The application of high purity diacylglycerol oil in whipped cream: effect on the emulsion properties and whipping characteristics

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ABSTRACT

The objective of this work was to examine the application of high purity diacylglycerol (DAG) oil in whipped cream as a partial substitute of hydrogenated palm kernel oil (HPKO). The DAG-enriched oil, with a purity of 94.50 wt%, was prepared via the enzymatic glycerolysis of palm oil/peanut oil blend and followed by molecular distillation. The substitute levels of 0, 10%, 20%, 30% and 40% (w/w) DAG for HPKO were employed, and the effects of DAG on emulsion properties, whipping characteristics and sensory quality were investigated. The result showed DAG oil promoted partial coalescence of fat globules in emulsion. As 0–20% DAG was involved in the emulsion, the average particle size ($d_{3,2}$), surface protein concentration (SPC), partial coalescence of fat and overrun increased during whipping. The results of textural characteristics and sensory evaluation showed that 10-30% DAG substitute for HPKO would be successfully applied in whipped cream.

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1. Introduction

Whipped cream is one of the most popular dairy products used in desserts, pastries, cakes, and ice creams. Whipped cream emulsion is a complex system because it is quiescently stable prior to freezing and is unstable with the occurrence of partial coalescence when shearing (Goff, 1997). Generally, partial coalescence plays an important role in stabilizing the structure of whipped cream and brings desirable texture for this product. The partial coalescence in whipped cream could increase the viscosity of the system due to the nonspherical shape of the fat aggregates and the ensuing formation of a continuous structural network (Stanley, Goff, & Smith, 1996). Stable and desired whipped cream is obtained when air bubbles are covered totally by fat network. Fredrick et al. and Petrut et al. reviewed the formation and assessment of partial coalescence in ordinary and whipped oil-in-water food emulsions (e.g. ice cream, whipped cream), respectively (Fredrick, Walstra, & Dewettinck, 2010; Petrut, Danthine, & Blecker, 2016). Zhao et al. studied the effects of xanthan gum, hydroxypropyl methylcellulose and sorbitan monostearate on the stability of whipped cream (Zhao et al., 2013; Zhao, Zhao, Li, et al., 2009; Zhao, Zhao, Yang, & Cui, 2009). Farahmandfar, Asnaashari, Salahi, and Rad (2017) explored the effects of three kinds of gum on the physical, textural and rheological properties of whipped cream. They found Basil seed gum was more suitable to obtain better hardness and adhesive- ness of cream than Cress seed gum and Quince seed gum. Nguyen, Duong, and Vu (2015) reported tempering at 30°C combined with fast cooling was beneficial for forming partial coalescence in cream. Sajedi, Nasirpour, Keramat, and Desobry (2014) modified the whey protein concentrate structure and applied in whipped cream, which resulted in desirable overrun and textural properties.

In whipped dairy emulsions, oils present different functionalities due to their crystallization behaviors in low temperature (Goff, 1997). The selection of oil is essential to the foamability and denseness of whipped cream, because its crystalline characteristic and solid fat content (SFC) would
affect the degree of partial coalescence as well as foam stability (Hotrum, Cohen Stuart, van Vliet, & van Aken, 2004; Ihara et al., 2010).

Currently, hydrogenated vegetable oil or its mixture with anhydrous milk fat is employed in whipped cream as the oil phase (Munk et al., 2013). However, there are relatively high contents of saturated fatty acids involved and trans-fatty acids might be formed during the hydrogenation process. An excessive intake of hydrogenated oil may cause some diseases such as obesity, hyperlipidemia, cardiopathy, etc. (Nelson, 1998). Therefore, developing healthier oils to substitute the hydrogenated vegetable oil in whipped cream is meaningful. Kim et al. reported coconut milk was suitable as a partial substitute for whipping cream in a type of chocolate ganache (Kim et al., 2017).

Since the 2000s, the beneficial effects of diacylglycerol (DAG) have been found on managing body weight, obesity and weight-related disorders (Maki et al., 2002; Nagao et al., 2000). Dietary DAG exhibits anti-obesity activity and may prevent postprandial hypertriglyceridemia in experimental animals and humans (Murase et al., 2001; Nagao et al., 2000). DAG in different degrees of purity was used as additives or carriers in fried, baked or frozen foods, and its applicability was examined (Cain, Manson, Quinlan, & Moore, 1999; Cheong et al., 2011; Li, Kimura, Endo, Maruyama, & Fujimoto, 2005). Matsumiya et al. stated the diglycerol ester of mono-oleic acid, a bacteriostatic emulsifier, would cause the coalescence of oil droplets stabilized by milk proteins and phase separation between oil and aqueous phase (Matsumiya, Takahashi, Nakanishi, Dotsu, & Matsumura, 2014). In our previous study, a high purity (95.0%) DAG was prepared through glycerolysis of peanut oil and it was employed to prepare an oil-in-water emulsion, whose properties and stabilities were compared with the peanut oil-based emulsion (Long et al., 2015). Interestingly, the DAG emulsion was found to exhibit good whipability, indicating that it was potential for applications in whipping cream food products.

In the present study, palm oil/peanut oil blend was used as the material, and the high purity DAG oil was prepared by enzymatic glycerolysis reaction and molecular distillation. Then, it was applied in whipped cream as a partial substitute of hydrogenated palm kernel oil (HPKO), which occupied 0, 10%, 20%, 30%, and 40% content, respectively, on the basis of hydrogenated palm kernel oil (HPKO), which occupied 0, 10%, 20%, 30%, and 40% content, respectively, on the basis of the total HPKO mass. The effects of different DAG content substrates on emulsion properties and whipping characteristics were investigated.

2. Materials and methods
2.1. Materials
HPKO (NO. BL-39) was donated by Southsea Oil & Fat Industrial Inc. (Shenzhen, China). Peanut oil was purchased from Yihai Grain & Oil Industrial Co., Ltd. (Guangzhou, China). Palm oil was purchased from Southsea Oil & Fat Industrial Inc. (Shenzhen, China). Lipase Lipzyme RM IM was supplied by Novozymes (Copenhagen, Denmark). Xanthan gum of food grade (80SP) was provided by the Cargill Group (Shanghai, China). Sorbitan monostearate (Span 60) was supplied by Danisco Co., Ltd. (Kunshan, China). Sodium caseinate with 95% of protein content was purchased from New Zealand Milk Products Co. (Santa Rosa, CA). Sucrose ester (S1170) was sourced from Mitsubishi Chemical Co. (Tokyo, Japan). Hydroxypropyl methylcellulose of food grade was kindly donated by Dow Chemical Co. (Midland, MI). Corn syrup, glucose, and glucose were supplied by a local supermarket. Oil Red O was supplied by AMRESCO (Ohio, USA).

2.2. High purity DAG oil preparation
Combined strategies of enzymatic glycerolysis and molecular distillation were adopted to obtain the high purity DAG oil. Reaction mixture consisting of a certain amount of palm oil, peanut oil, and glycerol was subjected to glycerolysis reaction in the presence of lipase Lipzyme RM IM in a solvent-free system under the selected glycerolysis conditions, which were palm oil/peanut oil mass ratio of 3:2, oil/glycerol mass ratio of 1:6, initial water content 4 wt% of substrates, and Lipzyme RM IM amount 5 wt% of substrates. After the reaction, the mixture was purified according to the method of Long et al. (2015). And the acylglycerol composition of the final product was determined by the method of Zhong et al. (2009).

2.3. Fatty acid (FA) composition, melting point, and SFC analysis
The FA composition, melting point and SFC of HPKO and DAG were analyzed according to the method of Long et al. (2015)

2.4. Emulsion preparation
The substitute levels of DAG were selected as 0, 10%, 20%, 30% and 40% on the basis of the total HPKO mass. The water phase contained 6.20% corn syrup, 5.00% sucrose, 16.50% glucose, 0.80% sodium caseinate, 1.00% hydroxypropyl methylcellulose, 0.06% xanthan gum, 0.04% sodium dihydrogen phosphate and 0.04% sodium hydrogen phosphate. These powders were dissolved in water overnight for full hydration. The oil phase contained 18% HPKO, 0.06% sucrose ester and 0.60% Span 60. All percentage presented above is based on the total mass of the water phase and oil phase. Pre-emulsions were prepared through mixing oil and aqueous phase under constant stirring with an agitation speed of 600 rpm at 60°C for 30 min using a digital overhead stirrer (RW20, IKA Co., Ltd., Germany). The lost emulsions during pre-emulsification were compensated by deionized water. Subsequently, a 2-stage single-piston homogenizer (ATS-Basic I, Ontario, Canada) was immediately employed to homogenize the pre-emulsions with a pressure of 60 MPa and 15 MPa, respectively, at the first and second stage. The prepared emulsions above were cooled to 15°C before hardening at −18°C overnight. The hardened emulsions should be thawed to 4°C prior to whipping.

2.5. Determination of average particle size
The average particle size of creams, when whipping for 0–4 min, was determined with Malvern Mastersizer 2000 (Malvern Instruments Co., Ltd., Worcestershire, UK). The refractive index and adsorption of the dispersed phase were set as 1.414 and 0.001, respectively, and the refractive index of the continuous phase was 1.330 (Long, Zhao, Yang, & Liu, 2012). The emulsions in the sample chamber were diluted 1000-fold
with deionized water. The surface area average diameter \(d_{3,2}\) (μm) was calculated by Equation (1).

\[
d_{3,2} = \frac{\sum n_i d_i^3}{\sum n_i d_i^2}
\]

where \(n_i\) represents the number of particles of the same diameter; \(d_i\) represents the particle size.

### 2.6. Measurement of surface protein concentration (SPC)

The method of Long et al. (2012) with minor modification was adopted to determine the surface protein concentration (SPC) of emulsion. A temperature-controlled centrifuge (Model GL-21 M, Xiangyi Instrument Co., Ltd., Changsha, China) was employed to centrifuge the samples at 10,000 \(\times g\) for 30 min at 25°C. After centrifugation, the supernatant was withdrawn by a 10 mL syringe. The protein content of the supernatant was determined by the micro-Kjeldahl procedure. The specific surface area (SSA, m²/g) of the fat globules was determined by the Malvern Mastersizer 2000. The SPC (\(\Gamma\), mg/m²) was calculated according to Equation (2).

\[
\Gamma = \frac{P_t - P_s}{M_c \cdot SSA} \times 1000
\]

where \(P_t\) represents the total protein content (g), \(P_s\) represents the protein content (g) of supernatant, and \(M_c\) represents the weight (g) of cream layer.

### 2.7. Determination of partial coalescence of fat

Oil Red O solution with the concentration of 0.0015 wt% (w/w, with respect to the oil mass) was prepared according to the method of Palanuwech, Potineni, Roberts, and Coupland (2003). A mixture containing 20 g emulsion and 10 g Oil Red O solution was added to a 50 mL centrifuge tube, and then centrifuged at 10,000 \(\times g\) for 30 min at 25°C using a Xiangyi Model GL-21 M centrifuge (Xiangyi Instrument Co. Ltd., Changsha, China). The absorbance of the supernatant of the diluted-dye solution was detected by UV-visible spectrophotometer (Perkin-Elmer, Lambda 3, Norwalk, CT) at 520 nm using corn oil as the blank. The alteration of the absorbance indicated the mass of the un-emulsified portion in the fat (\(\phi_d\)), which was calculated according to Equation (3).

\[
\phi_d = \frac{m_0(a - 1)}{m_e \varphi}
\]

where \(m_0\) is the mass of added Red Oil O solution, \(m_e\) is the mass of emulsion, \(a\) is the ratio of absorbance of Red Oil O solution before and after centrifugation, and \(\varphi\) is the mass fraction of oil in the emulsion.

### 2.8. Measurement of overrun

The overrun was measured according to the method of Scurlock (1986). It was performed by filling a tub to a set volume with the whipped cream. The overrun was related to the mass of this volume and the density of the cream before whipping. It was determined according to Equation (4).

\[
\text{Overrun (m}^3\text{air/100 m}^3\text{unwhippedcream)} = \frac{M_1 - M_2}{M_2} \times 100\%
\]

where \(M_1\) (g) represents the mass of the unwhipped cream with a certain volume, and \(M_2\) represents the mass of the whipped cream of the same volume.

### 2.9. Textural characteristics analysis

A TA-XT2i texturometer (Stable Microsystems, Surrey, UK) was employed to measure the force in penetration to analyze the textural characteristics of whipped cream. A cylindrical sample cup with a diameter of 5.0 cm and a height of 9.0 cm was employed. The probe penetrated into the sample to a depth of 25 mm at a rate of 2 mm/s and the 5 g trigger force exerted on the probe was automatically recorded. The analysis was performed at approximately 10°C, and four parameters (firmness, consistency, cohesiveness, and viscosity) were collected.

### 2.10. Sensory evaluation of whipped cream

Twelve trained panelists (6 male and 6 female) were recruited for the sensory evaluation of whipped cream. The sensory rating scale for body and texture, for flavor and taste, and for color and appearance were set as 1–10, 1–5 and 1–5, respectively (Akin, Akin, & Kirmaci, 2007). The standard for evaluation was as follows: (a) body and texture (10 for no criticism, 9–7 for crumbly and gummy, 7–4 for weak and fluffy, 5–1 for stiff and coarse, and 1–3 for the others); (b) flavor and taste (5 for no criticism, 4–1 for lack of sweetness and too sweet, 4–1 for light or heavy greasiness, 3–1 for lack of flavor); (c) color and appearance (5 for no criticism, 4–1 for dull color, 3–1 for unnatural color). To main the integrity and freshness of the whipped cream samples, they were preserved in the refrigerator at 4°C during sensory evaluation.

### 2.11. Statistical analysis

All the experiments were performed in triplicate. The analysis of variance (ANOVA) was performed using the SPSS 16.0 statistical analysis system. The level of confidence required for significance was defined at \(P < 0.05\) using Tukey’s test.

### 3. Results and discussion

#### 3.1. Determination of FA composition, melting points and SPC of HPKO and DAG

The obtained oil was composed by 4.78 wt% of triacylglycerol (TAG), 94.50 wt% of DAG, 0.61 wt% of monoacylglycerol (MAG), and 0.11 wt% of free fatty acids, respectively, which could be regarded as high purity DAG oil. The FA composition of HPKO and DAG were also measured, and the results are summarized in Table 1. The HPKO had a high concentration of saturated fatty acids (SFA) including lauric acid (C12:0, 48.83 wt%), myristic acid (C14:0, 14.48 wt %) and stearic acid (C18:0, 18.51 wt%), because it was obtained by hydrogenation of palm kernel oil. The DAG oil was obtained by the enzymatic glycerolysis of palm oil/peanut oil blend and molecular distillation, and it had a large quantity of long chain unsaturated fatty acids (UFA)
including oleic acid (C18:1, 42.01 wt%) and linoleic acid (C18:2, 22.53 wt%). Besides, it contained 26.95 wt% palmitic acid (C16:0).

The differential scanning calorimetry (DSC) melting thermograms of HPKO and DAG were shown in Figure 1a. For HPKO, a major endotherm peak (peak 2, 30.6°C) with two shoulder peaks at higher temperature (peaks 3, 38.6°C) and a lower temperature (peak 1, 19.8°C) were found. The melting curve of DAG showed four melting peaks, and the transition temperatures were 5.1°C (peak 1), 15.6°C (peak 2), 35.8°C (peak 3) and 38.7°C (peak 4) respectively. Both peak 2 and peak 3 had wider temperature ranges. The difference in the DSC melting thermograms between HPKO and DAG could result from the higher SFA content of HPKO and their different structures of acylglycerols.

SFC has a decisive effect on the characteristics and application range of lipids: SFC of lipids at 5°C can represent its crystallization property under refrigerated storage (Dian, Sundram, & Idris, 2007). At 25°C, it was concerned with the fusion characteristic of lipids at ambient temperature. SFC at 35°C determined the flavor of lipids. In this work, we measured the SFC of HPKO and DAG between 5°C and 55°C by a nuclear magnetic resonance (NMR) imaging device, and the results are shown in Figure 1b.

It could be found that SFC of HPKO was higher than that of DAG between 5°C and 45°C. At 5°C, the SFC of HPKO was 92.82% due to its high SFA content (97.56%). However, the SFA content of DAG was measured as 34.55% (Table 1), and the SFC (42.72%) of which at 5°C was far below than that of HPKO. When the temperature was 25°C, the SFC of HPKO and DAG decreased to 55.36% and 16.42%, respectively. According to the melting thermograms of HPKO and DAG (Figure 1a), all of the endotherm peaks of DAG located below 40°C, thus leading to almost melting between 35°C and 40°C. Nevertheless, HPKO had the wide endotherm peak 3 which spreading to 42.5°C. As a result, between 35°C and 40°C, the SFC of HPKO reduced to less than 10% whereas the SFC of DAG decreased to less than 2%.

The study of Boode and Walstra (1993) showed that whether emulsions can form a stable foam structure was related to the melting point of oil phase, because the SFC of lipids at ambient temperature determined whether partial coalescence of fat can happen in fat globules and the degree of that. Based on the DSC and SFC characteristics of DAG, when used in whipped cream, it should be obtained a melt-in-the-mouth feel.

### 3.2. Effect of DAG substitute on the emulsion properties of whipped cream

#### 3.2.1. Effect on the average particle size

For investigating the application of DAG as a partial substitute of HPKO, different DAG substitute levels (0, 10%, 20%, 30%, and 40%, on the basis of total HPKO mass) were studied.

Large fat globules are broken into small fat globules during homogenization. The particle size (d_{3,2} values) of cream samples in different whipping time (0–4 min) were measured. As illustrated in Figure 2, after homogenization, frozen and thaw process (0 min), the d_{3,2} of the control (no DAG involved) was 0.264 μm. And samples with 10–30% DAG substitute were all higher than the control. When 40% DAG substitute used, the d_{3,2} represented the highest value (0.998 μm). During whipping (1–4 min), the d_{3,2} of each sample increased constantly. After 4 min whipping, the d_{3,2} of five samples differed significantly (P < 0.05). From 0% to 40% DAG substitute, their d_{3,2} were 0.515, 2.011, 2.879, 3.996, and 5.398 μm, respectively. Namely, increase of DAG substitute led to a further increase of average particle size.

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**Table 1.** Fatty acid compositions (wt%) of hydrogenated palm kernel oil (HPKO) and diacylglycerol (DAG)*.

| Fatty acid | HPKO  | DAG   |
|-----------|-------|-------|
| C8:0      | 3.98  | N.D.  |
| C10:0     | 3.78  | N.D.  |
| C12:0     | 48.83 | N.D.  |
| C14:0     | 14.48 | 0.33  |
| C16:0     | 7.98  | 26.95 |
| C18:0     | 18.51 | 4.15  |
| C18:1     | 2.44  | 42.01 |
| C18:2     | N.D.  | 22.53 |
| C20:0     | N.D.  | 1.03  |
| C20:1     | N.D.  | 0.91  |
| C22:0     | N.D.  | 1.37  |
| C24:0     | N.D.  | 0.72  |
| Saturated fatty acid | 97.56 | 34.55 |
| Unsaturated fatty acid | 2.44 | 65.45 |

* Values show the means of three replicates. ** N.D. means not detected.

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**Figure 1.** DSC melting thermograms (a) and SFC (b) of hydrogenated palm kernel oil (HPKO) and diacylglycerol (DAG).

**Figure 1a.** Termogramas de fusión de DSC (a) y SFC (b) del aceite de palmito hidrogenado (HPKO) y el diacilglicerol (DAG).
Average particle size is an indicator of droplet size in the emulsion. It strongly influences the emulsion stability and whipping properties of whipped cream. Comparing with the control, DAG creams contained slight MAG. Both of them are amphiphilic compounds and can migrate to the oil–water interface to affect the crystallization behavior of HPKO. According to the theory of Bayés-García et al. (2015) the hydrophilic group (hydroxyl group) of DAG/MAG will reside in the aqueous side of the interface and the acyl chain exposed to the oil phase, so the association between DAG/MAG and fatty acid chains of HPKO occurred through van der Waals interactions, which were promoted by their similar acyl chain lengths match. During freezing, below the crystallization temperature, the associated acyl chains in the DAG/MAG and oil co-solidified via interfacial HPKO gathered at the oil–water interface, which was a DAG/MAG mediated crystallization. As a consequence, the crystals became thicker, spread, and covered the entire droplet with a solid fat crystal shell. After thawing, the gathered crystallization promoted the emulsion to exhibit lower elasticity of interfacial film, thus making the emulsion more prone to partial coalescence. Matsumiya et al. (2014) also stated DAG would occupy the oil droplet surfaces to promote coalescence of emulsion oil droplets probably because it actively migrated between oil and aqueous phase. In our previous study (Long et al., 2015), the peanut oil-based DAG was used in O/W emulsion. After the frozen-thawing process, the volume weighted average diameter of DAG emulsion was 25.744 μm, whereas the peanut oil emulsion was just 1.008 μm. In the present study, therefore, the more DAG used, the larger particle size ($d_{3,2}$) obtained at 0 min whipping. In addition, during whipping procedure, droplets connected fat clumps in the bulk and adhered to the air bubble surface, giving structural integrity to the foam and further increase of $d_{3,2}$ (1–4 min). Namely, the droplet size shifted to a larger range increasingly resulted from mechanical shear and air incorporation.

3.2.2. Effect on the surface protein concentration (SPC)
Determining the extent of protein adsorption is a straightforward method to obtain information on adsorbed layers. The effect of DAG substitute on SPC of whipped cream during whipping is shown in Table 2. Between 0 and 4 min, the SPC of the control and 10% DAG substitute samples were relatively low all the time (less than 1.30 mg/m$^2$). As to the other samples, their SPC increased gradually during 0–1 min whipping, and accelerated greatly when whipping for 2–4 min. After 4 min of whipping, the SPC of the control was 0.46 mg/m$^2$, and the samples with 10%–40% DAG substitute were 1.27, 2.76, 3.98 and 5.28 mg/m$^2$, respectively.

According to Equation. (2), SPC was determined by the absorbed total protein and the specific surface area (SSA) of fat globules (Long et al., 2012). With the extension of whipping time, the competitive desorption between emulsifier and protein would result in the decrease of the total protein adsorbed on the interface. From particle size measurement, along with DAG substitute increased from 0% to 40%, as the droplet size further increased, the SSA of fat globules decreased rapidly (data not shown), and the decrease velocity of which was much higher than the reduction velocity of total protein adsorbed on interface, thus leading to higher SPC for the higher DAG substitute samples. During whipping, a large quantity of air was whipped into creams, so new air–water interfaces were constantly made. The sharp increase of surface protein concentration could be attributed to the faster decrease of SSA than that of total surface protein load. As a result, a positive whipping time-dependent effect was observed.

3.2.3. Effect on the partial coalescence of fat
During whipping, air is incorporated into the initial emulsion of fat globules, and emulsion droplets are adhered to the air

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**Table 2.** Effect of diacylglycerol (DAG) substitute on the surface protein concentration (SPC) (mg/m$^2$) of whipped cream during whipping*.

| DAG substitute | Whipping time (min) |
|---------------|---------------------|
|               | 0                   | 1                   | 2                   | 3                   | 4                   |
| 0%            | 0.26 ± 0.02$^a$     | 0.31 ± 0.02$^a$     | 0.34 ± 0.03$^a$     | 0.39 ± 0.02$^a$     | 0.46 ± 0.04$^a$     |
| 10%           | 0.32 ± 0.04$^b$     | 0.39 ± 0.03$^a$     | 0.47 ± 0.03$^b$     | 0.94 ± 0.06$^c$     | 1.27 ± 0.06$^b$     |
| 20%           | 0.58 ± 0.02$^b$     | 0.95 ± 0.03$^c$     | 1.17 ± 0.06$^c$     | 1.98 ± 0.06$^d$     | 2.76 ± 0.11$^d$     |
| 30%           | 0.76 ± 0.02$^c$     | 1.41 ± 0.03$^d$     | 1.95 ± 0.04$^d$     | 3.47 ± 0.09$^e$     | 3.98 ± 0.10$^d$     |
| 40%           | 1.68 ± 0.07$^d$     | 2.83 ± 0.08$^d$     | 3.43 ± 0.05$^e$     | 4.79 ± 0.12$^a$     | 5.28 ± 0.02$^d$     |

* Data are expressed as means ± standard deviation. The values with different letters in each column are significantly different ($P < 0.05$).

* Los datos representan las medias ± desviación estándar. Los valores que presentan letras diferentes en cada columna son significativamente diferentes ($P < 0.05$).
bubbles where they can partially coalesce (Camacho, Martínez-Navarrete, & Chiralt, 2001). In our experiment, all samples were whipped at 4°C. We measured the SFC of oil blend (HPKO and DAG) and emulsions with 0, 10%, 20%, 30% and 40% DAG substitute. At 4°C, the SFC of oil blend were 93.2%, 88.1%, 83.2%, 78.0% and 72.9%, respectively. And the SFC of emulsions were 16.7%, 15.8%, 14.9%, 14.0% and 13.1%, respectively.

Table 3 shows the change of partial coalescence of fat in different DAG content creams during whipping. It can be seen that the partial coalescence of fat in every sample increased with the increase of whipping time. The control had the lowest partial coalescence of fat. The sample with 20% DAG substitute exhibited the highest partial coalescence of fat, which reached 62.59% when whipping for 4 min.

Partial coalescence of fat was proved to be related to the surfactant absorbed on the interface as well as the SFC of the droplets (Goff, Liboff, Jordan, & Kinsella, 1987). In whipped cream, the shear force makes the initial fluid emulsion convert into the desired visco-elastic product. Generally, DAG has interfacial activity because of their hydrophobic glycerol moiety and a hydrophilic moiety derived from the free hydroxyl group. Adding surfactant (e.g. MAG) to the emulsion can decrease the elasticity of the interfacial film (Petrut et al., 2016). Both of DAG and MAG would affect the crystallization behavior of HPKO, thus making the emulsion more prone to partial coalescence (see Section 3.2.1).

During whipping, the shearing causes the colliding globules to partially coalesce as a result of these fat crystals piercing the membranes (Stanley et al., 1996). As to the sample of 40% DAG substitute, during 0–1 min whipping, the emulsion contained a certain quantity of DAG, thus it had the highest partial coalescence of fat. When whipping for 2–4 min, however, the partial coalescence of fat of 40% DAG cream was lower than that of 0–30% DAG samples. The reason might be that increase of particle size (ds_{3,2}) of droplets led to reduction of the SSA, thereby increasing SFC. The slower increase of partial coalescence could be attributed to the dense adsorption layer that had restrained the coalescence of semi-solid fat droplets.

An appropriate amount ratio between fat crystal and fat liquid (or the SFC) was necessary condition for the formation of partial-coalesced fat globules (Nguyen et al., 2015). In the present study, the results showed that the SFC of emulsion more than 14% (or more than 78% of oil blend) seemed to ensure a desirable partial coalescence (>50%) in whipped cream. Davies et al. stated that partial coalescence was maximized in a SFC range 10–50% in ice creams (Davies, Dickinson, & Bee, 2000). Sung and Goff (2010) investigated the effect of SFC on structure in ice creams containing HPKO and high-oleic sunflower oil. They found that, at the draw temperature (~5°C), 60–80% SFC of oil blend could produce the highest partial coalescence and lowest rates of melt-down. The difference between their studies and ours might be attributed to the different whippable emulsion systems as well as environmental temperature.

### 3.2.4. Effect on the overrun

The overrun is the coefficient result of the velocity of partial coalescence of fat and the concentration of protein in liquid phase, which can represent the content of bubble in whipped cream (Goff, 1997). The effect of DAG substitute on the overrun of whipped cream is shown in Table 4. A positive whipping time-dependent effect was observed. It presented 3-stage of change tendency: (a) First, the overrun increased slowly. During 0–1 min, bubbles formed mainly because of the protein in the liquid phase. The velocity of partial coalescence of fat was very slow so that stable bubbles could not be formed even the system was incorporated with a large quantity of air, thus leading to the similar overruns (157.33–183.74%) of all samples. (b) Second, the overrun increased rapidly. As to the control, 10% and

| DAG Substitute | 1         | 2         | 3         | 4         |
|----------------|-----------|-----------|-----------|-----------|
| 0              | 157.33 ± 1.43<sup>a</sup> | 199.11 ± 2.93<sup>a</sup> | 241.34 ± 2.97<sup>a</sup> | 343.64 ± 3.12<sup>a</sup> |
| 10%            | 175.16 ± 2.41<sup>b</sup> | 224.58 ± 3.12<sup>b</sup> | 311.25 ± 1.71<sup>b</sup> | 347.86 ± 1.47<sup>b</sup> |
| 20%            | 178.95 ± 1.70<sup>a</sup> | 272.90 ± 2.19<sup>a</sup> | 326.77 ± 3.23<sup>a</sup> | 355.69 ± 3.75<sup>a</sup> |
| 30%            | 183.74 ± 1.82<sup>a</sup> | 299.28 ± 1.01<sup>a</sup> | 341.04 ± 2.05<sup>a</sup> | 295.45 ± 2.34<sup>a</sup> |
| 40%            | 169.97 ± 2.39<sup>a</sup> | 245.06 ± 2.32<sup>a</sup> | 258.56 ± 1.94<sup>a</sup> | 263.63 ± 1.66<sup>a</sup> |

<sup>a</sup> Data are expressed as means ± standard deviation. The values with different letters in each column are significantly different (<i>P</i> < 0.05).

<sup>b</sup> Los datos representan las medias ± desviación estándar. Los valores que presentan letras diferentes en cada columna son significativamente diferentes (<i>P</i> < 0.05).

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**Table 3. Effect of diacylglycerol (DAG) substitute on the partial coalescence of fat (%) of whipped cream during whipping.**

| DAG Substitute | 0 | 1 | 2 | 3 | 4 |
|----------------|---|---|---|---|---|
| 0              | 5.40 ± 0.06<sup>a</sup> | 11.96 ± 0.14<sup>a</sup> | 14.29 ± 0.08<sup>a</sup> | 29.37 ± 0.15<sup>a</sup> | 51.28 ± 0.17<sup>a</sup> |
| 10%            | 6.86 ± 0.14<sup>a</sup> | 13.51 ± 0.18<sup>a</sup> | 28.39 ± 0.10<sup>a</sup> | 51.67 ± 0.31<sup>a</sup> | 61.53 ± 0.27<sup>a</sup> |
| 20%            | 9.48 ± 0.22<sup>a</sup> | 16.27 ± 0.09<sup>a</sup> | 43.55 ± 0.21<sup>a</sup> | 57.43 ± 0.25<sup>a</sup> | 62.59 ± 0.17<sup>a</sup> |
| 30%            | 13.94 ± 0.09<sup>a</sup> | 19.51 ± 0.14<sup>a</sup> | 57.73 ± 0.29<sup>a</sup> | 61.52 ± 0.27<sup>a</sup> | 61.78 ± 0.31<sup>a</sup> |
| 40%            | 26.58 ± 0.17<sup>a</sup> | 29.56 ± 0.15<sup>a</sup> | 33.92 ± 0.11<sup>a</sup> | 45.88 ± 0.15<sup>a</sup> | 46.22 ± 0.27<sup>a</sup> |

<sup>a</sup> Data are expressed as means ± standard deviation. The values with different letters in each column are significantly different (<i>P</i> < 0.05).
20% DAG substitute samples, during 2–4 min of whipping, an increasing number of large bubbles broke into small bubbles because of gradual increase of partial coalescence of fat. After 4 min of whipping, there was a significant difference ($P > 0.05$) among the overrun of the three samples. However, if further whipping for 5 min, the overrun values decreased (data not shown). (c) Third, the overrun decreased. As to 30% DAG substitute sample, when whipping from 3 to 4 min, the whipping tolerability of bubbles became weak. As a result, the obtained small bubbles broke into large bubbles, leading to the decrease of overrun.

Actually, overrun of whipped cream depends on both factors: surface-mediated partial coalescence and the adsorption of the air bubble on the surface of proteins (Nguyen et al., 2015). When whipping, fat globules and proteins are absorbed onto these interfaces, forming a film. In the case of 40% DAG cream, the SPC was very high so that a dense adsorption layer was formed, which had restrained the coalescence of semi-solid fat droplets. The interfacial film was too thick to be pierced by fat crystals. As a result, it hard to incorporate enough air during the whipping operation, and this sample represented lower overrun all the time (less than 270%).

In general, a high overrun would lead to excellent foam stability and cream quality. Thus, according to the change tendency of overrun, the final whipping time of all samples can be confirmed: it needed 4 min whipping for the control, 10% and 20% DAG substitute samples, and 3 min for 30% DAG substitute one, respectively. The sample of 40% DAG substitute was difficult to reach a desired overrun.

### 3.3. Effect of DAG substitute on the textural characteristics of whipped cream

The textural characteristics are important for the processing properties and eating quality of food products. One of the goals in modifying the whipped cream formulation is to produce a product with a desirable texture (Stanley et al., 1996). We measured the textural characteristics of 0–30% DAG substitute samples at their respective whipping terminal. As to the 40% DAG substitute one, 4 min of whipping time was selected.

Firmness shows the force necessary to attain a given deformation (N). As shown in Table 5, the control was 2.95 N. When 10–30% DAG substitute used, the firmness of whipped creams increased to 3.56–3.70 N. However, for the 40% DAG substitute sample, the firmness value was relatively low (1.57 N). Cohesiveness represents the strength of internal bonds making up the body of the products as well as the extent to which a material can be deformed before it ruptures (Szczesniak, 2002). The cohesiveness value of the control was 34.97 Ns, significantly ($P < 0.05$) lower than that of 10–30% DAG substitute samples. As similar with the firmness, when 40% DAG substitute was used, the cohesiveness was very low (14.96 Ns).

Consistency and viscosity are two important viscoelastic properties of whipped cream, which have a great effect on the eating quality and acceptability of the final product. The 10–30% DAG substitute resulted in increase of consistency and viscosity values ($P < 0.05$) compared with the control. A sharp decrease was still observed when 40% level applied.

Form the results above, when 10–30% DAG substitute used, all the textural characteristic values increased. The reason should be that, during whipping, the viscous liquid became into plastic foam structure gradually, and this process depends on the partial coalescence of fat to a large extent (Fredrick et al., 2010; Zhao, Zhao, Yang, et al., 2009). In the present study, since 10–30% DAG promoted the increase of partial coalescence of fat, all of the textural characteristic values increased significantly ($P < 0.05$).

The special structure of whipped cream was the result of the balance between churning partial coalescence (in serum) and surface-mediated partial coalescence (at the surface of air bubbles) (Hotrum, Cohen Stuart, van Vliet, Avino, & van Aken, 2005; Nguyen et al., 2015). For 0–30% DAG creams, the favorable textural qualities resulted from the successful incorporation of air bubbles surrounded by partially coalesced fat globules into a stable product. In the case of 40% DAG cream, there might be two reasons for its weak textural properties. On the one hand, the SPC was too thick so that the fat crystals can hardly pierce the membranes. As a consequence, shearing could not cause the colliding globules to form churning partially coalesce. On the other hand, the dispersion of excessive liquid fat at the air/water interface resulted in thinning of the lamellae between bubbles, which ultimately led to film destabilization and air bubble collapse (Hotrum, Cohen Stuart, van Vliet, Avino, & van Aken, 2004), as well as the insufficient surface mediated partial coalescence. This was also responsible for the lowest of overrun of this 40% DAG cream. The results implied that 40% DAG substitute was too high to apply in whipped cream in this work.

### 3.4. Sensory evaluation

Table 6 illustrates the result of sensory evaluation of the cream samples with different DAG contents. When 10–30% DAG involved, as a result of moderate partial coalescence of fat facilitating the formation of stable and preferable foam, it showed no significant effect ($P > 0.05$) on the organoleptic properties compared with the control. As to the 40% DAG substitute cream, the emulsion system had a too low partial

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**Table 5. Effect of diacylglycerol (DAG) substitute on the textural characteristics of whipped cream**

| DAG Substitute | Firmness (N)       | Consistency (N·s) | Cohesiveness (N) | Viscosity (N·s) |
|----------------|-------------------|-------------------|------------------|-----------------|
| 0              | $2.95 \pm 0.13$   | $34.97 \pm 0.19$  | $2.73 \pm 0.18$  | $23.53 \pm 0.54$|
| 10%            | $3.64 \pm 0.10$   | $39.36 \pm 0.72$  | $3.09 \pm 0.07$  | $26.23 \pm 0.83$|
| 20%            | $3.70 \pm 0.15$   | $39.24 \pm 0.55$  | $3.14 \pm 0.11$  | $29.21 \pm 0.20$|
| 30%            | $3.56 \pm 0.22$   | $39.80 \pm 0.37$  | $3.12 \pm 0.07$  | $29.03 \pm 0.66$|
| 40%            | $1.57 \pm 0.20$   | $14.96 \pm 0.42$  | $1.08 \pm 0.07$  | $11.36 \pm 0.33$|

* Data are expressed as means ± standard deviation. The values with different letters in each column are significantly different ($P < 0.05$).

* Los datos representan las medias ± desviación estándar. Los valores que presentan letras diferentes en cada columna son significativamente diferentes ($P < 0.05$).
Table 6. Effect of diacylglycerol (DAG) substitute on the organoleptic properties of whipped cream*

| DAG Substrate | Body and texture | Flavor and taste | Color and appearance | Total |
|---------------|------------------|------------------|----------------------|-------|
| (1–10)        | (1–5)            | (1–5)            | (1–20)               |       |
| 0             | 8.31 ± 0.09a     | 4.43 ± 0.13a     | 4.46 ± 0.11ab        | 17.20 ± 0.06a |
| 10%           | 8.42 ± 0.15a     | 4.56 ± 0.05a     | 4.28 ± 0.09ab        | 17.26 ± 0.10a |
| 20%           | 8.48 ± 0.06ab    | 4.31 ± 0.11ab    | 4.58 ± 0.08ab        | 17.37 ± 0.08ab |
| 30%           | 8.54 ± 0.13a     | 4.38 ± 0.07ab    | 4.20 ± 0.09ab        | 17.11 ± 0.11a |
| 40%           | 4.83 ± 0.16b     | 2.52 ± 0.09b     | 2.22 ± 0.13c         | 9.57 ± 0.28b  |

* Mean values from 12 panelists. Data are expressed as means ± standard deviation. The values with different letters in each column are significantly different (P < 0.05).

* Valores medios de 12 panelistas. Los datos representan las medias ± desviación estándar. Los valores que presentan letras diferentes en cada columna son significativamente diferentes (P < 0.05).

coalescence of fat and overrun, thus leading to decline of texture, heavy greasiness and dull color. Overall, except for the sample of 40% DAG substitute, the organoleptic properties of other ones were desirable.

4. Conclusions
To our knowledge, this is the first study for systematically evaluating the potential of DAG in whipped cream for partially substituting HPKO. Within the certain range of substitution (10–30%), the whipping properties, textural characteristics, and sensory evaluation were desirable, which indicated that DAG exhibited great potential for using in whipped cream. However, too high DAG substitution (40%) would result in a decreased quality of final product. This study sheds light for further research involved in the application of DAG in whipped cream.

Disclosure statement
No potential conflict of interest was reported by the authors.

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