Suitable coating material for microencapsulation of spray-dried fish oil

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Abstract This study was conducted to screen the most suitable coating material for the production of microencapsulated fish oil powder using ternary blends of maltodextrin (15, 25 % w/w), Arabic gum (2.5, 7.5 % w/w), and methylcellulose (0.5, 1.5 % w/w). The physical properties of fish oil emulsion and encapsulated powders were evaluated. Arabic gum (5 % w/w) showed the most significant ($p<0.05$) effect on the surface mean diameter of the droplets in the emulsion. Maltodextrin had the most significant ($p<0.05$) effect on the centrifuge stability of the emulsion and the amount of surface oil of the powder at 15 and 20 % (w/w) respectively, whereas methylcellulose (0.5 % w/w) had the most significant ($p<0.05$) effect on the width distribution of the droplets in the emulsion. The total optimal area leading to the formation of coating material with desirable physical properties was expected to be obtained by the combination of 16 % (w/w) maltodextrin, 6.5 % (w/w) Arabic gum, and 0.88 % (w/w) methylcellulose respectively.

Keywords Microencapsulation · Fish oil · Maltodextrin · Arabic gum · Methylcellulose · Spray-drying

Introduction

In recent years, special attention has been given to refining the efficiency of encapsulation procedure through the spray-drying of flavors and oils by reducing the extent of oil at the external layer of powder particles, thereby avoiding core material losses (Tonon et al. 2011). The type of coating material and the characteristics of the active materials and the emulsion are the key factors that affect encapsulation efficiency of encapsulated oils and flavors (Tonon et al. 2011). The selection of appropriate wall materials is still difficult in the microencapsulation procedure. It is difficult to use only one biopolymer to obtain perfect properties in the encapsulation; therefore, a combination of two biopolymers is often used for the wall material. There are only few studies that have been reported on the use of a combination of three biopolymers as a wall material for the microencapsulation of fish oil; most of the studies were on the combination of two biopolymers. Moreover, the effects of wall materials on the properties of both fish oil emulsions and encapsulated powders are also not well-known. In the current study, maltodextrin, Arabic gum, and methylcellulose were selected as the wall materials. Maltodextrins are soluble in water and have the capability to decrease the level of undesirable reactions when applied in the microencapsulation of food constituents like fats and oils, vitamins, minerals, and colorants. They are normally used as co-encapsulating materials in the spray-drying of emulsions (Sliwinski et al. 2003). At a high solid content, maltodextrin has low viscosity and is bland in flavor (Apintanapong and Noomhorm 2003). Its main inadequacies include low retention of volatile compounds and a virtual lack of emulsifying ability (Reineccius 1991).

Arabic gum is also an efficient encapsulating material because of its high solubility and low viscosity in aqueous solutions, in comparison to other hydrocolloid gums. This property helps the spray-drying procedure. In addition, this

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wall material fulfills the roles of both a surface-active agent and a drying matrix (Tonon et al. 2011). Methylcellulose demonstrates inverse solubility properties. It is soluble in cold water and its solubility decreases with an increase in temperature. The solubility is very low at 30 °C and almost negligible at above 35–40 °C (Kolanowski et al. 2004). It forms gel when heated and returns to its initial liquid viscosity when cooled. The surface thermal gelation prevents oil droplets from joining and helps the creation of emulsions with stability at high temperatures (Huang et al. 2001). Moreover, the addition of methylcellulose results in a noteworthy drop and a narrowing of the particle size of emulsions (Kolanowski et al. 2006).

The aim of this study was to screen the best levels of these three types of carbohydrates as coating material leading to the least surface mean diameter (D_{32}) and width distribution of droplets (span), the highest centrifuge stability of the emulsion and the minimum amount of surface oil of the powders.

Materials and methods

Materials

Fish oil (Sigma Aldrich, St. Louis, Mo, USA) was used as the core material (<30.0 % palmitic plus stearic acid and 20.0 to 31.0 % omega-3; octadecatetraenoic, eicosapentaenoic and docosahexaenoic fatty acid as triglycerides). Butylated hydroxyanisole (BHA) as antioxidant was bought from (Sigma Aldrich, St. Louis, Mo, USA). The coating material was an aqueous solution containing maltodextrin DE 13.0 and Arabic gum (both from Sigma Aldrich, St. Louis, Mo, USA) and methylcellulose (TCI, Tokyo, Japan). Analytical grade petroleum ether with boiling point of 40–60 °C was provided from Merck (Darmstadt, Germany) while sodium azide was from Fisher Scientific (Pittsburgh, PA). Preparation of the solutions was carried out by using deionized water.

Preparation of the emulsion

In this study, 20 fish oil emulsions (9 % w/w) were prepared under different blends of variables; namely, maltodextrin, Arabic gum, and methylcellulose (Table 1). Aqueous phase was prepared by dispersion of maltodextrin, methylcellulose, and sodium azide (0.02 % wt) in deionized water. Arabic gum was added to deionized water (60 °C) and stirred for 3 min to help the hydration. Prepared mixture was set aside overnight at 10–12 °C to ensure full hydration was attained. Coarse emulsion was made by adding the core material (fish oil, 9 % w/w) along with BHA (0.02 % w/w) gradually into the aqueous phase containing the coating material while mixing. BHA was added to improve the oxidative stability of fish oil. Fine emulsification was achieved using a high shear

Table 1 Matrix of the full factorial design for coating materials

Treatments	Blocks	Maltodextrin	Arabic gum	Methylcellulose
1 (C)	2	20	5	1
2	2	25	2.5	1.5
3	2	15	2.5	0.5
4	2	25	7.5	0.5
5	2	15	7.5	1.5
6	1	25	2.5	1.5
7	1	15	7.5	1.5
8 (C)	1	20	5	1
9	1	25	7.5	0.5
10	1	15	2.5	0.5
11	3	15	7.5	0.5
12	3	25	2.5	0.5
13 (C)	3	20	5	1
14	3	15	2.5	1.5
15	3	25	7.5	1.5
16 (C)	4	20	5	1
17	4	25	7.5	1.5
18	4	15	7.5	0.5
19	4	25	2.5	0.5
20	4	15	2.5	1.5

C, center point

homogenizer (IKA T25, Digital Ultra Turrax, Deizisau, Germany) at a speed of 10,000 rpm for 5 min and then the emulsion was passed through a homogenizer (30 MPa) (APV, Crawley, UK.) at 4–6 °C. Each batch of homogenized emulsion weighed approximately 400 ml and was used for the production of microencapsulated fish oil.

Spray-drying

The fine emulsion (4–6 °C) was converted to encapsulated powder in a mini spray-dryer (Buchi B-290, Flawil, Switzerland). Inside chamber dimension: 110 cm height, 50 cm diameter equipped with 0.7 mm diameter nozzle. The pressure was adjusted to 3 kgf/cm² (294.2 kPa) and 100 % aspirator rate. The inlet and outlet temperatures were kept at 160 °C and 80±4 °C, respectively. The feed flow rate of emulsion was kept at 10 ml/min. Dried powders were kept in the dark and air tight bottles at 4 °C for more analysis.

Analytical methods

Emulsion droplet size (EDS) analysis

The EDS analysis was carried out using Mastersizer (Malvern, Model 2000, Worcestershire, UK). This instrument could identify the size of particles between 0.02 to 2,000 µm. Each sample was analyzed with two measurements. The surface

and volume weighted mean diameters of particles were stated as ($D_{32} = \sum n_i d_i^3 / \sum n_i d_i^2$) and ($D_{43} = \sum n_i d_i^4 / \sum n_i d_i^3$), respectively (Jafari et al. 2008). The emulsion droplet size was measured by adding about 1 drop of the emulsion to 700 ml deionized water whilst stirring in the beaker of this instrument. The analysis needs the refractive index of fish oil and dispersant (water) that was 1.48 and 1.33 respectively. The width distribution of the droplet sizes so-called as, 'span' was achieved from this formula.

$$\text{Span} = [d(v, 90) - d(v, 10)] / d(v, 50)$$

It should be mentioned that the diameters at 10, 50, and 90 % accumulative volume were stated as $d(v, 10)$, $d(v, 50)$, and $d(v, 90)$, respectively (Jafari et al. 2008; Desrumaux and Marcand 2002).

Centrifuge stability of the emulsion

The stability of the fish oil samples was determined based on the modified method of Huang et al. (2001). About 30 ml of each fish oil emulsion was poured into 45 ml plastic tube and immediately centrifuged using Kubota 2100 (Fujioka, Japan) at 4,000 g for 10 min at ambient temperature. The height of the primary emulsion and that of the residual emulsion that was formed after centrifugation were estimated. The initial height of emulsion was considered 30 ml. Three phases including oil phase on top, emulsion phase in the middle and aqueous phase on the bottom were formed after centrifugation. The height of residual emulsion was estimated by reading the height of emulsion phase line in the middle of centrifuge tube (Table 2). The stability of emulsion (ES) was calculated as a percentage: $\text{ES (\%)} = (\text{residual emulsion height} / \text{primary emulsion height}) \times 100$. Two measurements were done for each sample.

Surface oil content of the powder

The amount of free oil at the surface of the powders was measured according to the modified methods of Jafari et al. (2008) and Garcia et al. (2006). In this method, powder (5 g) was added to 100 ml of petroleum ether. The powder was separated from the solvent using a filter paper (Whatman No. 41, Maidstone, UK); the remaining powder was then washed with the 3–5 ml of petroleum ether. Finally, the filtrate solution having the extracted oil was evaporated using a rotary evaporator (Model R-210, Buchi, Flawil). After evaporation, the flask was put in an oven at 103 °C until constant weight (about 1 h) was achieved. The surface oil content was determined gravimetrically and expressed as a percentage of total oil in the microcapsules.

Table 2 Residual height of fish oil emulsion for stability measurement

Sample Runs	(Mean ± SD)
1	6.37±0.53
2	17.62±0.88
3	8.37±1.23
4	12.87±0.53
5	19.5±0.35
6	0±0
7	19.12±0.53
8	11.5±0.70
9	20.37±0.53
10	13.62±0.88
11	14±0.70
12	14.37±0.88
13	10.5±0.70
14	9.87±0.88
15	0±0
16	12±1.06
17	6.37±0.88
18	21.62±0.53
19	10.37±0.88
20	7.12±1.23

Experimental design and statistical analysis

Screening of the best coating material was done using full factorial design containing (X_1) maltodextrin concentration (15, 25 % w/w), (X_2) Arabic gum concentration (2.5, 7.5 % w/w), and (X_3) methylcellulose concentration (0.5, 1.5 % w/w) to encapsulate the fish oil. Then, their effects on the response variables including surface mean diameter (D_{32}), width distribution of droplets (span), centrifuge stability of emulsion, and the amount of surface oil of encapsulated fish oil powders was evaluated. As shown in Table 1, 20 experiments were carried out based on full factorial design with three factors and two levels for each factor. The regression model for predicting the variation of the responses is specified by Eq. 1.

$$Y_i = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_{12} + b_{13}X_{13} + b_{23}X_{23} \quad (1)$$

where Y_i is expected response, b_0 is offset, b_1 , b_2 and b_3 are main variable effects, b_{11} , b_{22} and b_{33} are quadratic effects and b_{12} , b_{13} and b_{23} are interaction effects. In this model, x_1 , x_2 and x_3 are the factors. Only significant ($p < 0.05$) terms were kept in the final regression model (Mirhosseini et al. 2008).

Optimization and validation procedure

In the current study, a group level of independent variables was needed to make fish oil emulsion and encapsulated powder with desired characteristics (i.e., the minimum oil droplet size, span, surface oil, and maximum centrifuge stability). The response optimizer in the Minitab software was applied for multiple numerical optimizations to determine the best level of factors cause to total response targets. The acceptability of the final reduced models for validation was verified by comparing the experimental and predicted data.

Results and discussion

Fitting the response models

The assessed regression coefficients and probability values for the responses in reduced model consisting R^2 and R^2 (adj) of the regressions, P-values and F-values are shown in Tables 3 and 4, respectively. Each response (Y_i) was evaluated as a function of main and linear interaction effects of maltodextrin, Arabic gum, and methylcellulose concentration. The results showed that the models were fitted for all responses with high coefficients of determination ($R^2 > 0.87$).

Therefore, more than 87 % of the changeability in the properties might be described by the full factorial models as a linear interaction of the factors. As displayed in Table 4, the centrifuge stability and the amount of surface oil were mostly affected by maltodextrin concentration. The Arabic gum and methylcellulose concentrations had the most significant ($p < 0.05$) effects on the surface mean diameter and span in the emulsion, respectively. The main and interaction effects of maltodextrin were significant ($p < 0.05$) in all reduced models that were fitted for all responses. The following models were fitted for every response variable:

Surface mean diameter:

$$Y_1 = 20.675 - 0.342x_1 - 2.939x_2 + 0.113x_{12} \quad (2)$$

Span:

$$Y_2 = -25.147 + 1.615x_1 + 3.164x_2 - 0.221x_3 - 0.222x_{12} + 1.216x_{23} \quad (3)$$

Stability:

$$Y_3 = 11.765 + 0.684x_1 + 12.289x_2 + 10.276x_3 - 0.648x_{12} \quad (4)$$

Surface oil:

$$Y_4 = 2.059 - 0.033x_1 + 0.063x_2 - 0.006x_{12} \quad (5)$$

Emulsion droplet size analysis

The effect of factors on the related responses was shown by surface plots. As shown in Table 4, the surface mean diameter (D_{32}) of droplets was significantly affected by the main terms of maltodextrin and Arabic gum as well as their interaction terms. The surface mean diameter was mostly affected by the Arabic gum concentration. Generally, the results showed that the main term of maltodextrin and Arabic gum had decreasing effect on surface mean diameter (D_{32}) and augment in these two independent variables had shown positive effect on lowering the D_{32} .

As shown in Fig. 1a, increasing the concentration of Arabic gum at all concentrations of maltodextrin caused a reduction in D_{32} . The reduction is due to the lowering effects of droplets surface mean diameter by the Arabic gum. By increasing the Arabic gum concentration, the adequate amounts of absorbed polysaccharide in the aqueous phase of the emulsion can be provided, and Arabic

Table 3 Regression coefficients, R^2 and adjusted R^2 probability values for variables

Coefficient	Surface mean diameter of emulsion (D_{32})	Span of emulsion	Centrifuge stability of emulsion	Surface oil of powder
b_0	20.675	-25.147	11.765	2.059
b_1 (MD)	-0.342	1.615	0.684	-0.033
b_2 (AG)	-2.939	3.164	12.289	0.063
b_3 (MC)	—	-0.221	10.276	—
b_{12}	0.113	-0.222	-0.648	-0.006
b_{13}	—	—	—	—
b_{23}	—	1.216	—	—
R^2	93.41%	87.87%	92.75%	95.84%
R^2 (adj)	89.56%	76.96%	87.47%	93.41%

* b_0 is a constant, b_i and b_{ij} are the linear and interaction coefficients respectively

1: Maltodextrin 2: Arabic gum 3: Methylcellulose concentration

Table 4 The significance probability (P-value, F-ratio) of the regression models

Variables		Main effects			Interacted effects		
		x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3
Surface mean diameter of emulsion (Y_1)	P-value	0.000*	0.000*	—	0.000*	—	—
	F-ratio	24.403	53.728	—	38.688	—	—
Span (Y_2)	P-value	0.002*	0.785	0.001*	0.001*	—	0.033*
	F-ratio	16.728	0.078	22.657	20.430	—	6.100
Centrifuge Stability (Y_3)	P-value	0.000*	0.382	0.018*	0.001*	—	—
	F-ratio	47.61	0.828	7.672	19.096	—	—
Surface oil (Y_4)	P-value	0.000*	0.000*	—	0.004*	—	—
	F-ratio	217.56	43.69	—	12.18	—	—

* x is factor, x_i and x_{ij} are the main and interaction effects of factors, respectively

1: Maltodextrin 2: Arabic gum 3: Methylcellulose concentration

*Significant ($p < 0.05$)

gum as an emulsifier can saturate the surface of droplets properly to produce small oil droplets.

As displayed in Table 4, the width distribution of the droplets (span) was mostly affected by methylcellulose

Fig. 1 Effects of maltodextrin, Arabic gum, and methylcellulose on surface mean diameter (a) and width distribution of the droplets in fish oil emulsion (b and c)

concentration. Methylcellulose helped to produce an emulsion with a narrow distribution of particles. The results showed that the interaction between Arabic gum with maltodextrin and methylcellulose had decreasing and increasing effects, respectively, on the span (Table 3). As illustrated in Fig. 1b, increasing the concentration of Arabic gum at low concentrations of maltodextrin caused an increase in width distribution of droplets; however, increasing the concentration of Arabic gum at high concentrations of maltodextrin had a reverse effect on the span. Therefore, there is an optimal area for maltodextrin and Arabic gum interactions to produce a fish oil emulsion with the minimum width distribution of droplets. Increasing the Arabic gum concentration at low concentrations of methylcellulose caused a reduction in width distribution of droplets; however, increasing the concentration of Arabic gum at high concentrations of methylcellulose had a reverse effect on the span. Thus, there is an optimal area for methylcellulose and Arabic gum interactions to produce a fish oil emulsion with the minimum span Fig. 1c. This results demonstrated that the size of droplets in the emulsion was significantly affected by the type of biopolymer; the same result was obtained by Jafari et al. (2008) and is in agreement with of the study by Teixeira et al. (2004), in which particles with maltodextrin were larger in size than those with Arabic gum or a combination of Arabic gum and maltodextrin. Furthermore, maltodextrin caused the formation of particles with a large span; the same effect was found by Omar et al. (2009).

Centrifuge stability of the emulsion

The results in Table 4 showed that the centrifuge stability was mostly affected by maltodextrin. The main terms of maltodextrin and methylcellulose had increasing effect on centrifuge stability and augment in main concentration of these two factors help to increase in this response. As illustrated in Fig. 2a, increasing the Arabic gum concentration at low concentrations of maltodextrin caused an increase in centrifuge stability of the emulsion; however, increasing the Arabic gum concentration at high concentrations of maltodextrin had a reverse effect on stability. Therefore, there is an optimal area for maltodextrin and Arabic gum interactions to produce a stable fish oil emulsion.

The oil-in-water emulsion stability was intensely affected by the existence of polysaccharides. The results indicate that at a high concentration of Arabic gum and a low concentration of maltodextrin, there is an adequate existence of absorbed polysaccharides in the aqueous phase of the emulsion. Dickinson et al. (1999) stated that when an adequate amount of emulsifier surrounds the surface of the droplets, an additional increase in the amount of emulsifier may lead to a bigger size of droplets and consequently coalescence is

triggered by the extra amounts of biopolymers which are not absorbed.

The main effect of methylcellulose in increasing centrifuge stability can be explained by the production of droplets with a reduced size and a narrow distribution range. These results prove that the droplet size and, subsequently, the physical stability of the emulsions, are significantly dependent on the proper ratio of coating materials. The same result was reported in a study by Mirhosseini et al. (2009), in which the low concentration of xanthan gum and high concentration of Arabic gum led to the greatest emulsion stability. Similar results were also found by Papalmprou et al. (2005) and Tsaliki et al. (2004). Moreover, these results are in agreement with the commonly held opinion that an emulsion with tiny droplets has more stability than an emulsion with large droplets; the rate of flocculation is typically slower when the droplet size is smaller (Klaypradit and Huang 2008).

Fig. 2 Effects of maltodextrin and Arabic gum on the centrifuge stability (a) and amount of surface oil (b) in emulsion and encapsulated fish oil respectively

Surface oil of the powder

Surface oil is only fragment of the oil that exists at the external layer of particles and described as free oil, extractable oil or unbounded oil. Extractable oil, determined as the extent of the oil that can be removed from microcapsules by an organic solvent. As displayed in Tables 3 and 4, the surface oil was significantly affected by the main and interaction terms of maltodextrin and Arabic gum. According to the Table 4, the amount of surface oil was mostly affected by the maltodextrin concentration. Results showed that the main term of maltodextrin and also its interaction with Arabic gum had a decreasing influence on amount of surface oil and augment in maltodextrin concentration had positive effect on lowering the amount of surface oil.

As displayed in Fig. 2b, reduced amounts of maltodextrin caused the production of powders with a high amount of free oil; however, at high concentrations, this independent variable with high concentrations of Arabic gum had a positive effect on lowering the amount of free oil, indicating that the maltodextrin is one of the primary wall materials to protect the fish oil from environment and prevent its release outside of the capsules. The same results were obtained in a study by Raja et al. (1989), in which the maltodextrins with a DE between 10 and 20 were demonstrated to have the greatest retention of

core materials when combined with other wall materials. Studies conducted by Krishnan et al. (2005), indicated that the combination of Arabic gum and maltodextrin was effective in the microencapsulation of cardamom oil; i.e., the retention of the core material was greater in blends of maltodextrin and Arabic gum.

Optimization procedure of the coating material

The fish oil emulsion can be considered as the best product if the procedure resulted in the smallest surface mean diameter (D_{32}), the narrowest width distribution of the droplets (span), the minimum amount of surface oil and the highest centrifuge stability. The optimal procedure was done by graphical and numerical response optimizations. The 3D response surface plotting was used for the graphical optimization procedure. Consequently, the optimum condition was specified by superimposed plots together. Moreover, a numerical optimization was done in order to check the best levels of factors leading to the desirable response objectives. In current study, the figures display the significant ($p < 0.05$) interaction effects of the three studied factors, making the desirable objectives for the relevant responses. According to the numerical optimization results, the most desired coating material for the encapsulation of fish oil was obtained when 16 % (w/w)

Table 5 Experimental and predicted values for all response variables

Run	* D_{32} (Y_1 , μm)		*Span (Y_2)		*Emulsion stability (Y_3 , %)		*Surface oil (Y_4 , %)	
	Y_0	Y_1	Y_0	Y_1	Y_0	Y_1	Y_0	Y_1
1	11.24	10.53	11.50	10.26	20.00	18.16	0.05	0.03
2	4.90	5.44	2.02	1.88	57.81	55.66	0.20	0.16
3	9.71	11.04	12.04	11.30	25.00	27.47	0.24	0.19
4	10.66	11.62	1.18	1.53	41.60	44.10	0.25	0.20
5	9.84	7.72	2.03	2.79	65.83	67.82	0.18	0.12
6	11.87	12.20	1.53	2.14	0.00	0.57	0.07	0.03
7	8.13	7.11	11.66	12.25	62.50	60.22	0.18	0.15
8	12.08	12.71	18.15	16.9	36.66	38.03	0.10	0.08
9	7.85	9.38	8.20	7.26	69.16	68.10	0.13	0.11
10	14.76	13.29	1.54	2.17	43.33	44.11	0.22	0.18
11	7.04	7.55	10.54	10.92	48.43	51.24	0.19	0.16
12	9.62	9.83	3.72	3.92	50.00	52.12	0.19	0.12
13	13.12	13.73	1.56	2.16	33.33	30.13	0.23	0.19
14	14.91	13.15	11.79	12.25	35.00	33.05	0.14	0.09
15	12.21	12.65	1.80	1.48	0.00	0.80	0.08	0.02
16	4.97	4.95	2.55	1.71	37.50	35.11	0.21	0.16
17	10.10	10.04	9.81	9.08	19.16	16.61	0.05	0.02
18	6.84	7.22	2.64	2.62	73.33	71.26	0.19	0.12
19	11.23	11.13	1.61	1.35	36.66	39.55	0.25	0.19
20	10.73	10.54	6.29	6.13	20.83	22.92	0.07	0.09

*No significant ($p > 0.05$) difference between experimental (Y_0) and predicted (Y_1) values

maltodextrin, 6.5 % (w/w) Arabic gum and 0.88 % (w/w) methylcellulose were used. In optimal condition, the respective response values for surface mean diameter (D_{32}), width distribution of droplets (span), centrifuge stability and amount of surface oil were found to be 5.86(μm), 5.32, 57.08 (%) and 0.16 (%), respectively.

Verification of models

The acceptability of the equations was tested by the assessment of trial and fitted values expected. Three fish oil emulsion and subsequently encapsulated powders were produced according to the expected best concentrations of maltodextrin, Arabic gum and methylcellulose. The properties of fish oil emulsion and encapsulated powders were assessed. In addition, for comparison between the experimental and expected values, the t-test was also carried out. As shown in Table 5, there was no significant ($p < 0.05$) differences between the predicted and experimental values. This verified the sufficiency of the regression models concerning the factors and response variables considered. The results showed that the respective experimental values for surface mean diameter (D_{32}), width distribution of droplets (span), centrifuge stability of emulsion and surface oil of powders that were prepared under desired conditions were 6.28 (μm), 4.71, 57.40 (%) and 0.13 (%), respectively.

Conclusions

In this study, the combination of maltodextrin, Arabic gum, and methylcellulose as coating material had positive effects in producing the fine fish oil emulsion, and encapsulated powder. Overall, the results showed that every selected response has been influenced significantly by the studied independent variables. Therefore, adjusting the concentration of all coating materials was found to be imperative in order to define the variations in the response variables. Empirically significant ($p < 0.05$) models for assessing the variation of surface mean diameter, width distribution of droplets, centrifuge stability and amount of surface oil, as a function of three types of coating materials concentrations including maltodextrin, Arabic gum, and methylcellulose were developed by a response surface methodology. In most cases, fitting of the linear and interaction regression models with the experimental data were sufficient to explain and predict the interaction between the coating materials. The physical properties of the fish oil emulsion and encapsulated powder ($R^2 > 0.87$) were found to be satisfactory. The fish oil emulsions that were prepared at 16 % (w/w) maltodextrin, 6.5 % (w/w) Arabic gum, and 0.88 % (w/w) methylcellulose were shown to provide the desired physical properties of the emulsion.

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