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A review on microencapsulation of Sacha inchi oil, flaxseed oil, chia seed oil and palm oil

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Sacha inchi oil contains about 82 percent of polyunsaturated fatty acids (PUFA) making this oil very vulnerable to oxidation. Therefore, microencapsulation could be used as a technique to improve the oxidative stability of this oil. Microencapsulation is a process of building a functional barrier between the core and wall material to maintain the functional and physicochemical properties of the core materials. Microencapsulation enhances the oxidative stability, thermostability and shelf-life of oils. Emulsification, spray drying and freeze drying techniques are frequently used in microencapsulation of oils. Maltodextrin, modified starch and sodium caseinate are the common wall materials used in microencapsulation of oils. The choice of an appropriate microencapsulation technique and wall material depends upon the end use of the product and the processing conditions involved. Most studies reported that the microencapsulated oils are usually produced in powder form. General analyses conducted to determine the quality and stability of microencapsulated oils are moisture content, water activity, particle size, surface oil, encapsulation efficiency, viscosity, peroxide value, oxidative stability and microcapsule morphology. In addition, microencapsulated vegetable oils have been applied in food formulations such as butter and soup. This review presents information on the chemical composition of vegetable oils including Sacha inchi, flaxseed, chia seed and palm oil. This review also described the common wall materials used in oil microencapsulation, microencapsulation techniques, common analysis of microencapsulated oils in order to determine its quality and the application of microencapsulated oils in the food industry.

Keywords: Sacha inchi, microencapsulation, core material, wall material

INTRODUCTION

Sacha inchi (*Plukenetia volubilis* L.) is a natural oil from the Amazonian region of Peru from a plant of the family Euphorbiaceae, which is also known as the Inca peanut. Its seed has high polyunsaturated fatty acids (PUFA) which were linolenic (omega-3) and linoleic acid (omega-6) and vitamin E (Chirinos et al. 2013). Besides that, other fatty acids such as oleic, palmitic and stearic were also present (Hamaker et al. 1992). In addition, the PUFA such as omega-3, are very important to the nutraceutical industry because they are associated with a number of health benefits such as preventing fatal cardiovascular disease, coronary heart disease, diabetes, hypertension and others (Poole et al. 2013; Chirinos et al. 2013). PUFA also able to heal wounds and improve immune function (Harbige et al. 2000). Apart from Sacha inchi, there are also other oils that have high PUFA content such as flaxseed and chia seed oil at 63.96% and 83% respectively (Mohd Ali et al. 2012; Bozan and Temelli, 2008). Palm oil also has an appreciable amount of PUFA which is 10.10% (Bonnie and Choo, 1999).

However, some of the major drawbacks of oils containing a high amount of PUFA are chemically unstable, susceptible to oxidative deterioration and loss of volatile compounds, especially when exposed to oxygen, light, moisture and heat. The quality of a product fortified with the oils may deteriorate due to oxidative degradation, formation of unpleasant tastes and off-flavors and the generation of free radicals. These changes have a negative effect on the shelf-stability, sensory properties and overall acceptability of the developed products (Velasco et al. 2003). Therefore, the use of microencapsulation technologies to retard the oxidation of these oils has drawn considerable attention (Sanguansri and Augustin, 2007). Microencapsulation is a method in which tiny particles or droplets are surrounded by a coating wall, or are embedded in a homogeneous or heterogeneous matrix to form small capsules (Calvo et al. 2011; Gharsallaoui et al. 2007). The obtained powders from microencapsulation process are characterised by presenting low water activity, easy handling and storage as well as they can be readily incorporated into foods (Helena et al. 2013). Comunian and Favaro-Trindade (2016) studied about microencapsulation of omega-3 fatty acids being incorporated into many food products such as chocolate, powdered drink mixes, instant coffees and teas. The foods fortified with microencapsulated omega-3 had an increase in the bioavailability of omega-3 fatty acids and shelf life.

This review summarises the chemical composition of Sacha inchi oil, flaxseed oil, chia seed oil and palm oil. Other than that, the common wall materials used in oil microencapsulation, microencapsulation techniques for oil microencapsulation, common analyses of microencapsulated oils in order to determine its quality and the application of microencapsulated oils in food industry are also reviewed.

Chemical composition of sacha inchi oil, flaxseed oil, chia seed oil and palm oil

Table 1 shows the chemical composition of Sacha inchi oil, flaxseed oil, chia seed oil and palm oil. Sacha inchi oil has high content of linolenic acid (omega-3), approximately 48.20% (Vicente et al. 2017; Chirinos et al. 2013). Besides, it also contains linoleic acid (omega-6) (34.10%), oleic acid (omega-9) (8.90%), palmitic acid (4.70%) and stearic acid (3.30%) (Cisneros et al. 2014; Follegatti-Romero et al. 2009; Guillen et al. 2003). Omega-3 and omega-6 are essential fatty acids which helps to prevent various diseases including arthritis, cancer, coronary heart disease, diabetes, hypertension, attention deficit hyperactivity disorder and inflammatory skin diseases (Zanqui et al. 2016). Sacha inchi oil has approximately twice the amount of omega-6 fatty acids than flaxseed oil (Maurer et al. 2012; Guillen et al. 2003). Omega-6 is a precursor of arachidonic acid that leads to the production of essential compound such as prostaglandins and leukotriens, which is crucial for the immune function and platelet aggregation (Gomez Candela et al. 2011).

For tocopherol composition, γ-tocopherol is the most abundant tocopherol in Sacha inchi oil which is 149 mg/100 g (Follegatti-Romero et al. 2009). β-Sitosterol (127.40 mg/100 g) is the dominant phytosterol in the oil, followed by stigmasterol (58.70 mg/100 g) and campesterol (15.30 mg/100 g) (Chirinos et al. 2013). These results are in agreement to those reported by Bondioli et al. (2006) for Sacha inchi oil where β-sitosterol was the most important phytosterol followed by stigmasterol and campesterol, representing 92% of total phytosterols. The same phytosterols have been reported as the most important in flaxseed and chia seed oils (Ciftci et al. 2012).

Evrim (2017) reported that flaxseed oil is a good source of omega-3 PUFA which contains 58.28% linolenic acid, followed by monounsaturated oleic acid (17.60%) and linoleic acid (14.86%). The major tocopherol was ɣ-tocopherol which is 33.90 mg/100 g while the major phytosterol was β-sitosterol (155.91 mg/100 g) (Matthaus and Ozcan, 2017). Tocopherol acts as an essential nutrient functioning as a chain-breaking antioxidant that protects cell membranes against oxidative damage (Bozan and Temelli, 2008). Meanwhile, phytosterols have been reported to be effective in lowering plasma cholesterol levels (Nagendran et al. 2000) and reduce the risk of certain types of cancer (Lagarda et al. 2006).

Chia seed oil contains about 59.76% linolenic acid and 18.89% linoleic acid (Masa et al. 2020; Diana et al. 2019). Both of these are polyunsaturated essential fatty acids (PUFA) which are not synthesised in the organism and helps in maintaining healthy serum lipid level (Mohd Ali et al. 2012). Chia seed oil is characterised as a good source of valuable bioactive components such as tocopherols, phytosterols, carotenoids and polyphenols (Grzegorz et al. 2018).

Palm oil contains 44.00% palmitic acid and 10.10% of omega-6 PUFAs (Bonnie and Choo, 1999). In addition, Mukherjee and Mitra (2009) stated that palm oil is one of the richest sources of vitamin E (tocotrienols 70% and tocopherols 30%). Tocotrienols and tocopherols have free radical scavenging properties which will protect biological systems against oxidative and carcinogenic stress (Diplock, 1994). It also contains carotenoids such as *α*-carotene and *β*-carotene ranges from 80% to 90% (Benade, 2013), phospholipids, ubiquinones, sterols and squalene (Choo et al. 2005). Carotenoids act as biological antioxidants protecting cells and tissues from the damaging effects of free radicals and singlet oxygen (Zeb and Mehmood, 2004).

Thus, due to high content of PUFA and valuable bioactive components like tocopherols and phytosterols, microencapsulation technology should be applied to these oils in order to retain their chemical composition that gives many health benefits for human consumption.

Table 1: Chemical composition of Sacha inchi oil, flaxseed oil, chia seed oil and palm oil.

Composition	Sacha inchi oil	Flaxseed oil	Chia seed oil	Palm oil
Fatty acids (%)				
Palmitic acid (C16:0)	4.70	4.67	7.04	44.00
Stearic acid (C18:0)	3.30	3.61	3.24	4.50
Oleic acid (C18:1, ω9)	8.90	17.60	7.30	39.20
Linoleic acid (C18:2, ω6)	34.10	14.86	18.89	10.10
Linolenic acid (C18:3, ω3)	48.20	58.28	59.76	0.40
Tocopherols (mg/100 g)				
α-Tocopherol	0.08	0.80	2.58	22.40
ß-Tocopherol	0.02	NA	NA	NA
γ-Tocopherol	149.0	33.90	54.10	NA
δ-Tocopherol	84.00	0.40	1.48	NA
Phytosterols (mg/100 g)				
Campesterol	15.30	78.64	81.30	6.30
Stigmasterol	58.70	34.31	33.10	6.30
β-Sitosterol	127.40	155.91	416.40	18.90

Masa et al. 2020; Diana et al. 2019; Vicente et al. 2017; Matthaus and Ozcan, 2017; Evrim et al. 2017; Cisneros et al. 2014; Chirinos et al. 2013; Follegatti-Romero et al. 2009; Kalyana et al. 2003; Guillen et al. 2003; Bonnie and Choo, 1999

NA-not available

Wall material for oil encapsulation

The selection of suitable wall materials in microencapsulation process is important because it influences their stability, encapsulation efficiency and the degree of protection. The ideal wall materials should be food grade, cheap, low viscosity at high solid contents and excellent emulsifying properties. Furthermore, it also should be stable, can hold the core material in its structure without any reactivity during processing or storage and can lead a controllable release of the core material when incorporated into a food product (Nedovic et al. 2013).

In addition, the wall materials should be chemically compatible with the core material and able to protect the active material from the environment adverse conditions (light, pH, oxygen, heat and other compounds present). It also should be flexible, impermeable and easily handled (Xiao et al. 2014; Nigam et al. 2011; Singh et al. 2010; Bansode et al. 2010; Dubey et al. 2009; Madene et al. 2006;).

A number of carbohydrates have been studied as wall materials, such as maltodextrin, gum arabic, pectin and sodium alginate. The major advantages of these carbohydrates are their excellent water solubility and low viscosity at high concentrations (Nesterenko et al. 2013). However, poor emulsifying properties greatly limit their application to encapsulate hydrophobic core materials. Therefore, carbohydrates are generally combined with proteins which offer good emulsifying properties (Chang and Nickerson, 2018).

Gum arabic is one of the most traditional wall materials used in the microencapsulation of oils due to its good emulsifying properties, high solubility and low viscosity in aqueous solutions. According to Madene et al. (2006), it fulfils the roles of both surface-active agent and drying matrix. However, it is high in cost, has limited availability and the presence of some impurities suggested the use of other types of wall materials as alternatives to replace gum arabic (Jafari et al. 2008).

Maltodextrins are produced from starch hydrolysis with values of dextrose equivalent (DE) below 20. The degree of hydrolytic conversion of starch, expressed as DE value, is the criterion for the classification and characterisation of hydrolysates (Dokic et al. 2004; Chronakis, 1998). Maltodextrin has been widely used in the microencapsulation of bioactive compounds due to its satisfactory performance, low relative cost as well as neutral taste and aroma. It is characterised by high solubility in water, low viscosity at high concentrations, film forming capacity and good protection against the oxidation of core materials (Kang et al. 2019; Zhou et al. 2017; Costa et al. 2015).

Whey proteins have been widely used in the encapsulation of oils and are considered successful agents that provide an effective barrier against lipid oxidation. Some n-octenylsuccinate anhydride (n-OSA) starches have also been successfully used as wall materials. The introduction of some side chains of lipophilic succinic acid results in modified starches with good emulsifying properties, which promote good volatiles retention and higher encapsulation efficiency (Charve and Reineccius, 2009; Partanen et al. 2008; Bae and Lee 2008; Drusch et al. 2006).

According to Jafari et al. (2008), the main factors that affect the encapsulation efficiency of microencapsulated oils are the type of wall material, core material properties (concentration, volatility), emulsion characteristics (viscosity, droplets size) and spray drying conditions (atomisation type, inlet air temperature, air flow). Another important factor in the microencapsulation of oils is the stability of the emulsions from which particles are produced, which is related to some emulsion properties such as droplets size and viscosity. In general, the greater the emulsion stability, the greater the encapsulation efficiency (Barbosa et al. 2005; Minemoto et al. 2002). Some studies have also demonstrated that the reduction in size of the emulsion droplets results in greater volatile retention and lower surface oil. This can be achieved by using high-pressure homogenisation, increasing the emulsion viscosity or decreasing the oil load (Soottitantawat et al. 2005; Liu et al. 2001).

A number of wall materials have been used for microencapsulation of vegetable oils. From Table 2, some wall materials give good microencapsulation efficiency (MEE) such as modified starch, maltodextrin and sodium caseinate. Zain and Luis-Felipe (2017) studied about microencapsulation of Sacha inchi oil using modified starch Hi-cap 100 and maltodextrin as wall materials. The highest MEE obtained in the study was 96.30%. The MEE is a process parameter usually used for determining the protecting degree of the microencapsulated oil. Some authors have mentioned that values of MEE for microencapsulated oils around 90% are adequate (Gallardo et al. 2013). MEE obtained from the study about microencapsulation of Sacha inchi oil by Zain and Luis-Felipe (2017) varied between 81.80 and 96.30%. Moreover, Zain and Luis-Felipe (2017) also found that both wall material solids and oil loading significantly affected ($p < 0.05$) the MEE of Sacha inchi oil. The highest MEE was obtained when processing emulsions containing 30% wall material solids loaded with 10% Sacha inchi oil, while the lowest MEE was obtained when processing emulsions containing 20 and 30% wall material solids loaded with 30% Sacha inchi oil. Polavarapu et al. (2011) studied about the microencapsulation of fish oil using sugar beet pectin which has MEE of 97.85% and also reported that emulsions formulated with high oil loadings will lead to insufficient amount of the continuous matrix needed to form a dense matrix around the dispersed oil droplets. The MEE results obtained in this study were similar to those reported by Silva et al. (2014) and Helena et al. (2013), who reached MEE of 86.70 and 95.70%, respectively, when microencapsulating green coffee and flaxseed oils using Hi Cap-100/maltodextrin in a mass ratio of 75:25.

Nancy et al. (2019) also studied the microencapsulation of Sacha inchi oil using modified starch Capsul TA as wall materials. It was found that the encapsulated oil had lower surface oil and consequently a higher MEE which was 96.50%. Other than that, according to Helena et al. (2013), the MEE of flaxseed oil was the highest (95.70%) when using combination of modified starch Hi-Cap and maltodextrin as wall materials. Renata et al. (2012) found that flaxseed oil microencapsulated with modified starch Hi-cap gave the highest MEE which was 97%. MEE of flaxseed oil varied from 37% to 97% and was significantly influenced by the type of wall material and the oil concentration. The emulsions prepared with modified starch resulted in the highest MEE, indicating that Hi-Cap 100 is an excellent encapsulating agent. Hi-Cap 100 is the chemically modified octenyl succinic anhydride (OSA) starch derived from waxy maize (Noello et al. 2016). This excellent performance is related to the good stability shown by the emulsions prepared with this wall material, which may have protected the emulsion droplets from disintegration and disruption during the atomisation process. Moreover, starches are known for their great film-forming capacity, which can positively influence the microencapsulation process avoiding oil migration to the particles surface (Renata et al. 2012).

Other than that, chia seed oil encapsulated with sodium caseinate and lactose exhibited the highest MEE of 95.20% (Ulil et al. 2018). The emulsification properties of sodium caseinate seem to offer the functional and physical characteristics necessary to encapsulate the oils (Hogan et al. 2001). Additionally, the positive effect of lactose could be related to the formation of a continuous glass phase of lactose whereby the dispersion of protein chains occurs, resulting in high MEE values (Ixtaina et al. 2015).

Table 2: Wall materials used for microencapsulation of Sacha inchi oil, flaxseed oil, chia seed oil and palm oil.

Oil	Wall material	Microencapsulation efficiency (MEE %)	References
Sacha inchi oil	Modified starch Hi-cap 100, maltodextrin	96.30	Zain and Luis-Felipe, 2017
Sacha inchi oil	Modified starch Capsul TA	96.50	Nancy et al. 2019
Flaxseed oil	Modified starch Hi-cap 100, maltodextrin	95.70	Helena et al. 2013
Flaxseed oil	Modified starch Hi-cap 100	97.00	Renata et al. 2012
Chia seed oil	Sodium caseinate, lactose	95.20	Ulil et al. 2018
Chia seed oil	Sodium caseinate, lactose	83.90	Claudia et al. 2017
Palm oil	Chitosan, xanthan gum	62.41	Rutz et al. 2017

Microencapsulation techniques of oils

Microencapsulation of vegetable oils has been conducted by employing different methods including emulsification, spray drying, coaxial electrospray system, freeze drying, coacervation, *in situ* polymerisation, melt-extrusion, supercritical fluid technology and fluidized-bed coating (Wang et al. 2014; Tatar et al. 2014; Sutaphanit and Chitprasert, 2014; Botrel et al. 2014; Soliman et al. 2013). Table 3 shows the common microencapsulation techniques of vegetable oils. Spray drying and freeze drying are the commonly used technique to encapsulate Sacha inchi oil, flaxseed oil, chia seed oil, olive oil and walnut oil. Encapsulated oil prepared with spray drying tends to have higher MEE than encapsulated oil prepared with other techniques (Nancy et al. 2019; Zain and Luis-Felipe, 2017; Vicente et al. 2017; Claudia et al. 2017; Noello et al. 2016; Tontul and Topuz, 2013; Calvo et al. 2012; Calvo et al. 2011).

Emulsification

Emulsification is a key step in the microencapsulation of oils. It is generally applied for the encapsulation of bioactives in aqueous solutions, which can either be used directly in the liquid state or can be dried to form powders after emulsification. An emulsion consists at least two immiscible liquids usually oil and water, whereby one of the liquids being dispersed as small spherical droplets in the other. A system that consists of oil dispersed in an aqueous phase is called an oil-in-water (O/W) emulsion, while a system that consists of water droplets dispersed in an oil phase is called a water-in-oil (W/O) emulsion. Emulsifiers are usually added in the emulsion system to obtain a stable solution. The diameters of the emulsion droplets in food systems range from 0.1 to 100 μm (Fang and Bhandari, 2010).

The emulsions are prepared by homogenising oil, water and emulsifier together using a mechanical device known as homogeniser. There were several types of homogeniser such as high shear mixer, high-pressure homogeniser, colloid mill, sonicator or membrane homogeniser. The O/W emulsion consists of small oil droplets dispersed in an aqueous medium, with the oil droplets being surrounded by a thin interfacial layer consisting of emulsifier molecules. The advantages of this microencapsulation technique are simple operation and low cost. However, it have the drawbacks of physical instability when exposed to heating, chilling, freezing, drying, pH extremes and high mineral concentrations and have limited controlled release (McClements et al. 2009).

Spray drying

Spray drying is a common technique used in microencapsulation technology. The advantages of this technique are producing microcapsules in a relatively simple, continuous operation, rapid and reproducible and allowing easy scale-up compared to other techniques (Schafroth et al. 2012; Pu et al. 2011). This technique has been successfully used for several decades to encapsulate various oils in the food industry. Recently, several studies have been done to encapsulate the oils by spray drying technique (Tatar et al. 2014; Shen and Quek, 2014; Liu et al. 2014; Kha et al. 2014; Fernandes et al. 2014; Domian et al. 2014).

Spray drying equipment is readily available and production costs are lower than other methods. The cost of spray drying is 30 to 50 times lower compared to freeze drying. Spray drying has been considered as a solution for conventional drying problems because the process is efficient and economical. The process is flexible, thereby offering substantial variation in the encapsulant matrix and produce good quality particles (Amr et al. 2016).

Spray drying involves the atomisation of emulsions into a drying chamber at a relatively high temperature. This will lead to very fast water evaporation. Therefore, the crust was formed at fast rate and causing quasi-instantaneous entrapment of oils (Renata et al. 2011). Water removal by spray drying is the most widely used practice in the food industry to ensure the microbiological stability of products. Furthermore, it helps to obtain a product with specific functional properties, avoid the risks of chemical or biological degradation and reduce the total storage and transport costs (Turchiuli et al. 2014; Gharsallaoui et al. 2007). The microencapsulation by spray drying involves 4 stages which are (i) preparation of the dispersion, (ii) homogenisation of the dispersion, (iii) atomisation of the emulsion and (iv) dehydration of the atomised particles. In the first stage, the wall materials were dissolved in distilled water. The solutions are kept overnight at room or refrigerator temperature to ensure full saturation of the polymer molecules and to avoid any changes due to temperature. The core material is added to the solutions with or without the addition of an emulsifier, depending on the emulsifying properties of the wall materials and the solutions are homogenised. In the spray drying process, the initial emulsion droplets are in the range of 0.1 to 100 μm in diameter. The formed emulsion must be stable over a certain period of time before the spray drying step (Liu et al. 2001). Besides, the viscosity of emulsion should be lower to prevent air inclusion in the particle and oil droplets should be smaller (Drusch, 2007). It was observed that emulsion droplet size has a significant effect on the encapsulation efficiency of oils during spray drying (Soottitantawat et al. 2003). Small oil droplets get enclosed more efficiently within the wall matrix of the microcapsules. Hence, the methods that produce small emulsion droplets encapsulate higher amounts of oil and allow less oil exposed to the microcapsule surface. Based on this theory, Jafari et al. (2007) used a microfluidiser to reduce the emulsion droplet size, thus obtained higher encapsulation efficiency and lower surface oil.

Spray drying also requires well-adjusted operating conditions, as well as the correct composition of the solution that contains the active principles (Soliman et al. 2013; Gallo et al. 2011). In order to obtain high microencapsulation efficiency, optimal spray drying conditions must be used. The feed temperature, air inlet temperature and air outlet temperature are the main factors in spray drying that must be optimised (Liu et al. 2004). When the feed temperature is increased, viscosity and droplets size should be decreased. The high temperature used in spray drying might cause volatility or deterioration of some heat-sensitive components (Zbicinski et al. 2002). Air inlet and outlet temperatures should be controlled during spray drying because inlet temperature affects the efficiency of water evaporation which will determine the quality of microcapsules, whereas outlet temperature impacts the denaturation of wall materials of microcapsules (Kha et al. 2014).

Fang et al. (2005) reported the drawback of this technique which is the use of air as the drying medium at very high temperature produces particles with a porous structure. Hence, the spray dried powder particles can readily undergo oxidation which will decrease their shelf-life. Besides, spray drying technique was limited by the available number of wall materials with good water solubility (Gharsallaoui et al. 2007).

Freeze drying

Freeze drying is a simple process and is used for the dehydration of almost all heat-sensitive materials and aromas like oils. Before drying, the oil is dissolved in water and frozen between −90 °C and −40 °C (Heinzelmann et al. 2000). Then the surrounding pressure is reduced and enough heat is added to allow the frozen water in the material to sublimate directly from the solid phase to the gas phase (Oetjen and Haseley, 2004). Freeze-dried materials seem to have the maximum retention of volatile compounds in comparison to that of spray drying (Krokida and Philippopoulos, 2006). This technique has been used successfully for microencapsulating some oils such as flaxseed, walnut and olive oil. Highest encapsulation yields (99.79 ± 0.51%) were achieved for olive oil when maltodextrin, carboxylmethylcellulose and lecithin were used as encapsulants (Karaca et al. 2013; Calvo et al. 2012; Heinzelmann et al. 2000). The major disadvantages are high energy use, long processing time and high production costs compared to other drying methods (Desobry et al.

Table 3: Common microencapsulation techniques of vegetable oils

Oil	Microencapsulation technique	Microencapsulation efficiency (MEE %)	References
Sacha inchi oil	Spray drying	96.30	Zain and Luis-Felipe, 2017
Sacha inchi oil	Spray drying	96.50	Nancy et al. 2019
Sacha inchi oil	Freeze drying	96.60	Vicente et al. 2017
Flaxseed oil	Spray drying	88.00	Karaca et al. 2013
Flaxseed oil	Spray drying	91.00	Tontul and Topuz, 2013
Flaxseed oil	Spray drying	90.00	Gallardo et al. 2013
Chia seed oil	Spray drying	99.95	Noello et al. 2016
Chia seed oil	Spray drying	96.23	Ulil et al. 2018
Chia seed oil	Freeze drying	83.90	Claudia et al. 2017
Palm oil	Complex coacervation	62.41	Rutz et al. 2017
Olive oil	Freeze drying	99.79	Calvo et al. 2012
Walnut oil	Freeze drying	69.09	Calvo et al. 2011
Wheat germ oil	Emulsification	88.00	Chan et al. 2000

1997). Freeze-dried products may have higher porosity, thereby exposing the core material to the surrounding environment (Sinha et al. 2007). Claudia et al. (2017) reported that MEE of encapsulated chia seed oil by freeze drying was 83.9% which was lower than encapsulated chia seed oil by spray drying (MEE 95%) as reported by Ixtaina et al. (2015). A lower MEE of freeze drying process in comparison with spray drying was also found by Chen et al. (2013), who reported that this phenomenon could be due to the dehydration of emulsifiers during the freezing of water phase, which promotes particle-particle interactions in emulsion and reduces the emulsion stability. Thus, the encapsulated materials could be released from the core when ice crystals are removed during the drying stage.

Common analysis for emulsion and powder form of microencapsulated oil

Microencapsulated oils are usually produced in emulsion form and powder form. There are few analyses that should be done to determine the quality and stability of these products. The analysis for emulsion and powder form of encapsulated oils is shown in Table 4. The analyses for emulsion form microencapsulated oil are viscosity measurement, emulsion stability and emulsion droplet size determination. Emulsion viscosity was measured at 25 ºC through the determination of steady shear flow curves while the emulsion stability was measured by the percentage of phase separation (Renata et al. 2012). The emulsion droplet size distributions were determined using a laser light diffraction instrument. The droplet mean diameter was expressed as the Sauter mean diameter and volume mean diameter (D_{32} and D_{43}, respectively) (Wan Mohamad et al. 2017; Jafari et al. 2007).

Emulsion properties (emulsion stability, droplet size and viscosity) greatly affect the properties of microcapsule produced. Emulsions should be stable over a certain period before the drying process. Therefore, smaller droplets are necessary to prevent destabilization and air inclusion in the particles, because they are more efficiently enclosed and embedded within wall matrix of microcapsules (Drusch, 2007). Emulsion stability was determined by droplet size whereby the rate of gravitational separation was lowered by the decrease of droplet size and increase of droplet concentration to hinder the movement of surrounding droplets (McClements et al. 2007). Emulsion stability was enhanced by the increase in protein concentration, since the thicker interfacial protein films at the droplet surface exhibit better ability against coalescence during storage that will results in better stability (Hogan et al. 2001). Emulsion viscosity is an important parameter to control in microencapsulation process because it can impact the stability and flow behavior of emulsions during the drying process. High viscosity of the feed emulsion interferes with the atomization during spray drying, lead to the formation of elongated particle and cause air inclusion in the particles (Rosenberg et al. 1990). Emulsion viscosity was determined by the viscosity of continuous phase (affected by the biopolymer concentration), droplet size and droplet concentration. Emulsion viscosity will increase when there is an increase in biopolymer concentration and droplet concentration (McClements, 2005).

Meanwhile, powder form microencapsulated oil can be analysed using physical, chemical or physicochemical analyses including determination of encapsulation efficiency, surface oil and payload, particle size, microcapsule morphology, oxidative stability and sensory performance. Encapsulation efficiency is the ratio of mass of core material which is encapsulated in the wall material to the mass of core material used in the formulation. Besides, measurement of surface oil is important whereby high surface oil tends to correlate with off-flavour of microcapsules and poor food application stability. Surface oil is defined as non-encapsulated oil on the surface of the dried microcapsules. Therefore, a higher encapsulation efficiency indicates a lower surface oil on the microcapsules (Kaushik et al. 2015). Surface oil ratio is calculated by dividing the surface oil of encapsulated powder with total oil in encapsulated powder (Asmaliza et al. 2017).

In addition, the particle size is an important parameter in the microencapsulation technology. Particle size influences in the desired application of the developed ingredient into the final product, such as controlled release of the active (Vos et al. 1996) and sensory properties (textural attributes) (Lemos et al. 2017). Besides, it is also a parameter contributing to the flowability, compressibility, bulk density and oxidative stability of the microcapsules (Koc et al. 2015). Bulk density was calculated by dividing the mass of powder by the volume occupied in the cylinder after being tapped by hand 50 times (Bruna et al. 2018). Several factors of formulation (the type of matrix, concentration, ratio, the type of core ingredient, loading level) and both process parameters (temperature, pH, stirring speed, time, cooling rate, drying process) can affect the final particle size (Marfil et al. 2018). The size of microcapsules for food applications should be below 100 µm to avoid impacting the mouth-feel of the food product. The distribution of the particle size should also be as narrow as possible in order to maintain product consistency (Kaushik et al. 2015). Besides, scanning electron microscopy is used to observe the morphology of the surface and cross-sectional structure of the encapsulated powders (Asmaliza et al. 2016; Basak et al. 2014).

According to Velasco et al. (2003), the commonly studied properties of microencapsulated oils include moisture content, water activity, particle size, surface oil and encapsulation efficiency. The moisture content is an important parameter to determine the storage stability of the microcapsules, where high moisture might lead to caking or agglomeration of the dried powder, microbial growth and lipid oxidation that will produce off-flavors. The water activity of the microcapsules can significantly affect microbial spoilage and lipid oxidation, which further determines shelf-life of the product. Oxidative degradation is limited when the water activity ranges from 0.2 to 0.3. This is due to the restriction of metal transition and retardation of hydroperoxide decomposition resulting from the quenching of free radicals and singlet oxygen. Other than that, oxidative stability of the encapsulated oils is important to be determined using different methods such as peroxide value and anisidine value. Accelerated oxidative test using the Rancimat method is employed to evaluate the oxidative stability and predict the shelf-life in a short period of time (Kochhar and Henry, 2009).

Application of microencapsulated oil in food industry

Nowadays, microencapsulation is highly recommended in food industry because it has many benefits such as thermostability enhancement, bioactive compound protection, controlled release, volatiles maintaining and texture improvement (Dordevic et al. 2014). At present, there have been few studies of microencapsulated oils that act as functional food ingredient being fortified into food formulations to enhance the nutrient content of the food product. Studies by Rubilar et al. (2012) found that the incorporation of encapsulated flaxseed oil in an optimised formulation of soup enhanced the oxidative stability of the soup. In addition, a value-added product with a high content of omega-3 and high consumer acceptability was also produced. Besides, studies carried out by Gallardo et al. (2013) on bread products demonstrated that the bread fortified with encapsulated flaxseed oil had a similar appearance to that of the control bread. The addition of microencapsulated oil did not modify the texture properties of bread.

Rahman et al. (2020) found that addition of microencapsulated chia seed oil into butter helps to increase the antioxidant capacity of butter from 30.75 to 35.16%. The radical scavenging activity and total antioxidant capacity of butter fortified with microencapsulated chia seed oil were also maintained during the storage period of 90 days. Supplementation of butter with microencapsulated chia seed oil also increased the amount of linolenic acid (omega-3) in butter. Other than that, the release profile of microparticles loaded with carotenoid-rich palm oil incorporated into food matrices was evaluated by Rutz et al. (2017). The microparticles were incorporated into yogurt and bread. Food samples with microencapsulated palm oil were placed under conditions simulating the gastrointestinal tract. For the bread, 38.9% of the carotenoids were released while for the yogurt 50.1% were released.

Table 4: Common analysis of microencapsulated oils in emulsion and powder forms

Emulsion form	Powder form
- Viscosity measurement (Renata et al. 2012) - Emulsion stability (Renata et al. 2012) - Emulsion droplet size (Wan Mohamad et al. 2017; Jafari et al. 2007)	- Encapsulation efficiency (Kaushik et al. 2015) - Surface oil (Asmaliza et al. 2017; Kaushik et al. 2015) - Particle size (Vos et al. 1996) - Microcapsule morphology (Asmaliza et al. 2016; Basak et al. 2014) - Oxidative stability (Kochhar and Henry, 2009) - Moisture content (Velasco et al. 2003) - Water activity (Velasco et al. 2003)

Additionally, according to the results obtained in the study, before incorporation into food, the bioactive materials from the microparticles had greater release during the simulation of the gastrointestinal tract, with greater degradation. After application in food, the release was lower and the compounds released were not degraded. This behavior indicates that the food matrices have the ability to interact with bioactive compounds in different ways to protect them (Sucupira et al. 2012).

An in vitro study with a dynamic artificial digestive system carried out by Chen et al. (2010) demonstrated that yogurt fortified with microencapsulated soybean oil significantly delayed the nutrient release (riboflavin), which could be desirable, because of the likelihood of reaching the bioactive components for intestinal absorption in an intact and active condition.

CONCLUSION

Microencapsulation is an effective tool to retain the chemical composition of vegetable oils including Sacha inchi oil, flaxseed oil, chia seed oil and palm oil which give many health benefits. This technology can also enhance the oxidative and thermal stability of these oils. Wall materials suh as modified starch, maltodextrin and sodium caseinate result in high MEE of these oils. The most commonly used techniques to microencapsulate oils are spray drying and freeze drying. Microencapsulation of oil by spray drying was found to have better MEE compared to other techniques. The common analyses involved to determine the quality and stability of the microencapsulated oils were viscosity measurement, emulsion stability, emulsion droplet size, encapsulation efficiency, surface oil, particle size, microcapsule morphology, oxidative stability, moisture content and water activity. Moreover, the microencapsulated oils has potential to be used as functional ingredient in food and pharmaceutical industries.

CONFLICT OF INTEREST

The authors declared that present study was performed in absence of any conflict of interest.

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AUTHOR CONTRIBUTIONS

FSR wrote the manuscript. ZZ, NH, AHAT, CAAB, NZRA and NS reviewed the manuscript.

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