International Food Research Journal 25(2): 784-792 (April 2018)
Journal homepage: http://www.ifrj.upm.edu.my

Oxidation stability of sesame oil encapsulated by spray drying

[1,*]Onsaard, E., [1]Putthanimon, J., [1]Singthong, J. and [2]Thammarutwasik, P.

[1]*Department of Agro-Industry, Faculty of Agriculture, Ubonratchathani University, Warinchumrap, Ubon Ratchathani, 34190, Thailand*
[2]*Department of Food Technology, Faculty of Agro-Industry, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand*

Article history

Received: 27 October 2016
Received in revised form: 22 January 2017
Accepted: 27 January 2017

Keywords

Encapsulation
Emulsions
Sesame oil
Spray drying
Oxidation
Storage

Abstract

The objective of this work was to study the oxidation stability of encapsulated sesame oil powders by spray drying. Microencapsulated powders were prepared from sesame oil-in-water emulsions containing 15% sesame oil, 0.5% whey protein concentrate, 0.2% κ-carrageenan and 0-30% maltodextrin with a dextrose equivalent (DE) of 10 by spray drying. The oxidation stability of encapsulated sesame oil was investigated up to 30 days storage at ambient temperature (26.8±1.1°C), cold storage temperature (2.7±1.6°C) and frozen storage temperature (-18.0±2.0°C). The microencapsulated powders had high encapsulation yields (86.73%) and low moisture content (3.19%) and water activity (a_w 0.28). They showed a spherical shape with a few cracks on the surface. Solubility index (SI) of the reconstituted emulsions decreased when storage time increased at various temperature storages. Reconstituted emulsion, with either bimodal or multimodal particle size distribution and with a slightly increase in mean particle diameter, were observed during storage. No significant difference (p>0.05) in TBARS value was observed during storage at ambient temperature, cold storage temperature and frozen temperature for 30 day storage. It was concluded that the microencapsulated powders containing WPC/κ-carrageenan/MD can protect oil oxidation during storage.

Introduction

Sesame (*Sesamum indicum* L.) is an important oilseed crop. Most sesame seeds are used for oil extraction and the rest are used for food ingredients (Deshpande *et al.*, 1996). In 2013, the world-wide production of sesame was 4,756,752 tons, with major production in Asia (2,464,403 tons) and Africa (2,117,585 tons) (FAOSTAT, 2015). Sesame seeds are not only used as a raw material for extracting cooking oil, but also as whole or roasted seeds in confectionary and bread, such as bread sticks, buns and as an ingredient in cookies and crackers. Besides being used for cooking, sesame seeds are often used in the nutritional, industrial and pharmaceutical industries (Mondal *et al*., 2010).

Sesame oil contains more than 80% unsaturated and less than 20% saturated fatty acids. The saturated fatty acids of sesame oil are mostly composed of palmitic (7.9-12.0%) and stearic (4.8-6.1%). Sesame oil can be classified in the oleic-linoleic acid group because the major unsaturated fatty acids have values of 36.7-52.4% of oleic and 30.4-51.6% of linoleic acid (Hwang, 2005; Mondal *et al.*, 2010; Nzikou *et al.,* 2010). Monounsaturated fatty acids (MUFAs) (~42.0%) and polyunsaturated fatty acids (PUFAs) (~40%) are also found in sesame oil (Orsavova *et al*., 2015). The high content of MUFAs and PUFAs in sesame oil increases the quality of the oil for human consumption, because the high proportion of unsaturated fatty acids relates to a source of essential fatty acids, with linoleic acid important for cell membrane structure and cholesterol transportation in blood. Sesame seeds are rich in important biologically active compounds, such as vitamin E and lignins (sesamin and sesamolin), that play an important role in health (Deshpande *et al.*, 1996). The vitamin E is effective on antioxidants to provide living systems an efficient defense against free radicals and the damage that they impart at the cellular level (Ball, 2006). The human daily requirement of vitamin E is estimated at about 30 IU (deMan, 1999). The lignans have been reported to have many beneficial properties such as antihypertensive, anticancerous and hypercholesterolemic activities (Dar and Arumugam, 2013). The tocopherols, sesamin and sesamolin contents, have been reported in sesame seeds (58 varieties) and in commercial sesame oils from Thailand (Rangkadilok *et al*., 2010). The range of total tocopherols in these sesame products

*Corresponding author.
Email: *ekasit.o@ubu.ac.th*
Tel: 66-45353519; Fax: 66-45288373

was 50.9-211 μg/g seed and the mean values of sesamin and sesamolin were 1.55 mg/g and 0.62 mg/g, respectively (Rangkadilok *et al*., 2010). In commercial sesame oils produced in Thailand, the ranges of total tocopherols, sesamin and sesamolin contents, were 304-647 μg/g oil, 0.93-2.89 mg/g oil and 0.30-0.74 mg/g oil, respectively (Rangkadilok *et al*., 2010).

Sesame oil is able to maintain oxidation stability, although it contains 85% unsaturated fatty acids. However, the oxidation of unsaturated fatty acids is the major cause of the production of off-flavor compounds that it made sesame oil less acceptable to consumers and reduced its nutrition value (Eunok *et al*., 2005). The oxidation of oil is affected by internal and external factors such as fatty acid composition and temperature during storage. Lee and Choe (2012) reported that sesame oil oxidation and off-flavor compounds were found in roasted sesame oil during accelerated storage at 70^{o}C in the dark for 4 weeks (Lee and Choe, 2012). Prolong heating of sesame oil makes it to undergo thermal degradation leading to oxidative rancidity, formation of hydroperoxides as primary reaction products, formation of secondary oxidation products and other products of degradation e.g. aldehydes, ketones, alcohols and hydrocarbons, as well as aliphatic or monocyclic or bicyclic products (Kamal-Eldin and Pokorn´y, 2005; Nzikou *et al.,* 2010). The concentration of relatively polar secondary oxidation products can be determined by chemical analysis. The frequently used test of quality oil is the thiobarbitutric substances (TBARS) method.

Microencapsulation is the process in which tiny particles or droplets are surrounded by a coating to form small capsules. Encapsulated materials or material inside the microcapsule are referred to as core material, internal phase or active ingredient. The outer or protective material around the core is referred to as the capsule, encapsulate, wall material, carriers, shell, or encapsulation matrix. The coating wall can protect the core material against environment effects (temperature, oxygen, humidity, light etc.) (Estevinho *et al*., 2013; Nesterenko *et al*., 2013; Kaushik *el al*., 2014). Novel interfacial engineering technology has been used in the preparation of emulsion, which has resulted in a better barrier against environmental conditions (Kagami *et al*., 2003; Gu *et al*., 2004; Rodríduez-Huezo *et al*., 2004; Gu *et al*., 2004; Onsaard *et al*., 2014). Proteins and polysaccharides are widely used in the preparation of multilayer interfacial membrane emulsion and serve as wall materials during the microencapsulation process such as corn oil, tuna oil, sesame oil and avocado oil (Klinkesorn *et al*., 2005a; Gu *et al*., 2005; Klinkesorn *et al*., 2006; Bae and Lee, 2008; Onsaard *et al*., 2014). The emulsions containing whey protein concentrate-κ-carrageenan-maltodextrin with dextrose equivalent of 10 can produce stability to droplet aggregation at pH 6-8, NaCl ≤ 300 mM and sucrose 0-20%, which can be used in the encapsulation of sesame oil (Onsaard *et al*., 2014). Spray drying of emulsions is generally the most commonly used method of microencapsulation and drying, due to its flexibility, economical costs, efficiency, ease to scaling-up, easily available equipment and production of good quality powder (Arshady, 1993). The spray drying process involves the dispersion of core material into a polymer solution, forming an emulsion, or dispersion, pumping of feed solution and atomization of emulsions into drying medium and dehydration of the particles to produce microencapsules (Kaushik *et al*., 2014; Martínez *et al*., 2015). Microencapsulation of oils by spray drying is an alternative method that has been studied by many researchers in order to protect unsaturated fatty acids (Tonon *et al*., 2011; Matalanis *et al*., 2012; Gallardo *et al*., 2013; Esquerdo *et al*., 2015). The information available on preparation of sesame oil emulsion, reports on the influence of maltodextrin and environmental stresses on stability of whey protein concentrate/κ-carrageenan which stabilized sesame oil-in-water emulsions (Putthanimon *et al*., 2012; Onsaard *et al*., 2014). No papers have been published on the encapsulation and oxidation stability of sesame oil encapsulated by spray drying. Therefore, the objective of this work was to study microencapsulation and oxidation stability of sesame oil encapsulated after spray drying.

Materials and Methods

Raw materials

Sesame oil was obtained from the Learning Organization and Development Center of Sesame for Sustainable Agro-Household Industry, Faculty of Agriculture, Ubonratchatani University, Thailand. Maltodextrin (MD) with a DE of 10 was purchased from Nutrition SC Co., Ltd. Thailand. Whey protein concentrate (WPC), containing 82.03% protein, 2.70% ash and 6.75% fat (dry weight basis) and 4.91% moisture (wet weight basis), was purchased from Siam Whey Co., Ltd. Thailand. Kappa carrageenan, dibasic sodium phosphate, dihydrogen phosphate, sodium assize, hydrochloric acid, sodium chloride and 2-Thiobarbituric acid were purchased from Sigma Chemical Co. (St Louis, MO, USA). Sodium hydroxide purchased from Merck (Darmastadt, FR, Germany).

Preparation of encapsulated sesame oil powders

A protein solution was prepared by dissolving 1.0% wt WPC into a 5 mM phosphate buffer, pH7, containing 0.04% sodium azide (NaN_3) as an antimicrobial agent. A carrageenan solution was prepared by dispersing 0.4% κ-carrageenan into a 5 mM phosphate buffer, pH 7, heating in a water bath at 70°C for 30 min and then cooling at 30°C. MD was dispersed at 15% (w/v) into the carrageenan solution and stirred for 15 min and then adjusted to pH 7 using either 0.1 N HCl or 0.1 N NaOH. A sesame oil-in-water emulsion was prepared by blending 30% sesame oil and 70% protein solution (1%wt WPC in 5 mM phosphate buffer, pH 7) using a high-speed blender at 10,000-15,000 rpm for 1 min (HR1357 300, Watt, Philips), and then passing through a homogenizer (TA18/D, Didacta, Italia) three times at 1,500 psi to reduce mean droplet diameter. This primary emulsion (1°) was diluted with carrageenan solution containing MD with a DE of 10 to form a secondary emulsion (2°). The 2° emulsions were disrupted by blending for 1 min and passing then through a homogenizer three times at 1,500 psi. The 2° emulsions containing MD (15%wt sesame oil, 0.5%wt WPC, 0.2% κ-carrageenan 0.02% sodium azide and 15% MD with DE of 10) were stored at room temperature prior to analysis. The mean droplet diameter of the 2° emulsions was 200-300 nm. The emulsion was fed into a spray drier (Niro A/S, Denmark) at a rate of 17-18 mL/min. The drying conditions were an inlet air temperature of 200 ± 2°C and an outlet air temperature of 80-100°C. The dried powders were collected in laminated pouches and stored at room temperature until analysis.

Characterization of encapsulated sesame oil powders

Encapsulation yield (EY): The percent of production yield was calculated from the weight of the microencapsulated powders with the total amount of solid mass to be spray dried (Wu, Zou, Mao, Huang and Liu, 2014).

Moisture content and water activity (aw): Moisture content of the microencapsulated powders used, was determined from AOAC standard (AOAC, 1999) and water activity of the powder was measured using a water activity analyzer (PS200 S/N 9809020, Novasina, USA).

Color: Color of the powders was measured using a colorimeter (Hunter Lab, Color Flex, USA) and reported as L^*, a^* and b^* values.

Powder morphology: The overall morphology of the powders was observed by a Scanning electron microscope (SEM). Before loading the powder samples, the samples were coated with gold using a sputter coater. The average coating time was 2 min. The micrographs of the sample were obtained with SEM at 10 kV x2,000 (JSM-5410L, JEOL, Japan).

Stability of reconstituted encapsulated sesame oil powders after storage

To evaluate emulsion stability, the microencapsulated powders were stored at ambient temperatures (26.8±1.1°C), cold storage (2.7°C) and frozen storage (-18.0±2.0°C) for up to 30 days. Evaluation of emulsion stability was conducted at 10 day intervals for solubility index (SI), mean droplet diameter, particle distribution and ζ-potential of reconstituted microencapsulated powders.

Solubility index (SI): SI was determined using a modification of the method of Mandala and Bayas (2004). The microencapsulated powders (5 g) were dispersed in 50 mL of 5 mM phosphate buffer pH 7. The reconstituted emulsion was centrifuged at 3000 rpm for 10 min (MIKRO 200/200R, Hettich, Germany). Supernatant was separated from the precipitated paste. The supernatant phase was dried at 105°C for 24 h. After cooling, the dried solid supernatant (WS) was weighted. The SI is the percentage of dry mass of soluble in supernatant to the dry mass of whole sample (WO). Solubility index (SI) was calculated as:

$$SI = (\text{soluble solid (WS)} / \text{dry mass of whole sample (WO)}) \times 100 \quad (1)$$

where WS is the dried solid in supernatant and WO is the dry mass of whole sample.

Particle size determination, particle size distribution and ζ-potential measurement:

Mean droplet diameter and particle size distribution: The mean droplet diameter and particle size distribution were measured using a dynamic light scattering instrument (Zetasizer Nano, Malvern Instruments Ltd., UK). Particle sizes of the emulsions were reported as the average diameter of particles. Particle size distribution of the emulsions was displayed by volume distribution or a distribution describing the relative proportion of multiple components in the emulsion sample based on their volume. To prevent multiple scattering effects, the emulsions were diluted to a droplet concentration of approximately 0.005% using buffer solutions. All measurements were made on three freshly prepared samples, and the results were reported as the mean and standard deviation.

ζ-potential measurement: Electrical charge (ζ-potential) of the emulsions were measured using a dynamic light scattering instrument (Zetasizer

Nano, Malvern Instruments Ltd., UK). ζ-potential measurement gave an indication of stability of the emulsion by measuring the magnitude of electrostatic and charge repulsion or attraction between particles in an emulsion. The ζ-potential was determined by measuring the direction and velocity of droplet movement in the applied electric field. To prevent multiple scattering effects, the emulsions were diluted to a droplet concentration of approximately 0.005% using buffer solutions. All measurements were made on three freshly prepared samples, and the results were reported as the mean and standard deviation.

Oxidative stability of encapsulated sesame oil powder during storage

To evaluate oxidative stability, the microencapsulated powders were stored at various temperatures. The powders (50 g each) were placed in laminated pouches and stored at ambient temperature (26.8±1.1°C), cold storage (2.7±1.6°C) and frozen storage (-18.0±2.0°C) for 30 days. Evaluation of oxidation stability was conducted at 5 day intervals for lipid oxidation as detailed below.

Lipid oxidation measurement: To evaluate oxidative stability, powder samples containing 15% sesame oil, 0.5% WPC, 0.2% κ-carrageenan and 15% MD with DE of 10, were stored at the above various temperatures for 30 days. Evaluation of oxidative stability was conducted at 5 days intervals for lipid oxidation. Oxidative changes during storage were measured by thiobarbituric acid reactive substances (TBARS) (Egan *et al*., 1981) as indicators of secondary lipid oxidation product.

TBARS were determined in the microencapsulated powders following the method of Egan *et al.* (1981). The results were expressed as mg of malondialdehyde per kg of sample (mg MAD/kg). Ten grams of the sample were homogenized with 50 mL of distilled water for 1 min and then transferred to the distillation flask, using 47.5 mL distilled water for washing. 2.5 mL of 4N HCl solution, antifoam and a few glass beads were added to the flask before boiling. The mixture was heated until 50 ml of distillate was collected. Pipette 5 mL of distillate was added to 5 mL of thiobarbutiric acid (TBA) reagent containing 0.02 M TBA in 90% glacial acetic acid. The mixture was incubated for boiling water for 35 min. After cooling with tap water, absorbance of the solution was read at 532 nm. The constant 7.8 was used to calculated as follows: The TBA value (mg MDA/kg) = 7.8 x A, where A was absorbance of sample vs blank.

Statistical analysis

All analysis and measurement were performed in three replicates. Averages and standard deviations from 3 measurements were reported. The experimental design was a completely randomized design (CRD). Data were analyzed by the analysis of variance (ANOVA) and mean comparison were carried out by Duncan's multiple-range test at $P < 0.05$ using SPSS software version 10.0.

Results and Discussion

Production and characteristic of encapsulated sesame oil powders

Previous work showed that the emulsion (WPC-κ-carrageenan-MDDE10) had stability to droplet aggregation with NaCl and sucrose, which can be used in the encapsulation of sesame oil (Onsaard *et al.,* 2014). The applications of microencapsulated sesame oil powders can be widely used in cooking as ingredients of foods or as components in lotions and cosmetics. Therefore, those initial experiments produced and characterized microencapsulated sesame oil powder. Emulsions containing MD (15%wt sesame oil, 0.5%wt WPC, 0.2% κ-carrageenan and 15% MD with DE of 10) were prepared and then dried using spray drying and the oxidative stability was monitored.

In general, microencapsulation is a method in which small particles are embedded in homogeneous or heterogeneous matrix to form capsules. Successful encapsulation of sesame oil was obtained resulting in fine and yellow encapsulated powders. The L^*(lightness), a^*(redness/greenness) and b^* (yellowness/blueness) value of powders were 86.79, 2.46 and 14.12, respectively. Encapsulation yields (EY) of the microencapsulated powders using spray drying was 86.73%. The encapsulated powders were found to have low moisture content (3.19%) and water activity (a_w ~0.28).

Many studies have shown that the low moisture content of microencapsulated powders could be prepared by spray drying (Klinkesorn *et al*., 2005b; Aghbashlo *et al*., 2012; Carneiro *et al*., 2013). Aghbashlo *et al*. (2012) reported that the moisture content of fish oil microcapsule within skim milk powder (SMP) by spray drying was in the range of 2.33–4.84%. Carneiro *et al.* (2013) also reported that moisture content values of microencapsulated flaxseed oil by spray drying using different combinations of wall materials was 1.11-1.65%. Dehydrated foods have aw value of about 0.3 in order to control, not only microbial growth, but other physic-chemical and biochemical reactions deleterious to color, texture, flavor and nutritive value of foods (Alzamora *et al*., 2003). Nawar (1997) reported that in dried

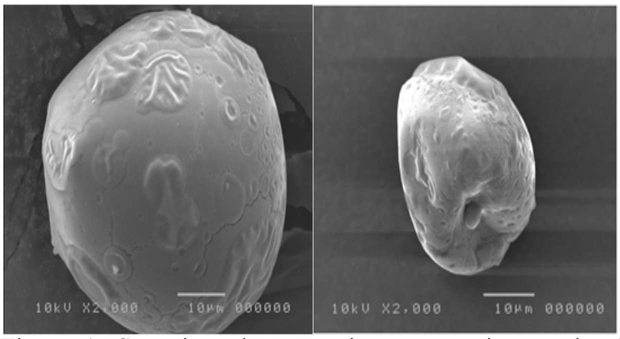

Figure 1. Scanning electron microscopy micrograph of encapsulated sesame oil powder at x2,000.

food with low moisture contents (about aw 0.3) lipid oxidation can be retarded reportedly by reducing metal catalysis, quenching free radicals, promoting non-enzymatic browning and/or impeding oxygen accessibility (Nawar, 1997).

Figure 1 shows the SEM microstructures of powders produced with WPC-κ-carrageenan-MDDE10 wall material at 2,000X. The SEM images show the morphological characteristics such as size and shape of the powder. Microcapsules showed a spherical shape with a few cracks on the surface. WPC-κ-carrageenan-MDDE10 as wall materials form spherical shapes with only a few cracks or fissures, which is an advantage because it implies that the microencapsulate powders have lower permeability to gases, increasing the protection of the sesame oil. The multilayer emulsion (WPC-κ-carrageenan-MDDE10) resulted in microspheres with smooth and rough surfaces. These results corroborate that structurally strong microencapsulate powders are obtained with good stability emulsion, prevented droplet aggregation and coalescence (Danviriyakul *et al.*, 2002; Rodea-Gonzalez *et al.*, 2012). The diameter of the encapsulated powder was around 30-50 µm (Figure 1). Matalanis *et al.* (2011) reported that diameters of particles within the spray-dried powder are usually in the 10-100 µm range (Matalanis *et al.*, 2011). Therefore, it can be concluded that the particle size and formation of the powders not only depends on the composition of wall materials and drying parameters, but also on the emulsification method used to prepare and the emulsion size (Jafari *et al.*, 2008).

Stability of reconstituted encapsulated sesame oil powders after storage

In this section, we studied stability of the reconstituted encapsulated emulsion after 30 days of storage (at ambient temperature (26.8±1.1°C), cold storage (2.7±1.6°C) and frozen storage (-18.0±2.0°C). The encapsulated sesame oil powders

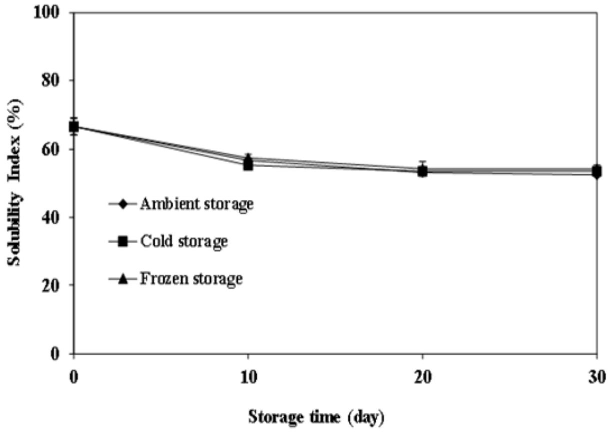

Figure 2. Solubility index of encapsulated sesame oil powder during storage at various temperatures.

were dissolved in a phosphate buffer (pH 7) to reconstitute encapsulated sesame oil emulsions and solubility index (SI). Mean particle size, particle size distribution and ζ-potential of droplets were measured. SI of initial emulsion (before spray drying) decreased for all samples. After 30 days of storage, the SI of the reconstituted emulsions also decreased from 66.58% (0 day) to 52.33% at ambient temperature, 53.45% with cold storage and 54.08% with frozen storage when storage time increased up to 30-day-old samples (Figure 2). These results suggest that the emulsion structure changed which was attributed to bridging aggregation and coalescence during spray drying and storage. The droplets may decrease in surface area which was attributed to a decrease in the surrounding water phase. Similar behavior in SI of the reconstituted encapsulated emulsions was observed at all samples after 30 days at all storage (at ambient temperature, cold storage and frozen storage). This result indicated that different storages have none or only a small influence on SI of the reconstituted emulsions.

Previous work investigated the influence of MD and environmental on stability of sesame oil-in-water emulsions containing droplets stabilized by WPC-κ-carrageenan (Onsaard *et al.,* 2014). In this work, it was found that the mean droplet diameter of 2° emulsions (15%wt sesame oil, 0.5%wt WPC, 0.2% κ-carrageenan and 0.02% sodium azide) containing different MD contents (15 and 30%) and DE (10 and 15) before spray drying were multimodal, which was mixture of small and large particles (225-289 nm) (Onsaard *et al.,* 2014). The particle size distribution and mean particle diameter of powder produced after spray drying and storage at various times are shown in Figure 3 and 4A. During 0-30 day of storage and reconstitution, the particle size distribution of the emulsions was either bimodal or

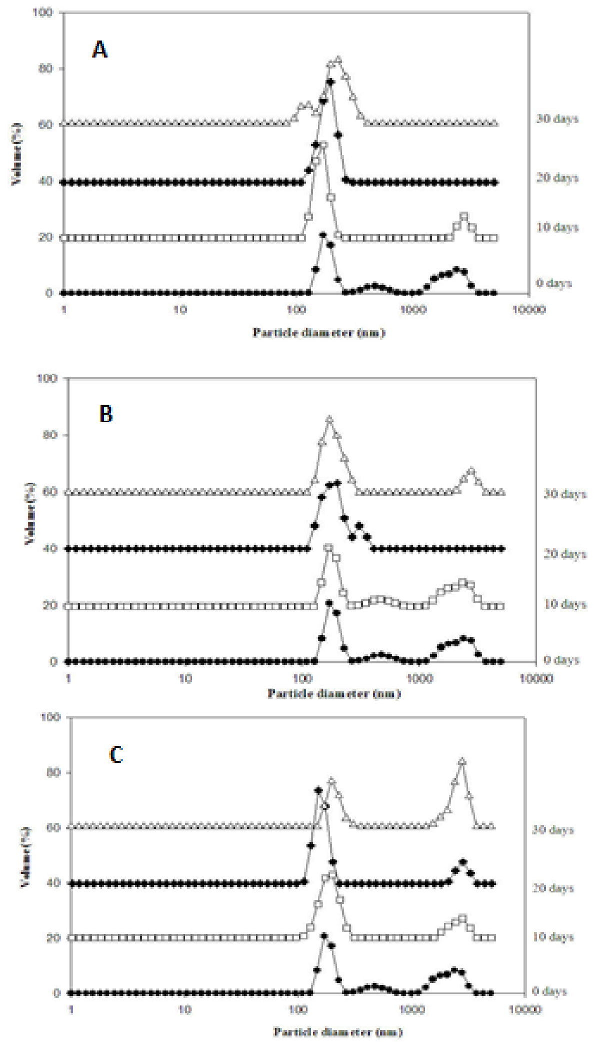

Figure 3. Particle size distribution of reconstituted spray-dried sesame oil powders during storage at (A) ambient temperature (27.0 ± 1.1°C) (B) chilled temperature (2.8 ± 1.6°C) and (C) frozen temperature (-18 ± 2°C).

multimodal during storage at various temperatures (Figure 3A-3C). A slight increase in mean particle diameter was observed when storage time increased up to 30 days of storage (Figure 4A). The mean particle diameter of the reconstituted emulsion slightly increased from 570 nm (0 day) to 601 nm of ambient storage, 638 nm of cold storage and 651 nm of frozen storage after 30 days of storage. From the results, the reconstituted emulsions had larger particles than the fresh emulsions. It was observed that droplet sizes increased during storage, indicating possible occurrence of aggregation and coalescence. Many studies have reported that emulsion droplets may coalesce during the intense shearing in the atomization device of spray drying, resulting in increased emulsion droplets and broader droplet size distribution (Keogh and O'Kennedy, 1999; Klinkesorn *et al*., 2005a; Aberkane *et al*., 2014).

Figure 4B shows ζ-potential of the reconstituted emulsion from spray-dried sesame oil powders during

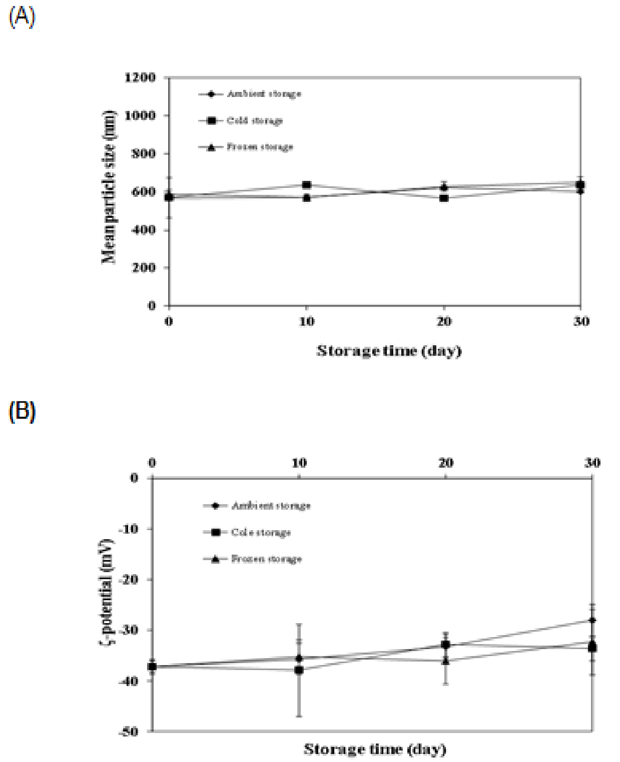

Figure 4. Mean particle size and ζ-potential of reconstituted spray-dried sesame oil powders during storage at various temperatures; (A) Mean particle size (B) ζ-potential.

storage at various temperatures. The ζ-potential of the reconstituted powders decreased with increasing storage time. We found that the ζ-potential of the reconstituted emulsion decreased from -37 mV at day 0 to -28 mV after ambient storage for 30 days, -33 mV after 30 days cold storage and -32 mV after 30 days frozen storage. This result may undergo aggregation via interaction during increase storage time, thereby decreasing in ζ-potential. These results are similar to those reported by Takeungwongtrakul *et al.* (2014), who found that the ζ-potential of shrimp oil droplets decrease during extended storage (Takeungwongtrakul *et al*., 2014). In general, the aggregation kinetics depends on the mechanism responsible for particle-particle encounters, the hydrodynamic and colloidal interactions acting between the droplets and the susceptibility of the thin film separating the particles to rupture (McClements, 2005).

Oxidative stability of microencapsulated sesame oil powders during storage

To monitor lipid oxidation during storage at various temperatures, the oxidative stability of microencapsulated sesame oil powders was evaluated by measuring the secondary oxidative products using TBARS assay, which is more selective for malondialdehyde (MDA), a short and

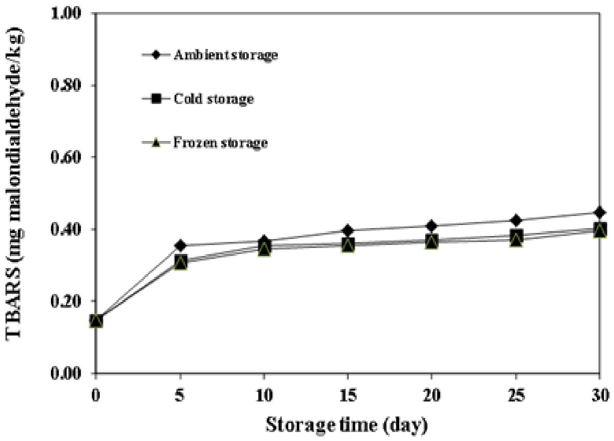

Figure 5. TBARS in spray dried sesame oil powders during storage at various temperatures.

volatile reactive aldehyde produced during advanced peroxidation of highly polyunsaturated fatty acids (Figure 5). Figure 5 shows the change in TBARS value of microencapsulated sesame oil powders during storage at ambient temperature (27.0 ± 1.1°C), cold temperature (2.8 ± 1.6°C) and frozen temperature (-18 ± 2°C) at 30 days. The TBARS value of microencapsulated sesame oil powders was 0.15 mg MDA/kg at 0 day. Sesame oil in this study had low initial TBARS (~0.15 mg MDA/kg) value compared to roasted nuts (pistachios, almonds and peanuts) and sesame seed products (tahini) in other studies (0.65 and 1.8 mg MDA/kg, respectively) (Yaacoub *et al*., 2008). The TBARS value of all powders increased gradually during the whole storage period, meaning that oxidation was taking place during the storage period. No significant difference (p>0.05) in TBARS value was observed during storage at ambient temperature (0.42 mg MDA/kg), cold temperature (0.38 mg MDA/kg) and frozen temperature (0.37mg MDA/kg) for 30 days. These result suggested that the increase in temperature during storage accelerated the oxidation process (Kołakowska and Bartosz, 2013). Although the results showed increase lipid oxidation during storage, this little increase oxidation suggested resistance of sesame oil to oxidation. Oxidation stability of sesame oil could be attributed to the presence of lignans such as sesamolin and sesamin, sesamol and tocopherol (Abou-Gharbia *et al*., 2000; Konsoula and Liakopoulou-Kyriakides, 2010; Lee *et al*., 2010). Furthermore, the microencapsulation has offered protection against oil oxidation during storages.

Conclusion

Sesame oil-in-water emulsions containing anionic droplets stabilized by interfacial membranes comprising whey protein concentrate/k-carrageenan/maltodextrin can be used to produce microencapsulation of sesame oil using spray drying. The addition of whey protein concentrate/k-carrageenan showed high encapsulation yields, low moisture content and water activity and spherical shape. Solubility index and mean particle size of the encapsulated sesame oil powder increased after reconstitution. This result may be due to bridging aggregation and coalescence during spray drying. Although microencapsulated sesame oil powder using spray drying affected solubility index and mean particle size, the powder performed better in protecting the sesame oil against oxidation during storage at different temperature storage. Therefore, the microencapsulated sesame oil powder using spray drying produced a remarkable product for use are in the food, pharmaceutical and cosmetic industries.

Acknowledgements

This research was supported by the Grant-in-Aid from Research Grant for New Scholar (co-funded by the Thailand Research Fund (TRF), the Commission on Higher Education (CHE) and Ubonratchathani University (UBU); MRG5380282) to Dr. Ekasit Onsaard. The authors would like to express their appreciation to Faculties of Agriculture and Pharmaceutical Science, Ubonratchathani University for providing the equipment used in the experiments. We would like to thank Prof. Dr. Michael D. Hare for editing the manuscript.

References

AOAC. 1999. Official Methods of Analysis. 16th ed. Washington DC: Association of Official Analytical Chemists.

Aberkane, L., Roudaut, G. and Saurel, R. 2014. Encapsulation and oxidative stability of PUFA-rich oil microencapsulated by spray drying using pea protein and pectin. Food and Bioprocess Technology 7(5): 1505-1517.

Abou-Gharbia, H. A., Shehata, A. A. Y. and Shahidi, F. 2000. Effect of processing on oxidative stability and lipid classes of sesame oil. Food Research International 33(5): 331-340.

Aghbashlo, M., Mobli, H., Rafiee, S. and Madadlou, A. 2012. Optimization of emulsification procedure for mutual maximizing the encapsulation and exergy efficiencies of fish oil microencapsulation. Powder Technology 225: 107-117.

Alzamora, S. M., Tapia, M. S., L'opez-Malo, A. and Welti-Chanes, J. 2003. The control of water activity. In Zeuthen, P. and Bogh-Sorensen, L. (Eds). Food Preservation Techniques, p. 126-153. New York:

Woodhead Publishing.
Arshady, R. 1993. Microcapsules for food. Journal of Microencapsulation 10(4): 413-435.
Bae, E. K. and Lee, S. J. 2008. Microencapsulation of avocado oil by spray drying using whey protein and maltodextrin. Journal of Microencapsulation 25(8): 549-560.
Ball, G. F. M. 2006. Vitamin in Foods, Analysis, Bioavailability and Stability. New York: CRC Press Taylor and Francis Group.
Carneiro, H. C. F., Tonon, R. V., Grosso, C. R. F. and Hubinger, M. D. 2013. Encapsulation efficiency and oxidative stability of flaxseed oil microencapsulated by spray drying using different combinations of wall materials. Journal of Food Engineering 115(4): 443-451.
Danviriyakul, S., McClements, D. J., Decker, E., Nawar, W. W. and Chinachoti, P. 2002. Physical stability of spray-dried milk fat emulsion as affected by emulsifiers and processing conditions. Journal of Food Science 67(6): 2183-2189.
Dar, A. A. and Arumugam, N. 2013. Lignans of sesame: Purification methods, biological activities and biosynthesis – A review. Bioorganic Chemistry 50: 1-10.
deMan, J. M. 1999. Principles of Food Chemistry. 3rd ed. Maryland: A Chapman Hall Food Science Book.
Deshpande, S. S., Deshpande, U. S. and D.K.Salunkhe. 1996. Sesame oil. In Hui, Y.H. (Ed). Bailey's Industrial Oil and Fat Products. 5 ed., Vol. 2. New York: John Wiley and Sons.
Egan, H., Kirk, R. S. and Sawyer, R. 1981. Pearson's Chemical Analyses of Foods. 8th ed. Edinburgh: Churchill Livingstone.
Esquerdo, V. M., Dotto, G. L. and Pinto, L. A. A. 2015. Preparation of nanoemulsions containing unsaturated fatty acid concentrate-chitosan capsules. Journal of Colloid and Interface Science 445: 137-142.
Estevinho, B. N., Rocha, F., Santos, L. and Alves, A. 2013. Microencapsulation with chitosan by spray drying for industry applications - A review. Trends in Food Science and Technology 31(2): 138-155.
Eunok, C., Jiyeun, L. and David, M. 2005. Chemistry for Oxidative Stability of Edible Oils Healthful Lipids: AOCS Publishing.
Gallardo, G., Guida, L., Martinez, V., López , M. C., Bernhardt, D., Blasco, R. and Hermida, L. G. 2013. Microencapsulation of linseed oil by spray drying for functional food application. Food Research International 52(2): 473-482.
Gu, Y. S., Decker, E. A. and McClements, D. J. 2004. Influence of pH and ι-carrageenan concentration on physicochemical properties and stability of β-Lactoglobulin-stabilized oil-in-water emulsions. Journal of Agricultural and Food Chemistry 52(11): 3626-3632.
Gu, Y. S., Decker, E. A. and McClements, D. J. 2005. Influence of pH and carrageenan type on properties of i-lactoglobulin stabilized oil-in-water emulsions. Food Hydrocolloids 19(1): 83-91.
Hwang, L. S. 2005. Sesame Oil. Bailey's Industrial Oil and Fat Products: John Wiley and Sons, Inc.
Jafari, S. M., Assadpoor, E., Bhandari, B. and He, Y. 2008. Nano-particle encapsulation of fish oil by spray drying. Food Research International 41(2): 172-183.
Kagami, Y., Sugimura, S., Fujishima, N., Matsuda, K., Kometani, T. and Matsumura, Y. 2003. Oxidative stability, structure and physical characteristics of microcapsules formed by spray drying of fish oil with protein and dextrin wall materials. Journal of Food Science 68(7): 2248-2255.
Kamal-Eldin, A. and Pokorn´y, J. 2005. Lipid Oxidation Products and Methods Used for Their Analysis. In Kamal-Eldin, A. and Pokorn´y, J. (Eds). Analysis of Lipid Oxidation. Illinois: AOCS Press.
Kaushik, P., Dowling, K., Barrow, C. J. and Adhikari, B. 2014. Microencapsulation of omega-3 fatty acids: A review of microencapsulation and characterization methods. Journal of Functional Foods 19: 868–881.
Keogh, M. K. and O'Kennedy, B. T. 1999. Milk fat microencapsulation using whey proteins. International Dairy Journal 9(9): 657-663.
Klinkesorn, U., Sophanodora, P., Chinachoti, P., Decker, E. A. and McClements, D. J. 2006. Characterization of spray-dried tuna oil emulsified in two-layered interfacial membranes prepared using electrostatic layer-by-layer deposition. Food Research International 39(4): 449-457.
Klinkesorn, U., Sophanodora, P., Chinachoti, P., McClements, D. J. and Decker, E. A. 2005a. Increasing the oxidative stability of liquid and dried tuna oil-in-water emulsions with electrostatic layer-by-layer deposition technology. Journal of Agricultural and Food Chemistry 53(11): 4561-4566.
Klinkesorn, U., Sophanodora, P., Chinachoti, P., McClements, D. J. and Decker, E. A. 2005b. Stability of spray-dried tuna oil emulsions encapsulated with two-layered interfacial membranes. Journal of Agricultural and Food Chemistry 53(21): 8365-8371.
Kołakowska, A. and Bartosz, G. 2013. Oxidation of Food Components: An Introduction. In Bartosz, G. (Ed). Food Oxidants and Antioxidants: Chemical, Biological and Functional Properties, p. 1-20. New York: CRC Press.
Konsoula, Z. and Liakopoulou-Kyriakides, M. 2010. Effect of endogenous antioxidants of sesame seeds and sesame oil to the thermal stability of edible vegetable oils. LWT - Food Science and Technology 43(9): 1379-1386.
Lee, E. and Choe, E. 2012. Changes in oxidation-derived off-flavor compounds of roasted sesame oil during accelerated storage in the dark. Biocatalysis and Agricultural Biotechnology 1(1): 89-93.
Lee, S. W., Jeung, M. K., Park, M. H., Lee, S. Y. and Lee, J. 2010. Effects of roasting conditions of sesame seeds on the oxidative stability of pressed oil during thermal oxidation. Food Chemistry 118(3): 681-685.
Martínez, M. L., Curti, M. I., Roccia, P., Llabot, J. M., Penci, M. C., Bodoira, R. M. and Ribotta, P. D. 2015. Oxidative stability of walnut (*Juglans regia* L.) and

chia (*Salvia hispanica* L.) oils microencapsulated by spray drying. Powder Technology 270: 271-277.

Matalanis, A., Decker, E. A. and McClements, D. J. 2012. Inhibition of lipid oxidation by encapsulation of emulsion droplets within hydrogel microspheres. Food Chemistry 132(2): 766-772.

Matalanis, A., Jones, O. G. and McClements, D. J. 2011. Structured biopolymer-based delivery systems for encapsulation, protection and release of lipophilic compounds. Food Hydrocolloids 25(8): 1865-1880.

McClements, D. J. 2005. Food Emulsions Principles, Practices and Techniques. New York: CRC Press.

Mondal, N., Bhat, K. V. and Srivastava, P. S. 2010. Variation in fatty acid composition in Indian germplasm of sesame. Journal of the American Oil Chemists' Society 87(11): 1263-1269.

Nawar, W. W. 1997. Biochemical processes Food Storage Stability: CRC Press.

Nesterenko, A., Alric, I., Silvestre, F. and Durrieu, V. 2013. Vegetable proteins in microencapsulation: A review of recent interventions and their effectiveness. Industrial Crops and Products 42:469-479.

Nzikou, J. M., Mvoula-tsiéri, M., Ndangui, C. B., Pambou-Tobi, N. P. G., Kimbonguila, A., Loumouamou, B. and Desobry, S. 2010. Characterization of seeds and oil of sesame (*Sesamum indicum* L.) and the kinetics of degradation of the oil during heating. Research Journal of Applied Sciences, Engineering and Technology 2(3): 227-232.

Onsaard, E., Putthanimon, J., Singthong, J. and Thammarutwasik, P. 2014. Influence of maltodextrin and environmental stresses on stability of whey protein concentrate/k-carrageenan stabilized sesame oil-in-water emulsions. Food Science and Technology International 20(8): 617-628.

Orsavova, J., Misurcova, L., Ambrozova. J.V., Vicha, R. and Mlcek, J. 2015. Fatty acids composition of vegetable oils and its contribution to dietary energy intake and dependence of cardiovascular mortality on dietary intake of fatty acids. International Journal of Molecular Sciences 16: 12871-12890.

Putthanimon, J., Jakchai, P. and Onsaard, E. 2012. Influence of pH and heat treatment on sesame oil emulsion stabilized by whey protein isolate-pectin membranes. Asian Journal Food and Agro-Industry 5(4): 322-330.

Rangkadilok, N., Pholphana, N., Mahidol, C., Wongyai, W., Saengsooksree, K., Nookabkaew, S. and Satayavivad, J. 2010. Variation of sesamin, sesamolin and tocopherols in sesame (*Sesamum indicum* L.) seeds and oil products in Thailand. Food Chemistry 122(3): 724-730.

Rodea-Gonzalez, D. A., Cruz-Olivares, J., Roman-Guerrero, A., Rodriguez-Huezo, M. E., Vernon-Carter, E. J. and Perez-Alonso, C. 2012. Spray-dried encapsulation of chia essential oil (*Salvia hispanica* L.) in whey protein concentrate-polysaccharide matrices. Journal of Food Engineering 111(1): 102-109.

Rodríduez-Huezo, M. E., Pedroza-Islas, R., Prado-Barragán, L. A., Beristain, C. I. and Vernon-Carter, E. J. 2004. Microencapsulation by spray drying of multiple emulsions containing carotenoids. Journal of Food Science 69(7): 351-359.

Takeungwongtrakul, S., Benjakul, S. and H-kittikun, A. 2014. Micro-encapsulation of pacific white shrimp oil as affected by emulsification condition. Food Science and Human Wellness 3(3-4): 175-182.

Tonon, R. V., Grosso, C. R. F. and Hubinger, M. D. 2011. Influence of emulsion composition and inlet air temperature on the microencapsulation of flaxseed oil by spray drying. Food Research International 44(1): 282-289.

Wu, Y., Zou, L., Mao, J., Huang, J. and Liu, S. 2014. Stability and encapsulation efficiency of sulforaphane microencapsulated by spray drying. Carbohydrate Polymers 102: 497-503.

Yaacoub, R., Saliba, R., Nsouli, B., Khalaf, G. and Birlouez-Aragon, I. 2008. Formation of lipid oxidation and isomerization products during processing of nuts and sesame seeds. Journal of Agricultural and Food Chemistry 56(16): 7082-7090.