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In vitro release behaviour of spray dried flaxseed oil Microcapsules for application in food system

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Abstract

In recent era, demand for plant-based polyunsaturated fatty acids (PUFAs) has increased rapidly due to changing lifestyle and dietary requirements. Flaxseed oil with the highest level of PUFAs, is more likely to be oxidized if handled or stored inappropriately. Presently, encapsulation of oils by various encapsulation techniques has gaining popularity as a promising way of preservation. With the intent current research was planned to encapsulate FSO using spray drying method. Flaxseed meal was subjected to gum extraction using ultrasound technique. Two different sets of emulsion samples were prepared i.e.; flaxseed oil (FSO)/regular dried polysaccharide gum (RDPSG) (for model 1 capsule) and flaxseed oil (FSO)/freeze dried polysaccharide gum (FDPSG) (for model 2 capsule). The resultant spray dried flaxseed oil (SDFSO) samples obtained from both models were subjected to physical characterization including moisture content, water activity and encapsulation efficiency. Both model typesof microcapsules exhibited good encapsulation efficiency as 90.45±2.67 and 92.62±4.28% for FSO/RDPSG and FSO/FDPSG, accordingly. The effect of the wall material on digestibility of SDFSO microcapsules was also investigated using simulated gastric fluid (SGF) and simulated intestinal fluid (SIF) models. The values observed for oil release in SGF were significantly higher in both models of SDFSO preparation when incubation was accompanied by heating. Similarly, A higher oil release percentage was found for FSO/FDPSG preparation as 65±3.95 with heating for 360 min followed by 45±3.42% without heating accordingly when observed under sequential (SGF+SIF) conditions. Flaxseed gums-based wall material was effective in carrying and delivering the flaxseed oil through gastrointestinal tract (GIT).

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Introduction

Polyunsaturated fatty acids (PUFAs) play a pivot role in human health for the maintenance of normal physiological function and preventing from biological disorders (Siscovick *et al.,* 2017). There are two families of fatty acids Ω-3 and Ω-6 fatty acids, which are metabolically and physiologically important. The α-linolenic acid (18:3n-3; ALA) and linoleic acid (18:2n-6; LA) are the precursors of Ω-3 and Ω-6 fatty acids. These are known as essential fatty acids (EFA) which means that inside human body they cannot be synthesized and must be taken from food sources (Gifford, 2002; Chang *et al.,* 2018). While eicosapentaenoic acid (20:5n-3; EPA) and docosahexaenoic acid (22:5n-3; DPAn-3) can be produced from ALA via conversion, yet the rate of conversion is very low. The valuable characteristics for health effects of Ω-3 PUFAs are due to the direct special effects of ALA and conversion of ALA to EPA & DHA and also the decline in the Ω-6: Ω-3 PUFAs ratio (Murakami *et al.,* 2008). The PUFAs are recommended for optimal health, as essential fatty acids LA and ALA, moreover EPA, DHA, and decosapentaenoic acid (DPA) as well. The incorporation of these PUFAs can be diet from plant, animals or fatty fish sources (Masurkar *et al.,* 2014; Rajaram *et al.,* 2017). Animals including humans have not capacity to construct long chain Ω-fatty acids, and they must be taken from diets. PUFAs are also found in some vegetable like hempseed oil, chia, perilla, olive, lingberry and flaxseed (Masurkar *et al.,* 2015). A vast variety of fish such as sardine, salmon, mackerel and herring are also recognized as the good source of Ω-3 fatty acids.Although marine sources are popular source but there are many short comings of fish oil such as undesirable taste and odor. Due to these reasons vegetarians shows unwillingness for its intake and consumptions. Additionally, various chemical processing methods as bleaching, deodorizing used for obtaining the fish oil, which further lead to accumulations of different hazard contaminants as dioxins, mercury and polychlorinated biphenyls (Dinu *et al.,* 2017).

Other than animals and marine sources the plants such as oil seeds are the also best source of PUFAs which are now trending all over the world. Oilseeds crops as plants and seeds are recommended and attractive option, because they have high oil productivity and PUFAs content in their oil (Baker *et al.,* 2016). The recent research has depicted the importance of flaxseed oil which is considered as one the finest sources of PUFAs and especially ALA as compared to eggs, fish oil, and others. Flaxseed is an important oil seed crop in Pakistan, cultivated in different regions depending on environmental and agricultural practices (Popa *et al.,* 2012). However, flaxseed oil with the highest level of PUFAs is more likely to be oxidized if handled or stored inappropriately (Lukaszewicz *et al.,* 2004). The degree of oxidation and the resulting metabolites can positively or negatively influence the efficacy quality of PUFAs. Likewise, lipid oxidation often leads to problems in processing and preserving food. During initial stages, it negatively affects the taste of food due to the formation of aldehydes and ketones. PUFAs oxidation ends in release of secondary oxidation metabolites which ultimately causes off-flavors (Let *et al.,* 2005). Moisture, light, oxygen and temperature are some of the main reasons of oxidative damage to unsaturated oils. Natural and synthetic antioxidants have been widely used for shielding unsaturated oils from oxidation till the recent years (Özbek *et al.,* 2017)Currently, encapsulation of oils and other sensitive bioactive molecules phenolic compounds, vitamins, flavors or probiotic bacteria by various encapsulation techniques has gaining popularity as a promising method of preservation. Encapsulation not only protects the oils against oxidation, it also improves the handling and supplementation of PUFAs enriched oils in different foods (Augustin *et al.,* 2012). A crucial step in creating microcapsules is the selection of a suitable wall/coating material that meets desired criteria i.e., compatibility with product, mechanical strength, thermal/dissolution release and reasonable particle size (Comunian *et al.,* 2016). The wall material for microencapsulation is usually selected on the basis of traditional trial and error method until perfection. Carbohydrates or polysaccharides are considered excellent coating/wall

materials for edible oils. The key function of polysaccharides in encapsulation process is to promote drying of wall material by increasing the crust formation over core (oil droplets) (Keogh *et al.,* 2001). Polysaccharide gums (PSG) from flaxseed are of commercial significance in the food industry due to their good emulsifying abilities, where; they may be used for emulsion stabilization, suspension of particulates, controlled crystallization, films formation, thickening agent as well as for encapsulation (Lipilina *et al.,* 2009).

Besides elongating shelf life and anti-oxidation, enumerating the release behavior of functional ingredients from encapsulation under human gastro-intestinal (GI) conditions is decisively vital to characterize the bioavailability of the encapsulated oils (Deglaire *et al.,* 2009).Understanding the factors that influence bioavailability of encapsulated PUFAs would help food industries to design food products to control, enhance or reduce lipid digestion and absorption within human GI tract. Although *in vivo* trials provide the most exact picture, yet they are costly and time consuming. Hence in-vitro digestion models provide a valuable alternative (Hur *et al.,* 2009). The aim of the proposed study was to enlighten the effects of innovative treatment such as ultrasound technology on extraction of PSG from flaxseed meal and development of improved standard process through which spray dried techniques may be employed for encapsulation of Ω-3-enriched oils. Finally, spray dried flaxseed oil powder was studied for in-vitro digestibility studies.

Materials and methods

Oilseed material

The seeds of flax plant (*Linum usitatissimum* L.) were bought from the Institute for Oilseed Research, Faisalabad, Punjab, Pakistan. The seeds of the chosen variety *Chandani* were cleaned to take out dirt and other foreign substance.

Extraction of oil and polysaccharides gums (PSG)

For each treatment, unprocessed flaxseeds were weighed by using electronic scales (model Kern 440-35N). For the extraction of oil from flaxseed samples, the seeds were pressed with the mini oil presser (model 6YL-550, with 2-3 kg/hour capacity). For extraction of PSG from flaxseed meal, ultrasound-assisted technology (model VCX 750, Sonics & Materials, Inc., USA) was used and distilled water was employed as solvent (Wang *et al.,* 2010).The extracted solution of PSG was filtered over 40-mesh screen and precipitated with two volumes of 95% ethanol. The separation of PSG was done by centrifugation and further dried in oven to develop regular dried polysaccharide gum (RDPSG) and a bench top laboratory freeze dryer was applied for development of freeze-dried polysaccharide gum (FDPSG).

Micro-Emulsion preparation

Table1 represents the two formulations of emulsions prepared for microencapsulation of FSO. These emulsions were prepared using two different wall materials: RDPSG and FDPSG. The wall materials (RDPSG and FDPSG) were added to distilled water at prescribed temperature (25 °C) and the mixture was stirred until completely dissolved. The concentration of total solid (wall material + oil) was fixed at 30%. FSO was then added to the wall material solution at a concentration of 20% with respect to total solids (Ahn *et al.,* 2008; Jafari *et al.,* 2008; Carneiro *et al.,* 2013). Emulsions were formed using a homogenizer operating at 18,000 rpm for 5 min. The wall materials were dissolved in distilled water under magnetic agitation one day before emulsification. In first formulation (FSO/RDPSG) oil dried flaxseed gum was mixed with distilled water followed by addition of flaxseed oil. In the second formulation (FSO/FDPSG), freeze dried flaxseed gum was also mixed with distilled water followed by addition of flaxseed oil. Coarse emulsions were prepared followed by mixing and homogenization of flaxseed oil and the wall solution.

Microencapsulation process

The oil microcapsules enriched with Ω-3 fatty acids were prepared using a mini spray dryer (Toption Lab Spray Dryer, Xi'an, China). The graphic diagram for

the lab-scale spray dryer is demonstrated in Figure 1. Spray dryer can be operated under maximum capacity of evaporated water and largest feed rate about 2000 mL/hour, respectively. The equipment presents external dimension as 940*850*1500mm (L*W*H). The temperature of inlet and outlet air can be maintained in the range of 40 °C ~ 300 °C and 40 °C ~ 140 °C, respectively. Maximum obtained atomizer speed is about 40000 rpm with two fluid type nozzle (diameter 1.00mm) and spray direction downwards and co-current. The emulsions can be fed into the main chamber through a peristaltic pump and the feed flow rate can be controlled by the pump rotation speed. The drying parameters selected for optimization process were: inlet air temperature (120, 140 and 160 °C), feed flow rate (200, 250 and 300 mL/hr), atomization speed (12000, 16000 and 20000 rpm) and outlet air temperature (60, 70 and 80 °C) at different levels.

Sample preparation

Two different sets of samples were subjected to in-vitro digestion process *i.e.* FSO/RDPSG and FSO/FDPSG.

Moisture content

The moisture contents of the resultant microcapsules were estimated by drying the respective samples in a vacuum oven at 70 °C till constant weight (AOAC., 2006).

Water activity

The water activity of oil microcapsules was determined by using NovasinaLabMaster-aw, Novasina, AG,(Switzerland).

Encapsulation efficiency

The total amount of FSO in microcapsules was computed as 3 g of dried microcapsules were extracted with 50 mL of petroleum ether under ultrasonic condition time for 15 min. The extraction was collected by repeated the process three times. Through the Whatman filter paper No. 1, the solvent was filtered and removal of petroleum ether was completed using rotary evaporator. The total oil content was then gravimetrically calculated (Hu *et al.,* 2016).

EE (%) = (Total amount of oil - surface oil)/Total amount of oil *100.

Behavior of spray dried flaxseed oil (SDFSO) studied in-vitro under simulated gastro-intestinal environments

Preparation of simulated gastric fluid (SGF)

In vitro release behavior of SDFSO was premeditated using a simulated gastrointestinal protocol detailed by Burgar *et al.* (2009)also used in US Pharmacopeia(2000). For the purpose, simulated gastric fluid (SGF) was prepared by dissolving 2g of NaCl and 7 mL of HCl (36%) in 900 mL deionized water. The addition of pepsin (3.2g) was preceded by pH adjustment of solution at 1.2 using 0.1 M HCl. The ultimate volume was made up to 1000mL by adding water. The mixture was stored at 4 °C till further use.

Preparation of simulated intestinal fluid (SIF)

The simulated intestinal fluid was formulated by following the procedure elaborated in the US Pharmacopeia (2000). For the intent, by 6.8 g of potassium hydrogen phosphate (K_2HPO_4) was mixed in 900 mL of deionized water, followed by subsequent addition of 0.2 M sodium hydroxide (NaOH, 77 mL) and 100g of (1× USP) pancreatin preceded by overnight stirring at 4°C. The pH of solution was attuned to 6.8 using either 1 M Sodium hydroxide (NaOH) or 1M HCl. Finally, the volume was made up to 1000 mL using water. The resultant solution was stored at temperature of 4°C until further use (US Pharmacopeia, 2000; Burgar *et al.*, 2009; Goyal *et al.,* 2016)

In-vitrorelease behavior of SDFSO exposed to SGF conditions only

Purposely, 6g of SDFSO powder was mixed with 50 mL distilled water. In the resultant solution 60ml of SGF was added and kept for incubation at 38°C for two hours. The subject was mixed thoroughly with help of magnetic stirrer and agitator by using the 30

mL of petroleum ether and diethyl ether each, the released flaxseed oil was extracted through separating funnel. This oil extraction was repeated twice times with petroleum and diethyl ether in 1:1 ratio. Afterwards, the solvent was evaporated at 80°C temperature. After that, this extracted oil was dried up with help of oven set at 100±4°C for 30 mins. The amount of free oil was calculated gravimetrically. The total quantity of oil in SDFSO was 38% as measured by chemical method. Hence, using this value as reference, percentage of released oil was calculated.

In-vitro release behavior of SDFSO as exposed to SGF+SIF

For knowing the serial exposure to both SGF and SIF we took same quantity of 6 mL of SDFSO powder and mixed it with 60 mL of SGF and incubated maintaining the same conditions as described in the aforementioned procedure. In the subsequent step after 2 hours, the pH of the sample was maintained at 6.8 using 1M NaOH. After that 60 mL of SIF also added and solution was incubated for 3 hours at temperature of 38°C. The volume of released flaxseed oil was determined by extraction with petroleum ether and diethyl ether 1:1 ratio after calculating gravimetrically.

Fatty acids profile of SDFSO samples

The fatty acid profile of SDFSO was revealed by gas chromatography (AOCS,1998). Briefly, the fatty acids were transformed to methyl esters using acid catalyzed methanolysis method. For the purpose, 10mg of extracted oil was heated with 4mL methanolic HCL for 90 minutes. Trailed by cooling, the methyl esters were extracted using hexane while, the hexane was dried over anhydrous sodium sulfate in the subsequent step. Next, 1/5th of a micro liter of extract was transferred to a gas chromatograph equipped with column, and flame ionization detector (FID). The transport gas used was nitrogen.

The temperature of the injection port and column was maintained at 170°C, whilst the temperature for detector was kept 240°C. The qualitative interpretation of the chromatogram was completed by relating the retention times of the fatty acids methyl esters (FAMES) of the sample with those of FAMES of standard. The estimation of the percentage for each fatty acid was carried out by measuring respective peak area.

Results and discussion

Physical characterization study of SDFSO samples

In this research study, two different coating materials were used for encapsulation of flaxseed oil i.e., RDPSG and FDPSG.

Table 1. Emulsion formulation for SDFSO.

SDFSO preparation	Moisture content %	Water activity AW	Encapsulation efficiency %
FSO/RDPSG	2.99±0.01	0.15±0.00	90.45
FSO/FDPSG	3.48±0.04	0.21±0.01	92.62

FSO/RDPSG: Flax seed oil/Regular polysaccharide gum.

FSO/FDPSG: Flax seed oil/Freeze dried polysaccharide gum.

The resultant SDFSO samples were subjected to physical characterization including moisture content, water activity and encapsulation efficiency as summarized in Table 2. The values recorded for moisture content were 2.99±0.01% and 3.48±0.04% and water activity as 0.15±0.01 and 0.21±0.01,for microcapsules produced using wall materials; RDPSG and FDPSG, respectively. Although both values are within safe limit however, relatively low moisture content of regular dried gum is attributed to high temperature used for drying of gum as compared to that used for freeze dried one. The decreased Aw obtained for both types of microcapsules confirms an optimal stability of encapsulated FSO powder as the obtained values are well below the established limit of 0.6. The findings of the current study are in

agreement with the values of those recorded for olive oil microcapsules (Calvo *et al.,* 2012). The observations of the current study are also in line with the work of Polavarapu *et al.* (2011), as they formulate microencapsulated fish oil powder and reported aw of 0.3 in freshly prepared samples. Carbohydrates or polysaccharides are considered excellent coating/wall materials for edible oils.

Table 2. Physical characterization study of SDFSO microcapsules.

Emulsion formulation	Flaxseed oil (FSO) %	Regular dried polysaccharide gum (RDPSG) %	Freeze dried polysaccharide gum (FDPSG) %	Distilled water %
FSO/RDPSG	20	11.5	-	68.5
FSO/FDPSG	20	-	11.5	68.5

The key function of polysaccharides in encapsulation process is to promote drying of wall material by increasing the crust formation over core (oil droplets) (Keogh *et al.,* 2001). The moisture contents of final powdered oil microcapsules also play a crucial role in prolonging shelf life of oils. As high moisture percentage may lead to caking and microbial growth, affecting its physiochemical stability and acceptability. Generally, the minimum moisture content limit is 3-4% for dried microcapsules of oils in food industry (Gallardo *et al.,* 2013).

Table 3. Oil release % of SDFSO under simulated gastric fluid (SGF) conditions.

SDFSO preparation	Oil released %					
	Incubation period without heating (minutes)			Incubation period with heating (minutes)		
	120	240	360	120	240	360
FSO/RDPSG	9±0.51	10±0.48	11±0.39	16±2.12	17±1.10	17±0.98
FSO/FDPSG	11.35±0.89	12±1.19	12±1.55	18±2.19	20±1.89	21±1.22

The results are also in accordance with the observations of Quispe-Condori *et al.* (2011), who reported 3.88-5.06% moisture content in microencapsulated flaxseed oil. Regarding the results of encapsulation efficiency, both types of microcapsules exhibited good efficiency as 90.45±2.67 and 92.62±4.28% for RDPSG and FDPSG, accordingly. Presence of free oil on surface and encapsulation efficiency (EE) of coating materials affects the physicochemical and oxidative stability of dry powders.

Polysaccharides gum although not studied before has shown proven efficiency in this study.

Table 4. Fatty acids characterization of SDFSO samples after the *in-vitro* digestion process.

SDFSO Preparation	PUFAs	MUFAs	SFAs
Unencapsulated oil	73.19±1.09	16.49±0.23	9.59±0.25
FSO/RDPSG	73.36±0.48	17.20±0.51	9.53±0.06
FSO/FDPSG	73.34±0.65	17.27±0.44	9.55±0.21

SFAs: saturated fatty acids; MUFAs: monounsaturated fatty acids; PUFAs: polyunsaturated fatty acids.

Still today, spray drying is considered as one of the most common and convenient methods for oil encapsulation, however choice of best wall material is a vital step in order to obtain a good quality oil powder with less water activity, ease of handling and storage (Gouin, 2004; Omar *et al.,* 2009). Additionally, coating or wall material if efficient provide better shield against oxidation of PUFAs

(Bakry *et al.,* 2016). Recently, Domian *et al.*(2017) explored the potential of legumes protein combined with dextrin from wheat and trehalose in different ratios, as an alternative coating material. The highest encapsulation efficiency (62-98%) was found for trehalose and soy protein isolates.

Behavior of SDFSO studied in-vitro under simulated gastro-intestinal environments

The associated health effects of microencapsulated Ω-3 rich oils depend on their bioavailability. Hence, it is very important to evaluate the release profile of encapsulated oils under gastrointestinal conditions. The effect of the wall material on digestibility ofSDFSOmicrocapsules was investigated by using (SGF) and (SIF) digestion models. The data regarding these parameters is summarized in Table 3 and Figure2, respectively. The quantity of oil obtained after the in-vitro digestion, expressed as released oil % has been assessed considering the types of microcapsule wall materials RDPSG and FDPSG.

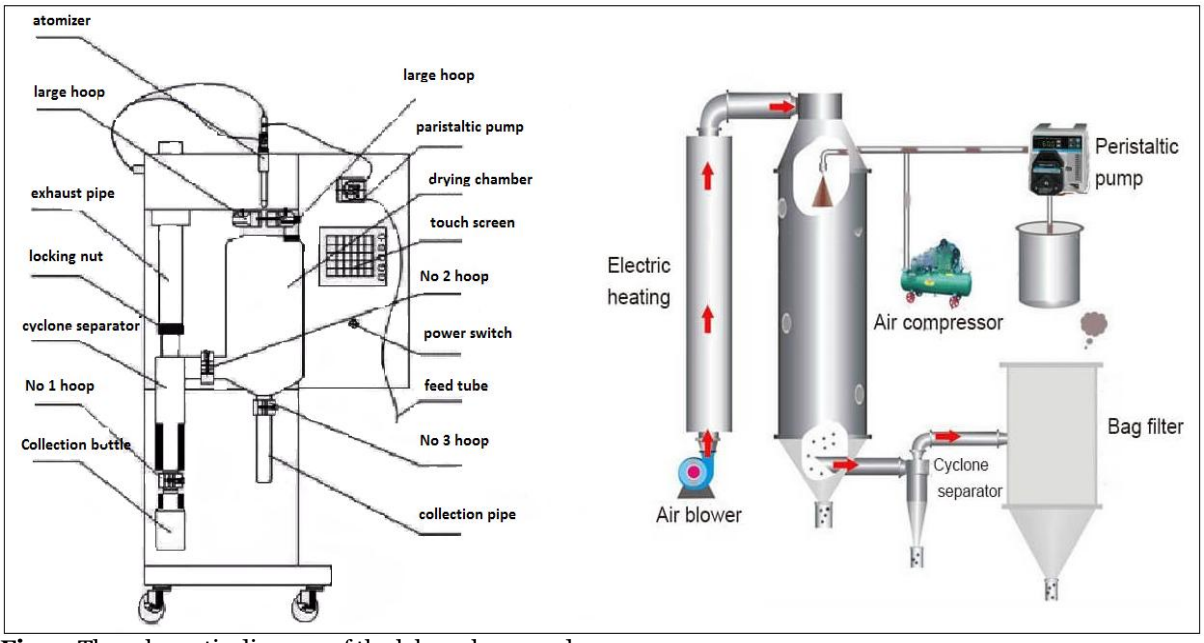

Fig. 1. The schematic diagram of the lab-scale spray dryer.

It is evident from the results recorded in Table 3 at 120 min without heating, that the percent oil released (9±0.51) from FSO/RDPSG was significantly lower as compared to 11.35±0.89% that was noticed for FSO/FDPSG.

This may be attributed to more compact structure of RDPSG formed during regular drying process, and stayed comparatively unaffected due to SGF environment.

Concerning data in Table 3 also exhibited that in both SDFSO formulations the oil release percentage inclined significantly as a function of exposure to SGF environment, as it increased from 120 to 360 minutes. Similarly, the values observed for oil release were significantly higher in both models of SDFSO preparation when incubation was accompanied by heating.

The highest oil percentage (21±1.22I was released for FSO/FDPSG at 360 min trailed by FSO/RDPSG as 17±0.98. During digestion process, food is first digested by gastric fluids or secretions followed by intestinal digestion due to presence of different intestinal enzymes and gradual shifts in different pH levels between both environments.

Hence in order to mimic the real gastrointestinal conditions, the resultant SDFSO preparations were also subjected to sequential SGF(120 min) + SIF(240 min) conditions as depicted in Table 3.

It is apparent from the results that a higher oil release percentage was found for SDFSO/FDPSG preparation as 65±3.95 with heating followed by 45±3.42% without heating the mixture. Similar trend was observed for FSO/RDPSG formulation with values 50±3.44 and 36±2.31%, accordingly (Fig. 2).

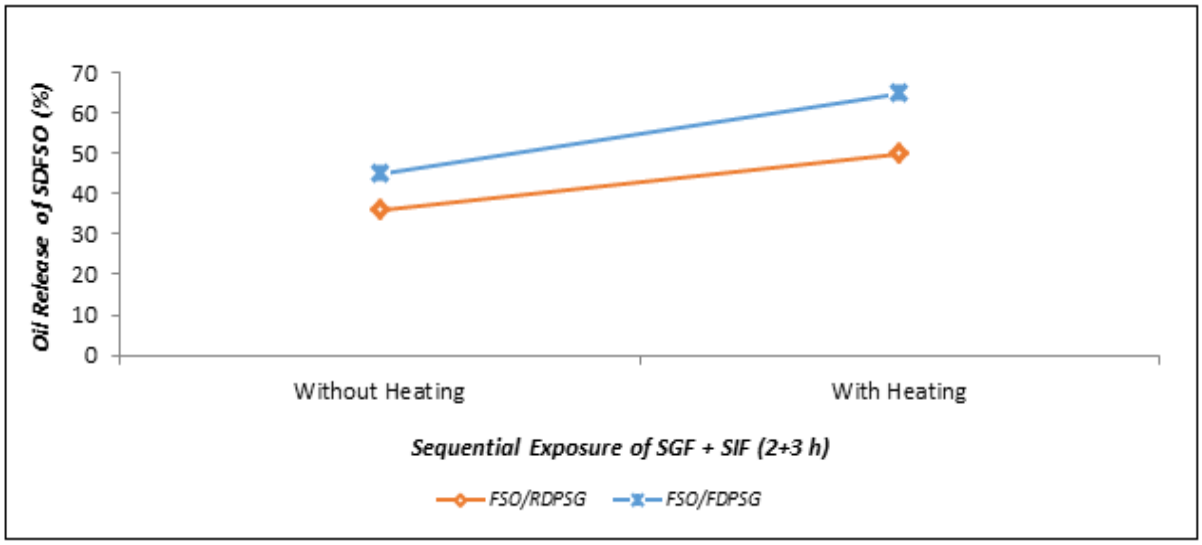

Fig. 2. Oil release % of SDFSO samples under sequential exposure of SGF + SIF (2+3 h).

Significantly higher percent oil release recorded in sequential exposure (SGF+SIF) of reconstituted SDFSO preparations, when compared to SGF conditions alone, might be due to increased degradation of the wall material due to intestinal enzymes *i.e.,* amylase and trypsin.

They help in degradation of wall materials either carbohydrates or protein based (Kosaraju *et al.,* 2009). Our results are in accordance with the findings of Goyal*et al.*(2016)as they reported20.00±3.66-59.99±9.29% oil release under gastrointestinal conditions, in SDFSO using sodium caseinate as wall material. Additionally, higher fish oil release percentage (80%) was reported by Binsi *et al* (2017); they used gum arabic in various combinations for spray dried microcapsule formulations. Earlier*Augustin et al.* (2014)evaluated the digestion profile of 12 types of spray dried canola oil powder and stated that the lipolysis of encapsulated canola oil varied from 12 to 68%.

Their findings proposed that in-vitro digestibility of microencapsulated oils depends on formulation, processing parameters as well as encapsulating materials.

Studies have shown that the digestion of encapsulated oil varies due to the nature of wall materials used for encapsulation. It is also reported that protein-based substances are readily digested by gastric fluids releasing oil from the matrix, however gum-based coating materials are not easily digestible yet they get solubilised in the gastrointestinal conditions (Timilsena *et al.,* 2017). Moreover, it has also been observed that wall materials comprising protein-gum complex are resistant to gastric juices and allow more oil release in the intestinal conditions. Additionally, physicochemical characteristics of microencapsulated oils also influence degree of lipolysis in the gastro-intestinal tract (Mun *et al.,* 2007).

Relatively low digestibility of SDFSO preparations observed in the current study can be explained by the fact that gastric lipase remains inactive at normal pH human stomach hence, only 10 to 30% of oil is digested in the gastric system producing a mixture of free fatty acids, diglycerides and monoglycerides (Gallier and Singh, 2012). At the end of the gastric digestion, oil enters into the small intestine and mixed with other enzymes (pancreatin) and get digested up to 70-90% of the lipids (Wickham *et al.,* 2002).

Fatty acids characterization of SDFSO samples after in-vitro digestion

In order to assess the in-vitro digestion process, the fatty acids composition of the digested oils was compared with the fatty acids composition of un-digested oil (control oil not subjected to digestion).According to Table 4. No significant differences were observed in chemical composition of PUFAs and SFAs of any sample of flaxseed oil preparation regardless of digested or undigested oils. However, concerning the values MUFAs (monounsaturated fatty acids), there was a noticeable decline in value of un-encapsulated flaxseed oil after digestion (16.49±0.23%) as compared to encapsulated ones (17.20±0.51 and 17.27±0.44%). So, it is evident from the results that, after the in-vitro digestion, same quantity of fatty acids were available irrespective of encapsulated or un-encapsulated flaxseed oil. The decline in MUFAs may be explained by the fact that encapsulated oil was protected from oxidative damage whilst in unencapsulated oil slight lipid oxidation was the cause of reduction in PUFAs. Hence, the wall material effectively protected the oils from oxidative and flavour change (Calvo *et al.,* 2012).

Conclusion

According to the findings of the current research, it may be concluded that RDPSG and FDPSG based microcapsule formulations are efficient for entrapment and gastrointestinal delivery of PUFAs rich flaxseed oil.

The source of wall material had significant effect on physicochemical properties, encapsulation efficiency and release behavior of SDFSO. PSG tested as innovative plant-based coating material showed a significant protective effect against oxidation and improved bioavailability of SDFSO. The microcapsules were able to deliver 65% of the encapsulated oil within the gastrointestinal tract. The observations suggest that flaxseed gums-based microcapsule systems tested were capable of effectively carrying, shielding and delivering the flaxseed oil.

Terms used

FSO= flaxseed oil, SDFSO= spray dried flaxseed oil, PSG= polysaccharide gum, RPSG= regular polysaccharide gum, FDPSG= freeze dried polysaccharide gum.

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Conflicts of Interest

The authors declare no conflict of interest.

References

Ahn JH, Kim YP, Lee YM, Seo EM, Lee KW, Kim HS. 2008. Optimization of microencapsulation of seed oil by response surface methodology. Food Chemistry **107(1),** 98-105.

AOAC. 2006. Official Methods of Analysis, 18th edition. Association of Official Analytical Chemists, Gaithersburg, Maryland.

AOCS. 1998**.** Official Methods and Recommended Practices of AOCS, 5th edition. American Oil Chemists Society, Champaign, IL, USA.

Augustin MA, Sanguansri L. 2012. Challenges in developing delivery systems for food additives, nutraceuticals and dietary supplements. Encapsulation technologies and delivery systems for food ingredients and nutraceuticals. Woodhead Publishing., 19-48.

Baker EJ, Miles EA, Burdge GC, Yaqoob P, Calder PC. 2016. Metabolism and functional effects of plant-derived omega-3 fatty acids in humans. Progress in Lipid Research **64,** 30-56.

Bakry AM, Abbas S, Ali B, Majeed H, Abouelwafa MY, Mousa A, Liang L. 2016.

Microencapsulation of oils: a comprehensive review of benefits, techniques, and applications. Comprehensive Reviews in Food Science and Food Safety **15(1),** 143-82.

Binsi PK, Nayak N, Sarkar PC, Jeyakumari A, Ashraf PM, Ninan G, Ravishankar CN. 2017. Structural and oxidative stabilization of spray dried fish oil microencapsulates with gum arabic and sage polyphenols: Characterization and release kinetics. Food Chemistry **219,** 158-68.

Burgar MI, Hoobin P, Weerakkody R, Sanguansri L, Augustin MA. 2009. NMR of microencapsulated fish oil samples during in vitro digestion. Food biophysics **4(1),** 32-41.

Calvo P, Castaño ÁL, Lozano M, González-Gómez D. 2012. Influence of the microencapsulation on the quality parameters and shelf-life of extra-virgin olive oil encapsulated in the presence of BHT and different capsule wall components. Food Research International **45(1),** 256-61.

Carneiro HC, Tonon RV, Grosso CR, Hubinger MD. 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),** 443-51.

Chang JP, Su KP, Mondelli V, Pariante CM. 2018. Omega-3 polyunsaturated fatty acids in youths with attention deficit hyperactivity disorder: a systematic review and meta-analysis of clinical trials and biological studies. Neuropsychopharmacology **43(3),** 534.

Comunian TA, Favaro-Trindade CS. 2016. Microencapsulation using biopolymers as an alternative to produce food enhanced with phytosterols and omega-3 fatty acids: A review. Food Hydrocolloids **61**, 442-57.

Deglaire A, Bos C, Tomé D, Moughan PJ. 2009. Ileal digestibility of dietary protein in the growing pig and adult human. British Journal of Nutrition **102(12),** 1752-9.

Dinu M, Abbate R, Gensini GF, Casini A, Sofi F. 2017. Vegetarian, vegan diets and multiple health outcomes: a systematic review with meta-analysis of observational studies. Critical reviews in food science and nutrition **57(17),** 3640-9.

Domian E, Brynda-Kopytowska A, Marzec A. 2017. Functional Properties and Oxidative Stability of Flaxseed Oil Microencapsulated by Spray Drying Using Legume Proteins in Combination with Soluble Fiber or Trehalose. Food and Bioprocess Technology **10(7),** 1374-86.

Gallardo G, Guida L, Martinez V, López MC, Bernhardt D, Blasco R, Pedroza-Islas R, Hermida LG. 2013. Microencapsulation of linseed oil by spray drying for functional food application. Food Research International **52(2),** 473-82.

Gallier S, Singh H. 2012. The physical and chemical structure of lipids in relation to digestion and absorption. Lipid Technology **24(12),** 271-3.

Gifford KD. 2002. Dietary fats, eating guides, and public policy: history, critique, and recommendations. The American Journal of Medicine **113(9),** 89-106.

Gouin S. 2004.Microencapsulation: industrial appraisal of existing technologies and trends. Trends in food science & technology **15(7-8),** 330-47.

Goyal A, Sharma V, Sihag MK, Arora S, Singh AK, Sabikhi L. 2016. Effect of microencapsulation and spray drying on oxidative stability of flaxseed oil and its release behavior under simulated gastrointestinal conditions. Drying Technology **34(7),** 810-21.

Hu L, Zhang J, Hu Q, Gao N, Wang S, Sun Y, Yang X. 2016. Microencapsulation of bruceajavanica oil: Characterization, stability and optimization of

spray drying conditions. Journal of Drug Delivery Science and Technology 36, 46-54.

Hur SJ, Decker EA, McClements DJ. 2009. Influence of initial emulsifier type on microstructural changes occurring in emulsified lipids during in vitro digestion. Food Chemistry **114(1),** 253-62.

Jafari SM, Assadpoor E, Bhandari B, He Y. 2008. Nano-particle encapsulation of fish oil by spray drying. Food Research International **41(2),** 172-83.

Keogh MK, O'kennedy BT, Kelly J, Auty MA, Kelly PM, Fureby A, Haahr AM. 2001. Stability to oxidation of spray dried fish oil powder microencapsulated using milk ingredients. Journal of Food Science **66(2)**, 217-24.

Kosaraju SL, Weerakkody R, Augustin MA. 2009. In-vitro evaluation of hydrocolloid–based encapsulated fish oil. Food Hydrocolloids **23(5),** 1413-9.

Let MB, Jacobsen C, Meyer AS. 2005. Sensory stability and oxidation of fish oil enriched milk is affected by milk storage temperature and oil quality. International Dairy Journal **15(2),** 173-82.

Lipilina E, Ganji V. 2009. Incorporation of ground flaxseed into bakery products and its effect on sensory and nutritional characteristics–a pilot study. Journal of Foodservice **20(1),** 52-9.

Lukaszewicz M, Matysiak-Kata I, Skala J, Fecka I, Cisowski W, Szopa J. 2004. Antioxidant capacity manipulation in transgenic potato tuber by changes in phenolic compounds content. Journal of Agricultural and Food Chemistry **52(6),** 1526-33.

Masurkar AA, Datar AG, Vakil BV. 2014. Screening and identification of PUFA producers from various fish of indian coastal and fresh water habitats. International Journal of Life Sciences Biotechnology and Pharma Research **3(3)**, 181.

Masurkar AA, Datar AG, Vakil BV. 2015. New Microbial Sources of Pufa From the Arabian Sea and Fresh Water Habitats of Indian Territory. International Journal of Pharmaceutical Sciences and Research **6(1),** 349-60.

Mun S, Decker EA, McClements DJ. 2007. Influence of emulsifier type on in vitro digestibility of lipid droplets by pancreatic lipase. Food Research International **40(6),** 770-81.

Murakami K, Mizoue T, Sasaki S, Ohta M, Sato M, Matsushita Y, Mishima N. 2008. Dietary intake of folate, other B vitamins, and ω-3 polyunsaturated fatty acids in relation to depressive symptoms in Japanese adults. Nutrition **24(2),** 140-7.

Omar KA, Shan L, Zou X, Song Z, Wang X. 2009. Effects of two emulsifiers on yield and storage of flaxseed oil powder by response surface methodology. Pakistan Journal of Nutrition **8(9),** 1316-24.

Özbek ZA, Ergönül PG. 2017. A review on encapsulation of oils. Celal Bayar Üniversitesi Fen Bilimleri Dergisi **13(2),** 293-309.

Polavarapu S, Oliver CM, Ajlouni S, Augustin MA. 2011. Physicochemical characterisation and oxidative stability of fish oil and fish oil–extra virgin olive oil microencapsulated by sugar beet pectin. Food Chemistry **127(4),** 1694-705.

Popa VM, Gruia A, Raba DN, Dumbrava D, Moldovan C, Bordean D, Mateescu C. 2012. Fatty acids composition and oil characteristics of linseed (LinumUsitatissimum L.) from Romania. Journal of Agroalimentary Processes and Technologies **18(2)**, 136-40.

Quispe-Condori S, Saldaña MD, Temelli F. 2011. Microencapsulation of flax oil with zein using spray and freeze drying. LWT-Food Science and Technology **44(9),** 1880-7.

Rajaram S, Valls-Pedret C, Cofán M, Sabaté J, Serra-Mir M, Pérez-Heras AM, Arechiga A, Casaroli-Marano RP, Alforja S, Sala-Vila A, Doménech M. 2017. The Walnuts and Healthy Aging Study (WAHA): protocol for a nutritional intervention trial with walnuts on brain aging. Frontiers in aging neuroscience **8,** 333.

Siscovick DS, Barringer TA, Fretts AM, Wu JH, Lichtenstein AH, Costello RB, Kris-Etherton PM, Jacobson TA, Engler MB, Alger HM, Appel LJ. 2017. Omega-3 polyunsaturated fatty acid (fish oil) supplementation and the prevention of clinical cardiovascular disease: a science advisory from the American Heart Association. Circulation **135(15),** 867-84.

Timilsena YP, Adhikari R, Barrow CJ, Adhikari B. 2017. Digestion behaviour of chia seed oil encapsulated in chia seed protein-gum complex coacervates. Food hydrocolloids **66,** 71-81.

US Pharmacopeial Convention. US Pharmacopeia and National Formulatory. 2000. USP 24 NF 19. Rockville, MD.

Wang XW, Hai H, Jin WY, Wang K, Yang D. 2010. Optimization of microwave-ultrasound assisted extraction of flavonids from ginkgo biloba leaves by response surface methodology. Food Science and Technology **3,** 058.

Wickham M, Wilde P, Fillery-Travis A. 2002. A physicochemical investigation of two phosphatidylcholine/bile salt interfaces: implications for lipase activation. Biochimica et Biophysica Acta (BBA)-Molecular and Cell Biology of Lipids **1580(2-3),** 110-22.