Production and evaluation of physicochemical and rheological properties of sorbitan mono-stearate and sorbitan tri-stearate based Oleogels as low SFA shortening

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Abstract

This research was conducted to investigate the structuring effect of sorbitan mono-stearate (SMS) and sorbitan tri-stearate (STS) to fabricate some fatty-based product. For this purpose, various binary mixtures (VBM) of SMS/STS: polyglycerol esters were added to base oils at concentrations of 3, 6 and 9 (wt %). The results showed that saturated fatty acid (SFA), slip melting point and solid fat content increased with an increase in the VBM of SMS and STS ($P < 0.05$). SMS and STS did not affect peroxide value and the free fatty acids. Rancimat test presents contradictory results. The rheological analysis revealed that G", G', G* and tan δ of the base oil were increased to 105 Pa. Consequently, SMS-based structured fats exhibited more consistency than STS-based one. With proper plasticity and low SFA, SMS/STS-based fats can be applicable in the production of some fatty-based products like soft tub margarine, bakery margarine and all-purpose shortening.

Introduction

The solidification of edible oils via some techniques like hydrogenation is always accompanied by an increase in the amounts of saturated fatty acids (SFA) and trans fatty acids (TFA) (Patel and Dewettinck, 2016). Such fatty acids play a crucial role in cardiovascular diseases which put at risk the health of consumers. Today, various techniques are applied to reduce the amounts of SFA and TFA in fatty-based products. These techniques are including the blending of some fats, esterification and recently oleogel system. Oleogels is known as a gel with three-dimensional, thermo-reversible networks (Gaudino et al., 2019). Accordingly, some compounds (at low concentrations) act as building blocks (oleogelator or structuring agents) in the formation of an oleogel system (Peyronel and Marangoni, 2014; Patel and Dewettinck, 2016). The gelling properties of some lipid-based oleogelators like monoacylglycerols (MAGs), diacylglycerols (DAGs), sorbitan mono-stearate (SMS) or sorbitan tri-stearate (STS) have documented by the literature (Naderi et al., 2016; Saberi et al., 2012; Peyronel and Marangoni, 2014; de Oliveira et al., 2015; Pehlivanoglu et al., 2017). In this regard, de Oliveira et al. (2015) introduced a SMS-based fat with low SFA. Their research distinguished that SMS was capable of increasing of canola oil consistency. Also, Peyronel and Marangoni (2014) revealed that the heat resistance of confectionary fat blends increased as a result of SMS addition.

Shortening and/or margarine are known as structured fats with high amounts of trans fatty acid (TFA) and saturated fatty acids (SFA) content (Ghotra et al., 2002). Such fats have broad applications in bakery and/or confectionery products. In terms of the rheological analysis, these fats are semi-plastic materials which are capable of creating the desirable textural properties in fatty-based foods. Sometimes, the blending of some fats does not lead to low-SFA plastic fat. For that reason, the producers are always searching the way to overcome this problem. Today, some structuring agents (oleogelator) have increasingly found application in low-SFA/TFA fat systems. Such compounds are capable of reducing SFA content in structured fats (Singh et al., 2017).

In the current research, SMS and STS along with polyglycerol esters (PGE) as an emulsifier have been applied as structuring agents. Chemically, SMS and STS consist of a sorbitol molecule (sugar-alcohol) esterified with 1 and 3 stearic acid molecules (C18:0), respectively (Peyronel and Marangoni, 2014). Some compounds such as lecithin, poly sorbate 60, stearoyl lactylate and PGE are known as commonly used emulsifiers in the shortening production (Ghotra et al., 2002).

Due to the necessity of reduction in SFA content and TFA content in fatty-based products, researchers and producers have prompted to identify the applicable techniques for producing healthy fats. This study was set up in order to the introduction of the structured fats with low-SFA/TFA which is suitable in the fabrication of shortenings and/or margarine.

Materials and methods

Material

Refined, bleached and deodorized rapeseed oil and palm stearin were kindly donated from Parto Daneh Khazar Co. (Behshahr, Mazandaran, Iran). SMS (0.1% C14:0, 46.9% C16:0, 51.9% C18:0 and 0.7% C18:1), STS (0.25% C14:0, 56.5% C16:0, 42.5% C18:0 and 0.5% C18:1) and PGE (1.7% C14:0, 60.1% C16:0, 36.8% C18:0 and 0.23% C18:1) were purchased from Sunilia Co. (Tehran, Iran). All chemicals were of analytical grade and purchased from Merk Co. (Darmstadt, Germany).

Methods

Preparation of oleogels

Initially, a binary blend was prepared with the proportion 1:4 of palm stearin and rapeseed oil (PS20: R80). The proportions of binary blends were selected in such a way that SFA content in the oleogel-based fats did not exceed 20%. To make the binary mixtures of oleogelators, at first, the proportions 100:0, 80:20, 60:40, 40:60, 20:80 and 0:100 of PGE: SMS/STS were mixed, respectively. For preparing oleogels, initially, PS20: R80 was heated up to 80°C. Then, the binary mixtures of oleogelators were incorporated to PS20: R80 at concentrations of 3, 6 and 9 (wt %). Next, the prepared oleogels were stirred at 200 rpm for 10 minutes. Finally, SMS/STS-based fats were cooled up to 20°C and kept for later analysis (Naderi et al., 2018).

Fatty Acids Composition

Preparation of methyl ester of fatty acids was carried out in accordance with American Oil Chemists' Society (AOCS) method Ce 2-66 (Brühl, 1996). Also, according to the AOCS Ce 1-91 method, the fatty acids profile of structured fats was examined using a Perkin Elmer gas chromatograph (model 1020, Perkin-Elmer Corp. USA) equipped with a BPX-70 capillary column (60 m $\times$ 0.25 mm $\times$ 0.25 mm; Restek, Bellefonte, PA, USA) and flame ionization detector. The carrier gas was nitrogen and a ratio of 1:100 was selected for injection. The temperatures of the detector, injector and oven were 220, 225, and 180°C, respectively (Naderi et al., 2018).

Slip Melting Point Measurement

In accordance with the AOCS open capillary tube method CC 3-25, the slip melting point (SMP) of SMS/STS-based fats was determined (Brühl, 1996).

Solid Fat Content Measurement

Using a pulsed nuclear magnetic resonance spectroscope (Minispec; Bruker, Hamburg, Germany), solid fat content (SFC) at 10, 20, 25, and 35°C was measured as described by AOCS method 16b-93 (Brühl, 1996).

Rancimat Test

The induction period of oleogels was examined at 110°C according to AOCS method cd 12b-92 with a 2 ml/min flow rate and 2.5 g samples using the Rancimat Methrom apparatus (model 743, Herisau, Switzerland) (Brühl, 1996).

Peroxide Value Evaluation

Using the AOCS method cd 8-23, peroxide value (PV) of structured fats was determined (Brühl, 1996).

Free Fatty Acid Determination

Free fatty acids (FFA) were evaluated in accordance with the AOCS method Ca 5a-40 (Brühl, 1996).

Rheological analysis

A dynamic temperature sweep test (from 5 to 40°C) at a constant frequency of 1 Hz and at a rate of 2.0°C/min was conducted using Anton Paar rheometer (Anton Paar GmbH, Graz, Austria) to attain loss modulus (G"), storage modulus (G'), complex modulus (G*) and damping factor (tan δ). For all SMS/STS-based fats, a concentric cylinder (d= 0 mm) geometry was used (Naderi et al., 2016).

Statistical analysis

One-way ANOVA was used to analyze the data by SPSS software version 16.0 (SPSS Inc. Chicago, IL, USA). Duncan test (at $p < 0.05$) was applied when differences were significant. All experiments were performed in triplicate and its results were presented as mean value ± standard deviation.

Results and discussion

Physicochemical properties

Fatty Acids Profile

As mentioned in Table 1, the predominant fatty acid in PS20: R80 was found to be oleic acid. Also, prevalent fatty acids in PGE, SMS and STS were palmitic acid and stearic acid, respectively. A significant difference was observed between fatty acids composition of the structured fats containing 3, 6 and 9 (wt %) oleogelator ($P < 0.05$). On the other hand, at the same concentration of oleogelator, the differences among the fatty acids composition of SMS/STS-based fats were not statistically significant ($P > 0.05$). In fact, the fatty acids composition did not change significantly ($P > 0.05$) with increasing SMS or STS in binary mixtures of oleogelators. Also, fatty acids composition showed a notable difference with increasing the SMS or STS level from 3 to 9% (w/w) in PS20: R80 ($P < 0.05$). Accordingly, the percentage of oleic acid decreased from 50 to 47 by increasing the level of SMS/STS from 3 to 9%. On the other hand, an increase was detected in the percentage of palmitic acid whereas linoleic acid and linolenic acid decreased as the oleogelator concentration increased from 3 to 9 (wt %) in PS20: R80. SFA content showed an increased trend with increasing the levels of SMS or STS in binary mixtures of oleogelator ($P < 0.05$). A similarity was identified in the results of the fatty acids composition of the structured fats fabricated using SMS and STS. This can be attributed to the similarity of the fatty acids profile of SMS and STS. Since lipid-based oleogelators such as SMS and STS, mainly contain saturated fatty acids, they are able to increase the amount of SFA. Given the SFA content of structured fats, being 20 to 26 %, they can be applied in the production of low-SFA/trans shortening. These results were in line with the findings of Naderi et al. (2015), Yılmaz and Öğütcü (2014), Naderi et al. (2016). All studies confirmed that due to the high saturation of the SMS and STS, SFA content in the structured fats increased.

Slip Melting Point (SMP)

The SMP is the temperature at which the state of fat changes from solid to liquid. This parameter is one of the most important physical properties of fats. The SMPs of SMS/STS-based fats are listed in Table 2. The statistical analysis detected a significant difference among the SMP of the structured fats containing 3, 6 and 9 (wt %) oleogelator ($P < 0.05$). In this regard, further decreasing trend was identified for STS-based fats than SMS-based ones. In fact, at all concentrations of 3, 6 and 9 (wt %), with increasing the proportion of STS in binary mixtures of oleogelator, the SMP showed a decreasing trend, more greatly. This result is related to the difference in the chemical structure of the utilized oleogelators. In SMS and STS molecules unlike MAG and/or DAG (which have glycerol), Sorbitol (known as sugar-alcohol compound) is found. Two free hydroxyl groups are found in SMS structure whilst in the STS structure all hydroxyl groups are esterified. This is a turning point to alter the functional properties of these compounds. In this regard, Saberi et al. (2012) revealed that the free hydroxyl groups are able to elevate the SMP of fat molecules. For this reason, MAGs and DAGs with 2 and 1 free hydroxyl groups, respectively possess higher SMP than TAGs with no free hydroxyl group. In other words, the greater number of free hydroxyl groups present in SMS leads to more SMP of SMS-based oleogels than STS-based ones. These results were in accordance with the findings of Naderi et al. (2016) as investigated the MAG impact on chicken fat. Also, Pernetti et al. (2007) reported the combination of STS and lecithin STS was able to form a gel network in edible oils and increased their SMP up to 40°C.

Solid Fat Content (SFC)

SFC indicates the number of crystals in a fat system at various temperatures. This characteristic is responsible for many of the product's functionality. Table 2 presents the SFC of structured fats at 10 to 35°C. Statistical analysis showed that there was a significant difference among various concentrations of the oleogelator (3, 6 and 9 wt %) added to PS20: R80 ($P < 0.05$). It was distinguished that SFC decreased with an increase in the portion of STS (from 0 to 100) at 3, 6 and 9 (wt %). Opposite to the results of STS-based fats, SFC exhibited an incremental trend as the proportion of SMS increased in binary mixtures of oleogelator. Further SFC is caused by a greater number of fat crystals (denser structure) at any temperatures. As mentioned earlier, SMS-based structured fats have more SMP in comparison with STS-based ones. The same trend is seen in the SFC. In other words, greater hydroxyl groups in SMS lead to increased thermal resistance. Saberi et al. (2012) reported that MAG/DAG-based fats possessed less SFC at 5 to 10°C and more SFC at above 20°C than TAG-based ones. Also, the SFC curves of SMS/STS-based oleogels present a flatter slope than those of TAG-based fats, indicating more consistency in their structure at various temperatures. For that reason, these structured fats can be applicable in the production of margarine and shortening. The crystallization process of fat systems is completely dependent on SFC. One of the main parameters in the crystallization process is the induction period (IP). In fact, the IP of crystallization is the time during which the primary crystalline nuclei form in a fat system. This parameter has an Inverse relationship with the nucleation rate. Basso et al. (2010) reported that MAG could intensify the IP of crystallization of palm oil. Also, Verstringe et al. (2013) found that with an increase in MAG concentration, the temperature required for crystallization increased. The findings of these researchers were in accordance with the results of the present study.

Rancimat Test

The Rancimat test examines the IP of oxidation of fats under accelerated conditions. The fats rich in unsaturated fatty acids emerge the less IP of oxidation (O'brien, 2008). Table 3 lists the IP of oxidation (h) of the STS/SMS-based structured fats. Statistical analysis indicated a significant difference between various concentrations of the oleogelator (3, 6 and 9 wt %) added to PS20: R80 ($P < 0.05$). With increasing the concentrations of the oleogelator from 3 to 9 (wt %), the IP of oxidation showed an irregular trend. Furthermore, SMS-based structured fats presented greater IP of oxidation compared to STS-based ones. In general, the results do not show a regular trend with an increase or decrease in the ratio of SMS or STS. The free hydroxyl groups in SMS and STS may act as an antioxidant. In fact, at the onset of the oxidation mechanism, these compounds can neutralize the effect of hydroperoxides through donating hydrogen, therefore increasing the IP of oxidation. Considerably, in all SMS/STS-based structured fats the least IP of oxidation was recorded when the portion of SMS or STS was 100 in binary mixtures of oleogelator. It was hypostatized that a synergistic effect may exist among SMS, STS and PGE. Similar to such an effect is observed between synthetic antioxidants such as butylated hydroxyl toluene (BHT) and butylated hydroxyl anisole (BHA). When simultaneously applied, BHT and BHA emerge a higher protective factor. In the present study, when the proportions of SMS and STS were not zero in the binary mixtures of oleogelator, a synergistic effect was observed. The SMS-based oleogels possessed greater IP of oxidation than STS-based ones; this can be related to greater free hydroxyl groups of SMS. The findings of Naderi et al. (2018) as well as Gomes et al. (2010) revealed that MAGs are capable of increasing the IP of oxidation. Naderi et al. (2018) attributed these results to the high SFA content of the structuring agents. Particularly, the oxidative stability results are contradictory which requires further investigation.

Peroxide Value (PV)

PV represents the amount of hydroperoxides generated by the oxidation mechanism of fats. Although these compounds lack odor, aldehydes and ketones (secondary oxidation products) caused by the breakdown of hydroperoxides, have an unpleasant odor. Despite the fact that PV is not a reliable indicator of edible oils quality, it has a linear relationship with the organoleptic properties of fats (O'brien, 2008). There was no significant difference between the levels 3, 6 and 9 (wt %) added oleogelator to PS20: R80 ($P > 0.05$). In this context, Caponio et al. (2011) revealed that the compound with free hydroxyl groups showed low-prooxidant effects at low concentrations (less than 1 wt %). On the other hand, they play an antioxidant role at high concentrations (greater than 3 wt %). They concluded that, at low concentrations, emulsifying compounds such as MAG, SMS and STS cause a reduced surface tension, which in turn allows more oxygen to be entered into the oil (prooxidant effect). Inversely, at high concentrations, these compounds lay on the oil surface and absorb oxygen through their hydroxyl groups, therefore preventing the entry of oxygen into the oil (antioxidant role). Considering that SMS and STS were used at high levels, lack of change in PV can be related to their antioxidant role. In this regard, Paradiso et al. (2014), Colakoglu (2007) and Mistry and Min (1988) reported the same results.

Free Fatty Acid (FFA)

The percentage of FFA indicates the hydrolytic rancidity of oils (O'brien, 2008). Both animal fats and vegetable oils consist of certain and minor amounts of FFA, which this content may increase because of hydrolysis reactions. Statistical analysis proved that there was no significant difference between the levels 3, 6 and 9 (wt %) added oleogelator to PS20: R80 ($P > 0.05$).

In this regard, (Naderi et al., 2018) confirmed that the presence of 3 or 5 wt % MAG leads to an increase in FFA throughout storage time. Also, Zhang et al. (2015) and Krishnamurthy (1982) found that the compounds with free hydroxyl groups cause a catalytic effect in the hydrolysis of fats. Also, Vichi et al. (2003) revealed that, at relatively mild temperatures, the aforementioned compounds played a negative role in the hydrolysis reaction of fats.

Rheological Properties

Viscose (G") and Elastic (G') moduli

The elastic modulus (G') shows the amount of energy stored or recovered during each deformation cycle. Therefore, for fully solid material, all energy is stored and the stress and strain applied are co-phase (Rao, 2010). The viscous modulus (G") represents the amount of energy lost (the heat lost due to friction between the molecules). In fact, for fully liquid material, all energy is dissipated as heat and G' is zero (Rao, 2010). As highlighted in Figure 1 A and B, in all STS/SMS-based oleogels (containing 6 % binary mixture of oleogelator), G' curves are higher than G" curves. This indicates that the structured fats manufactured by STS and SMS emerge further solid-like nature. The rheological findings were in agreement with SMP and SFC results. In other words, the SMP of the oleogels was about 40°C as verified by the obtained rheological curves. It is well-known that fats with further SFC emerge a more solid-like nature (Farmani and Gholitabar 2015). At 35°C, the structured fat showed an SFC of 4 to 5%. This is in accordance with the G' curves of the structured fats did not vanish even at 35 to 40°C. In fact, the fat crystals continue to present at these temperatures cause G' curves not to vanish. At above 40°C, the G' curves vanished due to melting all fat crystals.

Complex modulus (G*)

Complex modulus (G*=[?]((G')2+(G")2)) represents the overall resistance of a material to strain. Also, G* modulus indicates the hardness of fats (Rao, 2010). In Figure 2, the G* curves of all the SMS/STS-based oleogels (containing 6 % binary mixture of oleogelator) were illustrated to compare their hardness. It is observed that when the proportions of SMS, STS and PGE are relatively equal in the oleogelator mixtures, the structured fats do not have a high hardness. For this reason, oleogelators prepared with a ratio of 60:40 or 40:60 of SMS/STS: PGE resulted in the oleogels with fewer G* moduli. Conversely, binary mixtures of oleogelators with a ratio 0:100, 100:0, 20:80, and 80:20 of SMS/STS: PGE exhibited the greatest amount of hardness. This phenomenon can be attributed to the various patterns of molecular interaction which may occur during the formation of the oleogels.

τaν δ

Phase angle (δ) is the arctangent of G"/G', which varies from 0° to 90°. Thus, by crossing δ over 45°, the G" modulus dominates over G' modulus. In other words, when G" modulus and G' modulus have the same values (G"= G'= 1), it is known as the gel point and/or crossover point. In fact, when the tan δ curves cross this line (G"= G'= 1), this indicates a shift from solid-like state to liquid-like state in fats. As shown in Figure 3, the tanδ curves of PS20: R80 intercept the line of G"= G'= 1 at a lower temperature in comparison with other SMS/STS-containing samples. Accordingly, this can be concluded that PS20: R80 (without oleogelator) possessed more liquid-like properties than other oleogels, being in accordance with the findings of G', G" and G* moduli. Considering that the least G', G* moduli and earliest crossover are related to PS20: R80, this can be concluded that SMS and STS as oleogelators play a crucial role in the structuring of fats. Particularly, structured fats present more solid-like nature. As mentioned earlier, the G", G' and G* curves of all SMS/STS-based oleogels were completely visible at 5 to 35°C. This confirms that the manufactured oleogels possess marked heat-resistance and retain their consistency at a relatively high-temperature range. Plastic fats (like margarine and shortening) exhibited a greater G' modulus than G" modulus. Hence, the SMS/STS-based oleogels are plastic fats. It is well-known that physical properties such as SMP and SFC are directly associated with the rheological properties of fats, so their results can be generalized to each other. As mentioned before, the SMS-based oleogels possessed greater SFC and SMP than those of STS-based ones, which was in accordance with findings rheological analysis. Patel and Dewettinck (2015) reported fats should have a G' modulus of 104 to 105 Pa to present desirable properties. It is important to note that SMS and STS have been able to increase the G' modulus of PS20: R80 from fewer than 100 to 105 Pa. According to Figures 1-3, all manufactured oleogels have a G' modulus of between 104 and 105 Pa, which makes them applicable to be used in fatty-based products. (Peyronel and Marangoni, 2014), who worked on the heat-stable fat blends utilized in confectionery products, reported that a 1:3 blend of SMS and hydrogenated palm kernel oil at 40°C emerged a G' modulus of 3×105 Pa. The results obtained in the present study are in accordance with the findings of Naderi et al. (2016) as examined the effect of MAGs on chicken fat, Naderi et al. (2015) which evaluated the impact of MAGs on sunflower oil, Lupi et al. (2012) Who investigated the effect of MAGs as a gelling agent on cocoa butter and olive oil.

Potential application

After evaluating the physicochemical and rheological properties of the SMS/STS-based fats, now, we investigate their applications in the production of some commercial fats. The consistency and plasticity of fats are influenced by their SFC. Hence, commercial fats with the same SFC exhibit similar characteristics. To check the potential application, the SFC curves of the manufactured SMS/STS-based oleogels and some commercial fats were plotted (Figure 4). It is mentionable that some SFC curves of STS/SMS-based fats widely differentiated with those of commercials fat were eliminated for more clarity. As shown in Figure 4, some SMS/STS-based fats can be applied in the production of soft tub margarine, all-purpose shortening and bakery margarine. Soft tub margarine should be spreadable in the consumption time and has a phase of liquid to solid less than stick margarine. All-purpose shortenings are particularly suitable for cooking, frying, and pastry use. Bakery margarine should provide texture, crispness, mouth feel, air entrapment and uniform heat transfer in bakery products.

Conclusions

The current paper investigated the impact of SMS/STS as structuring agents. These compounds played an effective role in the fabrication of structured fats with low-SFA content. To sum up, SMS and STS increased significantly the SMP and SFC of PS20: R80. However, the PV and FFA content of structured fats did not show a notable difference. The results of the IP of oxidation at 110°C present an irregular trend. The addition of various binary mixtures of SMS/STS: PGE significantly increased G', G" and G* moduli of PS20: R80 by 105 Pa. For that reason, manufactured fats have the application for fatty-based products or food emulsions which require low-SFA content. Given the SFC curves of structured fats, they are suitable for soft tub margarine, bakery margarine and all-purpose shortening.

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Table 1. The fatty acids composition of SMS/STS-based structured fats

Treatment	SFC at 10 °C	SFC at 20 °C	SFC at 30 °C	SFC at 35 °C	SMP (°C)
PS80:R20	12.4±0.2^{Fa}	10.8±0.2^{Db}	7.3±0.2^{HIc}	4.7±0.2^{Ed}	39.5±0.6^{ab}
3%:0STS:100PGE	12.4±0.2^{Fa}	10.8±0.2^{Db}	7.3±0.2^{HIc}	4.7±0.2^{Ed}	39.5±0.6^{ab}
3%:20STS:80PGE	12.4±0.2^{Fa}	10.8±0.2^{Db}	7.3±0.2^{HIc}	4.7±0.2^{Ed}	40.0±0.6^{a}
3%:40STS:60PGE	12.3±0.2^{Fa}	10.6±0.2^{Db}	7.3±0.2^{HIc}	4.2±0.2^{Ed}	39.5±0.6^{ab}
3%:60STS:40PGE	12.3±0.2^{Fa}	10.3±0.2^{Db}	7.3±0.2^{HIc}	2.8±0.2^{Hd}	39.0±0.6^{bc}
3%:80STS:20PGE	12.2±0.2^{Fa}	9.8±0.2^{Db}	5.9±0.2^{Jc}	1.4±0.2^{IJd}	39.0±0.6^{bc}
3%:100STS:0PGE	12.1±0.2^{Fa}	9.2±0.2^{Db}	5.9±0.2^{Jc}	0.7±0.2^{JKd}	36.0±0.6^{ef}
3%:0SMS:100PGE	11.2±0.2^{Ga}	9.2±0.2^{Eb}	4.4±0.2^{Kc}	0.5±0.2^{Kd}	36.0±0.6^{f}
3%:20SMS:80PGE	12.4±0.2^{FGa}	10.8±0.2^{Db}	7.3±0.2^{HIc}	4.8±0.2^{Dd}	40.0±0.6^{ab}
3%:40SMS:60PGE	13.3±0.2^{EFa}	11.6±0.2^{Db}	8.3±0.2^{GHc}	5.6±0.2^{Fd}	40.0±0.6^{ab}
3%:60SMS:40PGE	14.3±0.2^{Da}	12.3±0.2^{Db}	9.4±0.2^{Dc}	6.4±0.2^{Fd}	40.0±0.6^{ab}
3%:80SMS:20PGE	15.2±0.2^{Da}	12.8±0.2^{Db}	10.1±0.2^{EFc}	7.5±0.2^{Gd}	40.0±0.6^{ab}
3%:100SMS:0PGE	15.9±0.2^{Ca}	13.2±0.2^{Eb}	10.5±0.2^{DEc}	8.2±0.2^{Hd}	39.0±0.6^{b}
6%:0STS:100PGE	14.6±0.2^{Da}	12.7±0.2^{GHb}	9.2±0.2^{EFc}	5.3±0.2^{Bd}	40.0±0.6^{a}
6%:20STS:80PGE	14.6±0.2 ^{Da}	12.4±0.2^{GHb}	8.2±0.2^{GHc}	4.8±0.2^{Ed}	39.5±0.6^{ab}
6%:40STS:60PGE	14.4±0.2^{Da}	12.1±0.2^{GHb}	7.4±0.2^{HIc}	3.6±0.2^{Gd}	38.0±0.6^{d}
6%:60STS:40PGE	14.3±0.2^{Da}	11.7±0.2^{Hb}	6.4±0.2^{Ic}	3.4±0.2^{Gd}	36.0±0.6^{f}
6%:80STS:20PGE	14.2±0.2^{Da}	11.6±0.2^{Hb}	5.8±0.2^{Jc}	2.4±0.2^{Hd}	36.0±0.6^{f}
6%:100STS: 0PGE	13.8±0.2^{Da}	11.3±0.2^{Hb}	5.8±0.2^{Jc}	1.3±0.2^{IJd}	35.0±0.6^{g}
6%:0SMS:100PGE	14.6±0.2^{Da}	12.2±0.2^{GHb}	9.0±0.2^{Fc}	5.3±0.2^{Ed}	40.0±0.6^{a}
6%:20SMS:80PGE	15.6±0.2 ^{Ca}	13.1±0.2^{Fb}	9.6±0.2^{EFc}	6.2±0.2^{Ed}	40.0±0.6^{a}
6%:40SMS:60PGE	16.4±0.2^{BCa}	13.9±0.2^{EFb}	10.4±0.2^{DEc}	7.6±0.2^{Dd}	39.0±0.6^{bc}
6%:60SMS:40PGE	17.3±0.2^{ABa}	14.3±0.2^{DEb}	11.1±0.2^{Cc}	8.4±0.2^{CDd}	39.0±0.6^{bc}
6%:80SMS:20PGE	17.9±0.2^{ABa}	15.3±0.2^{Cb}	11.8±0.2^{BCc}	9.4±0.2^{BCd}	39.0±0.6^{bc}
6%:100SMS:0PGE	18.3±0.2^{Aa}	15.7±0.2^{BCb}	12.6±0.2^{ABc}	10.3±0.2^{Bd}	39.0±0.6^{bc}
9%:0STS:100PGE	17.0±0.2^{Ba}	14.7±0.2^{DEb}	11.1±0.2^{Cc}	6.2±0.2^{Ed}	39.5±0.6^{ab}
9%:20STS:80PGE	16.7±0.2^{BCa}	14.4±0.2^{DEb}	9.4±0.2^{Bc}	5.5±0.2^{Ed}	39.0±0.6^{bc}
9%:40STS:60PGE	16.6±0.2^{BCa}	14.4±0.2^{DEb}	7.5±0.2^{Dc}	4.2±0.2^{Fd}	37.0±0.6^{e}
9%:60STS:40PGE	16.6±0.2^{BCa}	14.3±0.2^{DEb}	7.3±0.2^{Dc}	4.2±0.2^{Fd}	36.0±0.6^{f}
9%:80STS:20PGE	16.5±0.2^{BCa}	14.2±0.2^{DEb}	7.1±0.2^{Dc}	4.1±0.2^{Fd}	35.0±0.6^{gh}
9%:100STS:0PGE	16.4±0.2^{BCa}	14.1±0.2^{DEb}	7.0±0.2^{Dc}	3.7±0.2^{Gd}	34.0±0.6^{h}
9%:0SMS:100PGE	17.0±0.2^{Ba}	14.3±0.2^{DEb}	11.1±0.2^{Cc}	6.9±0.2^{DEd}	40.0±0.6^{a}
9%:20SMS:80PGE	17.7±0.2^{ABa}	15.1±0.2^{Cb}	11.4±0.2^{Cc}	7.5±0.2^{Dd}	40.0±0.6^{a}
9%:40SMS:60PGE	18.2±0.2^{Aa}	16.2±0.2^{Bb}	11.5±0.2^{BCc}	8.2±0.2^{CDd}	39.0±0.6^{bc}
9%:60SMS:40PGE	18.6±0.2^{Aa}	17.3±0.2^{ABb}	12.3±0.2^{ABc}	9.3±0.2^{BCd}	39.0±0.6^{bc}
9%:80SMS:20PGE	19.1±0.2^{Aa}	17.5±0.2^{Ab}	12.4±0.2^{ABc}	10.1±0.2^{Bd}	39.0±0.6^{bc}
9%:100SMS: 0PGE	19.4±0.2^{Aa}	18.1±0.2^{Ab}	13.0±0.2^{Ac}	11.3±0.2^{Ad}	39.0±0.6^{bc}

Data are reported as mean± standard deviation of 3 replicates. In each column, the data with the same letters indicate no significant difference at P <0.05. PGE, polyglycerol ester; STS, sorbitan tri-stearate; SMS, sorbitan mono-stearate; C16:0, palmitic acid; C18:0, stearic acid; C18:1, oleic acid; C18:2; linoleic acid; C18:3, linolenic acid

Table 2. The solid fat content (SFC) and slip melting point (SMP) of SMS/STS-based structured fats

Treatment	SFC at 10 °C	SFC at 20 °C	SFC at 30 °C	SFC at 35 °C	SMP (°C)
PS80:R20	12.4±0.2^{Fa}	10.8±0.2^{Db}	7.3±0.2^{HIc}	4.7±0.2^{Ed}	39.5±0.6^{ab}
3%:0STS:100PGE	12.4±0.2^{Fa}	10.8±0.2^{Db}	7.3±0.2^{HIc}	4.7±0.2^{Ed}	39.5±0.6^{ab}
3%:20STS:80PGE	12.4±0.2^{Fa}	10.8±0.2^{Db}	7.3±0.2^{HIc}	4.7±0.2^{Ed}	40.0±0.6^{a}
3%:40STS:60PGE	12.3±0.2^{Fa}	10.6±0.2^{Db}	7.3±0.2^{HIc}	4.2±0.2^{Ed}	39.5±0.6^{ab}
3%:60STS:40PGE	12.3±0.2^{Fa}	10.3±0.2^{Db}	7.3±0.2^{HIc}	2.8±0.2^{Hd}	39.0±0.6^{bc}
3%:80STS:20PGE	12.2±0.2^{Fa}	9.8±0.2^{Db}	5.9±0.2^{Jc}	1.4±0.2^{IJd}	39.0±0.6^{bc}
3%:100STS:0PGE	12.1±0.2^{Fa}	9.2±0.2^{Db}	5.9±0.2^{Jc}	0.7±0.2^{JKd}	36.0±0.6^{ef}
3%:0SMS:100PGE	11.2±0.2^{Ga}	9.2±0.2^{Eb}	4.4±0.2^{Kc}	0.5±0.2^{Kd}	36.0±0.6^{f}
3%:20SMS:80PGE	12.4±0.2^{FGa}	10.8±0.2^{Db}	7.3±0.2^{HIc}	4.8±0.2^{Dd}	40.0±0.6^{ab}
3%:40SMS:60PGE	13.3±0.2^{EFa}	11.6±0.2^{Db}	8.3±0.2^{GHc}	5.6±0.2^{Fd}	40.0±0.6^{ab}
3%:60SMS:40PGE	14.3±0.2^{Da}	12.3±0.2^{Db}	9.4±0.2^{Dc}	6.4±0.2^{Fd}	40.0±0.6^{ab}
3%:80SMS:20PGE	15.2±0.2^{Da}	12.8±0.2^{Db}	10.1±0.2^{EFc}	7.5±0.2^{Gd}	40.0±0.6^{ab}
3%:100SMS:0PGE	15.9±0.2^{Ca}	13.2±0.2^{Eb}	10.5±0.2^{DEc}	8.2±0.2^{Hd}	39.0±0.6^{b}
6%:0STS:100PGE	14.6±0.2^{Da}	12.7±0.2^{GHb}	9.2±0.2^{EFc}	5.3±0.2^{Bd}	40.0±0.6^{a}
6%:20STS:80PGE	14.6±0.2 ^{Da}	12.4±0.2^{GHb}	8.2±0.2^{GHc}	4.8±0.2^{Ed}	39.5±0.6^{ab}
6%:40STS:60PGE	14.4±0.2^{Da}	12.1±0.2^{GHb}	7.4±0.2^{HIc}	3.6±0.2^{Gd}	38.0±0.6^{d}
6%:60STS:40PGE	14.3±0.2^{Da}	11.7±0.2^{Hb}	6.4±0.2^{Ic}	3.4±0.2^{Gd}	36.0±0.6^{f}
6%:80STS:20PGE	14.2±0.2^{Da}	11.6±0.2^{Hb}	5.8±0.2^{Jc}	2.4±0.2^{Hd}	36.0±0.6^{f}
6%:100STS: 0PGE	13.8±0.2^{Da}	11.3±0.2^{Hb}	5.8±0.2^{Jc}	1.3±0.2^{IJd}	35.0±0.6^{g}
6%:0SMS:100PGE	14.6±0.2^{Da}	12.2±0.2^{GHb}	9.0±0.2^{Fc}	5.3±0.2^{Ed}	40.0±0.6^{a}
6%:20SMS:80PGE	15.6±0.2 ^{Ca}	13.1±0.2^{Fb}	9.6±0.2^{EFc}	6.2±0.2^{Ed}	40.0±0.6^{a}
6%:40SMS:60PGE	16.4±0.2^{BCa}	13.9±0.2^{EFb}	10.4±0.2^{DEc}	7.6±0.2^{Dd}	39.0±0.6^{bc}
6%:60SMS:40PGE	17.3±0.2^{ABa}	14.3±0.2^{DEb}	11.1±0.2^{Cc}	8.4±0.2^{CDd}	39.0±0.6^{bc}
6%:80SMS:20PGE	17.9±0.2^{ABa}	15.3±0.2^{Cb}	11.8±0.2^{BCc}	9.4±0.2^{BCd}	39.0±0.6^{bc}
6%:100SMS:0PGE	18.3±0.2^{Aa}	15.7±0.2^{BCb}	12.6±0.2^{ABc}	10.3±0.2^{Bd}	39.0±0.6^{bc}
9%:0STS:100PGE	17.0±0.2^{Ba}	14.7±0.2^{DEb}	11.1±0.2^{Cc}	6.2±0.2^{Ed}	39.5±0.6^{ab}
9%:20STS:80PGE	16.7±0.2^{BCa}	14.4±0.2^{DEb}	9.4±0.2^{Bc}	5.5±0.2^{Ed}	39.0±0.6^{bc}
9%:40STS:60PGE	16.6±0.2^{BCa}	14.4±0.2^{DEb}	7.5±0.2^{Dc}	4.2±0.2^{Fd}	37.0±0.6^{e}
9%:60STS:40PGE	16.6±0.2^{BCa}	14.3±0.2^{DEb}	7.3±0.2^{Dc}	4.2±0.2^{Fd}	36.0±0.6^{f}
9%:80STS:20PGE	16.5±0.2^{BCa}	14.2±0.2^{DEb}	7.1±0.2^{Dc}	4.1±0.2^{Fd}	35.0±0.6^{gh}
9%:100STS:0PGE	16.4±0.2^{BCa}	14.1±0.2^{DEb}	7.0±0.2^{Dc}	3.7±0.2^{Gd}	34.0±0.6^{h}
9%:0SMS:100PGE	17.0±0.2^{Ba}	14.3±0.2^{DEb}	11.1±0.2^{Cc}	6.9±0.2^{DEd}	40.0±0.6^{a}
9%:20SMS:80PGE	17.7±0.2^{ABa}	15.1±0.2^{Cb}	11.4±0.2^{Cc}	7.5±0.2^{Dd}	40.0±0.6^{a}
9%:40SMS:60PGE	18.2±0.2^{Aa}	16.2±0.2^{Bb}	11.5±0.2^{BCc}	8.2±0.2^{CDd}	39.0±0.6^{bc}
9%:60SMS:40PGE	18.6±0.2^{Aa}	17.3±0.2^{ABb}	12.3±0.2^{ABc}	9.3±0.2^{BCd}	39.0±0.6^{bc}
9%:80SMS:20PGE	19.1±0.2^{Aa}	17.5±0.2^{Ab}	12.4±0.2^{ABc}	10.1±0.2^{Bd}	39.0±0.6^{bc}
9%:100SMS: 0PGE	19.4±0.2^{Aa}	18.1±0.2^{Ab}	13.0±0.2^{Ac}	11.3±0.2^{Ad}	39.0±0.6^{bc}

Data are reported as mean± standard deviation of 3 replicates. The data with the same lowercase and uppercase letters in each row and column respectively, showed no significant difference at P <0.05. PGE, polyglycerol ester; STS, sorbitan tri-stearate; SMS, sorbitan mono-stearate; PS80:R20: the blend palm stearin and rapeseed oil with ratio of 20:80.

Table 3. The peroxide value (PV), free fatty acids (FFA) and induction period at 110 °C (IP_{110}) of SMS/STS-based structured fats

Treatment	PV (meq O2/kg)	FFA (%)	IP_{110} (h)
PS80:R20	2.1±0.3^{a}	0.35±0.01^{a}	27.5±0.7^{i}
3%:0STS:100PGE	2.1±0.3^{a}	0.35±0.01^{a}	35.2±0.7^{f}

Treatment	PV (meq O2/kg)	FFA (%)	IP_{110} (h)
3%:20STS:80PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	52.2 ± 0.7^{c}
3%:40STS:60PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	50.9 ± 0.7^{d}
3%:60STS:40PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	48.0 ± 0.7^{d}
3%:80STS:20PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	45.8 ± 0.7^{g}
3%:100STS:0PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	32.4 ± 0.7^{g}
3%:0SMS:100PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	35.2 ± 0.7^{f}
3%:20SMS:80PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	32.0 ± 0.7^{g}
3%:40SMS:60PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	31.5 ± 0.7^{g}
3%:60SMS:40PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	30.4 ± 0.7^{g}
3%:80SMS:20PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	30.0 ± 0.7^{g}
3%:100SMS:0PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	29.0 ± 0.7^{h}
6%:0STS:100PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	40.0 ± 0.7^{e}
6%:20STS:80PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	59.3 ± 0.7^{b}
6%:40STS:60PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	59.9 ± 0.7^{b}
6%:60STS:40PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	52.9 ± 0.7^{c}
6%:80STS:20PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	53.3 ± 0.7^{c}
6%:100STS: 0PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	35.8 ± 0.7^{g}
6%:0SMS:100PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	40.0 ± 0.7^{e}
6%:20SMS:80PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	49.6 ± 0.7^{d}
6%:40SMS:60PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	41.0 ± 0.7^{e}
6%:60SMS:40PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	38.8 ± 0.7^{e}
6%:80SMS:20PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	38.0 ± 0.7^{e}
6%:100SMS:0PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	32.0 ± 0.7^{g}
9%:0STS:100PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	48.6 ± 0.7^{d}
9%:20STS:80PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	66.3 ± 0.7^{a}
9%:40STS:60PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	65.9 ± 0.7^{a}
9%:60STS:40PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	60.9 ± 0.7^{b}
9%:80STS:20PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	60.9 ± 0.7^{b}
9%:100STS:0PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	40.0 ± 0.7^{e}
9%:0SMS:100PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	48.6 ± 0.7^{d}
9%:20SMS:80PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	50.8 ± 0.7^{d}
9%:40SMS:60PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	49.9 ± 0.7^{d}
9%:60SMS:40PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	48.8 ± 0.7^{e}
9%:80SMS:20PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	48.0 ± 0.7^{e}
9%:100SMS: 0PGE	2.1 ± 0.3^{a}	0.35 ± 0.01^{a}	35.0 ± 0.7^{f}

Data are reported as mean± standard deviation of 3 replicates. In each column, the data with the same letters indicate no significant difference at P <0.05. PGE, polyglycerol ester; STS, sorbitan tri-stearate; SMS, sorbitan mono-stearate, PS80:R20: the blend palm stearin and rapeseed oil with ratio of 20:80.

Figure legends

Figure 1. The elastic (G') and viscose (G") moduli of SMS-based- (A) and STS-based structured fats (B) containing 6 % binary mixture of oleogelator determined by sweep test from 5 to 50 °C. PGE, polyglycerol ester; STS, sorbitan tri-stearate; SMS, sorbitan mono-stearate

Figure 2. The complex (G*) modulus of SMS/STS-based structured fats containing 6 % binary mixture of oleogelator determined by sweep test from 5 to 50 °C. PGE, polyglycerol ester; STS, sorbitan tri-stearate; SMS, sorbitan mono-stearate

Figure 3. The damping factor (Tan δ) of SMS/STS-based structured fats containing 6 % binary mixture of

oleogelator determined by sweep test from 5 to 50 °C. PGE, polyglycerol ester; STS, sorbitan tri-stearate; SMS, sorbitan mono-stearate

Figure 4. The potential applications of SMS/STS-based structured fats. PGE, polyglycerol ester; STS, sorbitan tri-stearate; SMS, sorbitan mono-stearate

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