when the first weight loss peak appeared, indicating that the SPI-PS-WOG structure was damaged to a greater extent at this stage. When the temperature exceeded 650 °C, the weight of all samples remained basically unchanged, and the volatile substances in these samples were nearly completely volatilized. The thermal stability of the SPI-PS-WOG samples that were ultrasonically processed may be related to the changes in their internal and external structures. For the internal structure, ultrasonic treatment can increase its compactness. As for the external structure, the cavitation, mechanical, and super mixing effects of ultrasonic treatment can change the advanced structure of SPI [34], and strengthen the complex formed by PS and SPI, to increase the strength of the external structure.

Fig. 1. TGA analysis of SPI-PS-WOG treated with different ultrasound powers.
3.2. OHC analysis

Oleogel is a semi-solid substance formed by liquid oil trapped in the three-dimensional network system composed of gelling agents. Its ability to trap liquid oil is an important indicator to evaluate the quality of the oleogel. Fig. 2 shows the OHC of the SPI-PS-WOG under different ultrasonic power treatments. Notably, with increasing ultrasonic power, the trend of the SPI-PS-WOG OHC first increased and then decreased. The maximum OHC occurred when the ultrasonic power was 450 W, reaching 95.3 %. When the ultrasonic power increased from 0 W to 450 W, the OHC of SPI-PS-WOG increased from 84.7 % to 95.3 %, and the difference in OHC was significant. When the ultrasonic power was increased from 450 W to 600 W, the OHC decreased to a certain extent but remained significantly better than that of the SPI-PS-WOG without ultrasonic treatment. The reason for this phenomenon may be that the oleogel structure was improved by ultrasonic treatment. As for the internal structure, ultrasonic treatment can promote the formation of small crystals [35]. Moreover, the bubble collapse caused by cavitation increased the nucleation sites of the whole system [36], increasing the number of crystals. These changes could hinder the migration of WO, thereby increasing the OHC. For the external structure, the ultrasonic treatment caused the partial structure of SPI to be decomposed and folded, which led to the exposure of hydrophobic groups, and the degree of hydrophobic binding to PS increased, and the external structure was denser and more stable, which also favored the increase of the OHC [37]. When the ultrasonic power reached 450 W, the ultrasonic treatment caused the changes in the internal and external structures of SPI-PS-WOG to reach a relatively stable state. At this time, the OHC reached the highest value. When the ultrasonic power was further increased, the SPI reached the emulsification due to the excessive exposure of hydrophobic groups [38], the protective effect of the external structure decreased, and the OHC decreased.

3.3. FT-IR analysis

FT-IR is usually used to reflect the functional groups and interactions contained in substances [39]. The images of SPI-PS-WOG treated with different ultrasonic powers are shown in Fig. 3. Symmetric and antisymmetric P=O stretching vibrations could be observed at 1082 cm⁻¹ and 1237 cm⁻¹. Moreover, there were many characteristic peaks at the same position in the infrared spectra of all samples, such as the C=O stretching vibration peak at 1659 cm⁻¹, the C–H stretching vibration peak at 2917 cm⁻¹, and the O–H stretching vibration peak at 3296 cm⁻¹.

3.4. XRD analysis

The diffraction patterns of the SPI-PS-WOG treated with different ultrasonic powers under the X-ray diffractometer are shown in Fig. 4. Studies have shown that the short spacing of the characteristic peaks of
α-type crystals is 0.42 nm, the strong diffraction peaks of the characteristic peaks of β'-type crystals are approximately 0.38–0.42 nm, and the strong diffraction peaks of characteristic peaks of β-type crystals are approximately 0.47 nm [44]. From the analysis of the diffraction peak positions in Fig. 4, it was found that all the samples had a higher diffraction peak at 2θ = 28°, and there was no significant difference in the peak positions of each group sample. Not only that, all samples had weak diffraction peaks at 0.47, 0.41, and 0.39 nm, indicating that there were multiple crystal forms in all the samples. The intensity of the diffraction peak at 0.39 nm was relatively high, indicating there were relatively more β'-type crystals in the system. β'-type crystals have an orthogonal and vertical subcellular structure, which can form a finer three-dimensional network structure, thereby fixing more liquid oil [45]. The difference in the SPI-PS-WOG samples treated with different powers appeared mainly in the diffraction peak intensity. With increasing ultrasonic power, the intensity of the diffraction peak near 0.32 nm increased, and the crystallinity increased [46]. XRD results showed that ultrasonic treatment could increase the crystallinity of SPI-PS-WOG without changing its crystalline form. Li et al. [47] studied the ultrasonic treatment of candelilla wax oleogel and reached similar conclusions.

3.5. CLSM analysis

Fig. 5 shows the imaging diagrams of the SPI-PS-WOG samples processed using different ultrasonic powers under a CLSM, which was used to observe the distribution of WO in the internal structure. The red areas in the images represent the distribution of WO. Notably, when the SPI-PS-WOG sample was not ultrasonically processed, the WO particles were the largest and were unevenly distributed in the entire system, with a high degree of WO accumulation, and the effect was not ideal. The reason may be that the internal structure of SPI-PS-WOG was relatively loose at this time, so that part of the WO was not retained. When the ultrasonic power reached 150 W, the WO distribution began to improve significantly. Furthermore, when the ultrasonic power was 450 W, the WO distribution was uniform and compact, and no large sample

![Fig. 5. CLSM images of SPI-PS-WOG treated with different ultrasound powers.](image-url)
accumulation was obtained. Possibly, ultrasound produced cavitation activity and high local shear force, causing the formation and rupture of bubbles or cavities, increasing the number of nucleation sites in the entire system [48], and reducing the size of crystals in the internal structure, thus showing a more even and finer WO distribution. In terms of the OHC of WO, the changes in the internal and external structure had a positive effect on it. The small and dense crystal structure in the internal structure increased the contact area and interaction of the crystals, and the compactness of the three-dimensional network system increased. Concurrently, ultrasound cavitation changed the spatial structure of SPI and the arrangement of the PS molecules. In the external structure, SPI and PS were more closely bound, so SPI-PS-WOG had a stronger ability to trap oil and reduced the appearance of red in the larger area caused by untrapped WO in the image. The exception was that when the ultrasonic power reached 600 W, large red areas appeared again. This may be because when the ultrasonic power was too high, the hydrophobic groups of SPI were greatly exposed, which caused the SPI to aggregate, thereby reducing the coating effect on WO. This showed that proper ultrasonic treatment can improve the structure of SPI-PS-WOG and make the WO wrapped inside evenly and densely distributed. If the ultrasonic power was too large, the WO would accumulate in a small area, which is consistent with the results of the OHC.

3.6. SEM analysis

The external structure of the SPI-PS-WOG was based on the electrostatic interaction between the positively charged SPI surface and the negatively charged PS, as well as the hydrophobic interaction between the SPI and the polar head of the PS [49]. To more accurately reflect the influence of ultrasonic power on the microstructure of SPI-PS-WOG, samples were observed under SEM, and the images are shown in Fig. 6. The squares in Fig. 6 indicate the agglomeration on the surface of SPI-PS-WOG. According to these microscope images, all the samples were irregular and porous. When there was no ultrasonic treatment, there were large agglomerations in some areas were observed. However, the ultrasonic power gradually increased resulting in the agglomeration on the surface of the SPI-PS-WOG gradually decreased compared to the untreated samples. Especially the ideal state was approached at ultrasonic power of 450 W, at this time, almost no large agglomeration was observed on the surface, and it was in a fine state. Marcuzzo et al. showed that ultrasonic treatment can improve the appearance of protein membranes [50]. When the ultrasonic power was 450 W, the ultrasonic treatment promoted the uniform dispersion of SPI and reduced the agglomeration during the gelation process. In addition, ultrasonic treatment increased the number of hydrophobic groups of SPI [51], which combined more closely with PS, and enhanced the compactness of the external structure. The exception occurred in the SPI-PS-WOG
sample processed with the ultrasonic power of 600 W. Although the surface of the SPI-PS-WOG was denser at this time, there was a small agglomerated area, which may be related to protein aggregation caused by the high ultrasonic power [52].

3.7. Oxidation stability

SPI-PS-WOG is prone to oxidation during storage, which limits its applicability in actual production and life to some extent. To further explore the protective effect of ultrasonic treatment on the oxidation stability of the SPI-PS-WOG, the WO and SPI-PS-WOG were stored at a constant temperature for a certain period, and the peroxide value was measured. The Fig. 7 shows the results of peroxide value. It can be seen that the peroxide value of all the samples increased with increasing storage time, having the WO sample the most significant increasing trend. On the 50th day, the peroxide value of the WO sample reached 18.1 mmol/kg oil. At this time, the peroxide value of the SPI-PS-WOG samples under the ultrasonic power of 450 W was 9.8 mmol/kg oil that was 8.3 mmol/kg oil lower than the WO alone. Compared with the SPI-PS-WOG samples treated with different ultrasound powers, the SPI-PS-WOG without ultrasonic treatment showed the worst oxidation stability, with its peroxide value reached to 7.8 mmol/kg oil on the 30th day. As the ultrasonic power gradually increased from 0 W, the peroxide value of samples stored for the same number of days showed an overall decreasing trend. The exception occurred in the samples treated with 600 W ultrasound power, whose peroxide value was higher than that of the samples treated with ultrasonic power of 300 W and 450 W after 10 days, which may be related to the low OHC observed at 600 W. Briefly, the double-layer structure played a positive role in prolonging the oxidation stability of SPI-PS-WOG. The three-dimensional network system formed by the internal structure limited the free flow of WO and played a protective role [53]. The dense external structure added a protective barrier to the internal structure. Additionally, the oxidation stability of SPI-PS-WOG was the best under the 450 W ultrasound treatment, which was also related to the improvement of the internal and external structures. Ultrasonic treatment increased nucleation sites through cavitation, reduced the size of crystals, and enhanced forces such as hydrogen bonding to maintain the three-dimensional network system, thereby optimizing the internal structure [47]. Moreover, ultrasonic treatment changed the conformation of SPI and then enhanced the hydrophobic interactions between SPI and PS in the external structure. Therefore the compactness and stability of the external structure were improved.

4. Conclusions

In this study, the effect of ultrasonic treatment on SPI-PS-WOG was explored. The study found that when the ultrasound power of 450 W was applied to SPI-PS-WOG, its thermal stability and OHC could be improved. With increasing ultrasound power, the WO distribution became more uniform and denser, the interactions between PS and SPI in the external structure gradually increased, and the SPI-PS-WOG showed better surface characteristics. However, a too high ultrasound power would reduce the properties of SPI-PS-WOG. Furthermore, SPI-PS-WOG also showed significant advantages in improving the oxidation stability of WO. Therefore, the use of ultrasonic treatment to prepare SPI-PS-WOG is a novel idea that can be used to extend the oxidative stability of liquid vegetable oils with a high unsaturated fatty acid content and provide a theoretical foundation for the production of oleogels.

CRedIT authorship contribution statement

Yingjie Yu: Methodology, Investigation, Writing – original draft. Tong Wang: Investigation, Validation, Data curation. Yuhang Gong: Visualization. Weining Wang: Investigation. Xue Wang: Validation.

Fig. 7. Oxidation stability analysis of WO and SPI-PS-WOG treated with different ultrasound powers. Note: The values of different letters (a-e) are significantly different (p < 0.05).

Dianyu Yu: Conceptualization, Methodology, Writing – review & editing. Fei Wu: Supervision, Conceptualization. Liqi Wang: Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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