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Improved physical properties and structural stability of value-added mayonnaises based on red palm olein by using high-shear homogeniser

[1]Samsuri, N. S., [1]Abd Hadi, H. M., [1]Ismail-Fitry, M. R., [2]Ab Karim, N. A. and [1]*Mat Yusoff, M.

[1]*Department of Food Technology, Faculty of Food Science and Technology, Universiti Putra Malaysia,*
43400 UPM Serdang, Selangor, Malaysia
[2]*Department of Processing Technology - Oils and Fats, Sime Darby Plantation Research Sdn. Bhd.,*
42960 Carey Island, Selangor, Malaysia

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Abstract

The present work formulated value-added mayonnaises based on red palm olein (RPOL) with improved physical properties and structural stability using a high-shear homogeniser (H-mayonnaise) as compared to the use of a lab-scale mixer (M-mayonnaise). The fat portions of the mayonnaises were blends of palm olein and RPOL at different ratios of 100:0, 75:25, and 50:50. The H-mayonnaises exhibited significantly smaller ($p < 0.05$) droplet size (448.95 - 515.61 vs 532.44 - 672.37 μm) and amount of separated oil (0.00 - 1.83 vs 16.83 - 42.68%) with more intact structure than M-mayonnaises. As the RPOL was increased from 0 to 50% (w/w), significant decrease ($p < 0.05$) was observed in the L^* value (M-, 74.80 to 64.76; H-, 77.73 to 70.64), while both the a^* (M-, -1.61 to 15.22; H-, -1.49 to 11.49) and b^* (M-, 28.37 to 59.64; H-, 25.34 to 55.13) values increased in palm-based M- and H-mayonnaises. However, the fat portions had no significant effect on water activity, droplet size, and the amount of separated oil. All H-mayonnaises had higher storage modulus (G' values), which highlighted greater mechanical rigidity and solid-like texture than M-mayonnaises. Different RPOL contents had no significant effect on the sensory acceptability of H-mayonnaises, except for the colour properties and overall acceptability. Overall, the physical properties and structural stability of RPOL-based mayonnaises were significantly improved by high-shear homogenisation relative to the use of a lab-scale mixer, while their sensory acceptance was comparable with mayonnaise prepared using soybean oil. Findings reported herein highlighted the potential development of mayonnaise based on RPOL for commercialisation purposes. There is also a potential for continuous demand of RPOL which could help to sustain its production, thus benefiting both the food and agricultural sectors.

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Introduction

In the palm oil industry, physical and chemical refining processes are commonly applied for the conversion of crude palm oil to refined, bleached, and deodorised (RBD) palm oil. The RBD palm oil is further fractionated into palm olein and palm stearin. Palm olein is liquid at room temperature, and stable as cooking oil, especially for deep-fat frying as reported by a number of studies, both individually and upon blended with other vegetable oils (Barrisuo *et al.*, 2013; Garcia-Pérez *et al.*, 2017; Nur Arslan *et al.*, 2017). For wider food industry applications, fractions from the RBD palm oil are exposed to additional separation steps.

In comparison to RBD fractions, production of refined red palm oil (RPO) involves refining of good quality crude palm oil. The oil is pre-treated using degumming and bleaching processes, followed by deacidification and deodorisation using molecular distillation (Van Rooyen *et al.*, 2008). These milder processes allow the oil to retain beneficial phytonutrient compounds such as carotenes and antioxidants that are lost during physical and chemical palm oil refining processes (Loganathan *et al.*, 2020). There are reports of the potential use of RPO and its derivatives in the development of fat-based food products such as margarine and shortening (Nagendran *et al.*, 2000). Cassiday (2017) reported the presence of 325 - 365 ppm valuable

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*Corresponding author.
Email: masniyusoff@upm.edu.my

micronutrients in RPO. The efficacy of RPO in ameliorating vitamin A deficiency in children and woman have been reported in Indonesia, Honduras, Papua New Guinea, Tanzania, and Burkina Faso (Delisle, 2017). Moreover, due to its excellent properties, RPO has been utilised as a natural antioxidant in vegetable oils to limit the use of synthetic antioxidants such as butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), and tertiary-butylhydroquinone (TBHQ) (Andarwulan *et al.,* 2016).

RPO can be fractionated into olein (liquid) and stearin (solid) of different physicochemical properties, thereby optimising its use in a wide range of food applications. Red palm olein (RPOL) is the liquid fraction of RPO which has ample carotenoid content, ranging from 500 - 800 mg/kg oil, and responsible for its red-yellowish colour. This value is 15 and 300 times higher than those found in carrots and tomatoes, respectively, which highlight its potential application as food ingredient (Rice and Burns, 2010; Chawla and Saxena, 2013; Riyadi *et al.,* 2016; Loganathan *et al.,* 2017). The consumption of carotenoids can reduce the risk of lung, colon, and breast cancers (Tang and Pantzaris, 2017). Furthermore, five types of vitamin E isomers (α- and γ-tocopherol, and α-, γ- and δ-tocotrienols) have been identified in RPOL, which are responsible for its oxidative stability (Nagendran *et al.,* 2000; Basiron, 2005; Kumar and Krishna, 2014; Cassiday, 2017). Tocotrienols are important in improving cognition, bone health, longevity, and cholesterol level in blood plasma, besides exhibiting neuro- and skin-protective effects (Meganathan and Fu, 2016; Cestaro *et al.,* 2017). A number of studies reported the synergistic effect of carotenoids and vitamin E as super natural antioxidant in oils (Kamaruzaman *et al.,* 2015; Loganathan *et al.,* 2020).

Due to presence of these beneficial compounds, studies were also conducted to incorporate RPOL in food products. In a study by Ahmad and Idris (2005), a cake made using RPOL exhibited an excellent quality, and resembled the cake made using margarine and shortening in terms of their colour. Wan Rosnani *et al.* (2009) also successfully developed an ice cream formulation exhibiting desirable physical properties based on RPOL. Similarly, Ismail *et al.* (2020) formulated an ice cream using RPOL, which was stabilised with the addition of guar and xanthan gums. In another study done by Loganathan *et al.* (2020), the incorporation of RPOL contributed to cupcakes with high carotenoid retention after baking, besides equal sensory acceptance with that formulated using palm olein.

In light of these findings, the product of interest of the present work was a value-added mayonnaise containing RPOL. Mayonnaise is an oil-in-water emulsion system consisting of a minimum fat portion (65%; w/w), which significantly impacts the product's semi-solid, viscoelastic behaviour, texture, emulsion, and flavour properties (Stern *et al.,* 2001; Widerström and Öhman, 2017). The common oils used are soft vegetable oils such as soybean, sunflower, olive, canola, and corn oils. These oils exhibit liquid properties at room temperature resembling palm olein and RPOL, with the latter containing supplemental nutritional values of carotenoid, tocopherol, and tocotrienol. Therefore, RPOL has the potential to be used in the development of a value-added mayonnaise.

In mayonnaise processing, the commonly used mixer consists of a whisk blade attached to a rotating shaft located at the mixing vessel's centre. With a rotation speed of 20 to 150 rpm, the mixer enhances the formation of coarse emulsion during the oil phase. Towards the end of the process, the whisking of the emulsion is continued until the desired consistency is obtained (Brennan, 2006). Another widely used device for the preparation of emulsion is the high-shear homogeniser. In contrast to the lab-scale mixer, a high-shear homogeniser results in the formation of coarse emulsion and emulsification. The coarse emulsion is formed upon adding oil into the water phase at a consistent rate. On the other hand, the onset of emulsification is when the shear rate is increased to decrease the coarse emulsion droplet size for better stability (Widerström and Öhman, 2017). Ali *et al.* (2016) and Yong *et al.* (2017) reported that the use of high-shear rates could result in smaller emulsion droplet size with enhanced emulsion stability.

Despite the well-known operational mechanisms of mixing and homogenisation, the effect of these processes on the physical properties and structural stability of mayonnaises formulated using different amounts of RPOL were uncertain. The sensory acceptance of the RPOL-based mayonnaise was also doubtful. These uncertainties have limited further use of RPOL in food products. Therefore, the present work aimed to blend RPOL with palm olein at different ratios, and incorporate them into mayonnaise formulations by using both lab-scale mixer and high-shear homogeniser. The RPOL was blended with palm olein for several reasons, including the undesirable deep red-orange colour of RPOL, and high availability and lower price of palm olein. Besides, palm olein is liquid at room temperature, which is similar to the state of soft oils commonly used for mayonnaise products. The physical properties, structural stability, and sensory acceptance of these developed mayonnaises were further evaluated against mayonnaise based on soybean oil as a control sample. We hypothesised that using a high-shear homogeniser will result in RPOL-based mayonnaise with improved physical properties and structural stability as compared to the use of lab-scale mixer, besides receiving comparable sensory acceptance with that of formulated using soybean oil (SBO).

Materials and methods

Preparation of mayonnaise

All ingredients for the mayonnaise preparation were purchased from local markets in Serdang, Selangor. As shown in Table 1, the mayonnaise formulation was based on the description provided by Su *et al.* (2010) with slight modification. Various methods and mixing mechanisms were used for the mayonnaise preparation, *i.e.* lab-scale mixer (M-mayonnaise) and high-shear homogeniser (H-mayonnaise). The total fat portion (100%, w/w) of each mayonnaise was 73 g fat/100 g mayonnaise, composing 100% soybean oil (M-SBO, H-SBO) and blends of palm olein and RPOL at different ratios of 100:0 (M-0, H-0), 75:25 (M-25, H-25), and 50:50 (M-50, H-50). These ratios were determined based on the findings from preliminary studies demonstrating oil phase separation following the use of higher RPOL contents in the mayonnaise formulation. SBO was employed as the control samples since it is the most commercially available mayonnaise products in the market. All the analytical methods were conducted in six replications based on two mayonnaise batches (*n* = 6).

The lab-scale mixer method was carried out as described by Su *et al.* (2010). The lab-scale mixer (Taiwan Cake Mixer, B5, Heromie Jaya Services) consisted of a whisking blade with three different speed settings of low-, medium-, and high-speeds. All ingredients were weighed based on the formulation listed in Table 1. The egg yolk was added into a mixing bowl, and beaten thoroughly at medium speed. In a separate container, salt, sugar, and vinegar were mixed until completely dissolved. This mixture was added into the mixing bowl containing the beaten egg, followed by mixing for 3 min at medium speed. The speed was further increased to high, and the oil portion was slowly added into the mixture within 8 min, forming a mayonnaise. The mayonnaise was mixed for an additional 5 min at medium speed.

Table 1. Mayonnaise formulations with different fat portions prepared using a lab-scale mixer (M) and high-shear homogeniser (H).

Ingredient	**Amount (g)**			
	M-SBO; H-SBO	**M-0; H-0**	**M-25; H-25**	**M-50; H-50**
Oil				
Soybean oil	73.00	0.00	0.00	0.00
Palm olein	0.00	73.00	54.75	36.50
Red palm olein	0.00	0.00	18.25	36.50
Egg yolk	14.05	14.05	14.05	14.05
Vinegar	9.20	9.20	9.20	9.20
Sugar	2.70	2.70	2.70	2.70
Salt	1.05	1.05	1.05	1.05
Total	**100.00**	**100.00**	**100.00**	**100.00**

M-SBO and H-SBO are mayonnaises containing 100% (w/w) (73.00 g) soybean oil as the fat portion, while other mayonnaises contain 0% (M-0, H-0), 25% (M-25, H-25), and 50% (M-50, H-50) red palm olein blended with palm olein for the total fat portion of 100% (w/w) (73.00 g).

On the other hand, the high-shear homogeniser (Silverson L4RT, Silverson Machines Inc., USA) is made up of a rotor and a stator. A modified method was applied based on the lab-scale mixer's parameters. All ingredients were weighed based on the formulation listed in Table 1. In a 500 mL beaker, egg yolk was beaten thoroughly at 800 rpm. In a separate container, salt, sugar, and vinegar were mixed until completely dissolved. The mixture was added into the beaker containing the beaten egg, followed by homogenisation for 3 min at 800 rpm. The speed was further increased to 4,000 rpm, and the oil portion was slowly added into the mixture within 8 min, forming a mayonnaise. The mayonnaise was mixed for an additional 5 min at 1,500 rpm.

Determination of water activity

Water activity (a_w) of the mayonnaise samples was measured using an Aqualab water activity meter (Decagin Devices Inc., WA, USA).

Determination of colour properties

The colour properties of the mayonnaises (L^*, a^*, and b^* values) were determined using a Minolta Colorimeter CR-300 (Konica Minolta Business Technologies Inc., Langenhagen/Hannover, Germany). As described by Amin *et al.* (2014), the L^* value represents the lightness ranging from black to white; a^* value represents the colour of green to red in the range of - (greenness) to + (redness); and b^* value represents the range of - (blueness) to + (yellowness).

Determination of droplet size distribution

A laser diffraction method (Mastersizer 2000 instrument, Worcestershire, UK) was applied to determine the droplet size distribution of the mayonnaise samples. The best-fit between the experimental measurements and Mie theory was used to estimate the parameter. Following the method described by Thaiudom and Khantarat (2011), 0.05 g of mayonnaise sample was diluted in 100 mL of 0.1% sodium dodecyl sulphate solution to stop multiple scattering effects. The diluted samples were further homogenised (Ultra-Turrax, IKA-Labortechnik, Germany) for 3 min before measurement. The droplet size was reported as volume-weighted mean diameter (D4,3) at the optical measurement of refractive index and absorption of 1.46 and 0.00, respectively.

Microstructural analysis

A light microscope (Nikon Eclipse 80i Binocular, USA) was used to evaluate the microstructure of all the mayonnaise samples. The procedure was conducted at room temperature (25.0 ± 3.0°C), and the microscope was equipped with a camera (Nikon 5 megapixel, Kanagawa, Japan) and a digital image processing software (NIS-Elements Basic Research, Nikon Instruments). Briefly, a drop of mayonnaise sample without dilution was placed on the microscope slide, covered with its coverslip, and observed under the microscope at 40× magnification (Ng *et al.*, 2014).

Determination of oil phase separation

The determination of oil phase separation of all mayonnaise samples was carried out as described in a previous study (Thaiudom and Khantarat, 2011). Briefly, 20 g (F0) of each sample was transferred into a 50 mL centrifuge tube with a tightly sealed plastic cap. The samples were stored at 50°C for 48 h, and centrifuged for 10 min at 3,000 rpm (Heraerus Multifuge X1, Thermo Scientific, Langenselbold, Germany). The oil phase was weighed (F1) and calculated as the separated oil portion in percentage (%) using the following equation: $(F0 - F1 / F0) \times 100$.

Determination of rheological properties

By focusing on the viscoelastic properties of all mayonnaise samples, rheological properties were determined by using a controlled-stress rheometer (Rheostress 6000, Haake, Karlsruhe, Germany) at room temperature (25.0 ± 3.0°C). Standard methods (*i.e.* Rheowin Data Manager software version 4.00) were applied for the analysis. The parameters used were based on the studies conducted by Maruyama *et al.* (2007) and Ng *et al.* (2014) with slight modifications. To determine the viscoelastic properties, oscillatory shear tests were conducted. To evaluate the stress range and corresponding linear viscoelasticity (LVE), a strain sweep (0.1 - 70.0%) at a fixed frequency of 1 Hz was used to initiate the process. In the linear region, *G'* (storage modulus) and *G"* (loss modulus) were measured with increased stress from 10 to 500 Pa. LVE range was determined by plotting the curves of *G'* and *G"* against the stress sweep in Pa.

Determination of sensory acceptance

Mayonnaise samples with desirable physical properties and structural stability were selected for further testing, and compared with a commercial mayonnaise (CM-mayonnaise) sample. The parameter employed for the comparison was the sensory acceptance among 50 untrained panellists. The hedonic sensory test was conducted using a 9-point scoring scale (*i.e.* 1 = disliked extremely, 5 = neither likes nor disliked, and 9 = liked extremely). The acceptance scores were obtained for each sample's appearance, colour, odour, taste, and overall acceptability.

Statistical analysis

All results were expressed as mean ± standard deviation (SD). Minitab Statistical Software (Version 18, Pennsylvania, USA) was used for all the data analysis. A *p*-value of 0.05 was considered as the significance level. Statistical comparison involving two sets of data was carried out by using the two-sample *t*-test. To compare the means between three or more datasets, One-way Analysis of Variance (ANOVA) followed by Tukey's multiple comparison test was conducted.

Results and discussion

Water activity

As shown in Table 2, no significant difference ($p > 0.05$) was observed in the water activity between all M-mayonnaise (0.65 - 0.75 a_w) and H-mayonnaise (0.74 - 0.78 a_w) samples, with M-mayonnaise samples showing lower values.

Table 2. Physical and structural properties of mayonnaises with different fat portions prepared using a lab-scale mixer (M) and high-shear homogeniser (H).

		Mayonnaise		
Physical and structural property	**M-SBO**	**M-0**	**M-25**	**M-50**
Water activity (a_w)	0.69 ± 0.10^{aA}	0.69 ± 0.14^{aA}	0.75 ± 0.12^{aA}	0.65 ± 0.06^{aA}
Colour properties				
L^* value	77.61 ± 1.30^{aA}	74.80 ± 1.84^{bA}	68.01 ± 1.78^{cA}	64.76 ± 1.70^{dA}
a^* value	1.89 ± 0.84^{cA}	-1.61 ± 0.82^{dA}	9.65 ± 0.59^{bA}	15.22 ± 0.54^{aA}
b^* value	28.44 ± 3.03^{bA}	28.37 ± 2.09^{bA}	56.50 ± 3.73^{aA}	59.64 ± 3.37^{aA}
Vol. weighted mean D [4,3] (µm)	532.44 ± 91.99^{bA}	644.85 ± 73.32^{aA}	644.62 ± 38.34^{aA}	672.37 ± 51.30^{aA}
Separated oil portion (%)	16.83 ± 7.26^{aA}	24.27 ± 20.83^{aA}	42.68 ± 15.25^{aA}	27.97 ± 21.71^{aA}
Physical and structural property	**H-SBO**	**H-0**	**H-25**	**H-50**
Water activity (a_w)	0.78 ± 0.10^{aA}	0.74 ± 0.08^{aA}	0.75 ± 0.09^{aA}	0.76 ± 0.12^{aA}
Colour properties				
L^* value	77.33 ± 0.95^{aA}	77.73 ± 1.51^{aB}	72.43 ± 2.09^{bB}	70.64 ± 0.95^{bB}
a^* value	2.08 ± 0.34^{cA}	-1.49 ± 0.33^{dA}	5.19 ± 0.55^{bB}	11.49 ± 1.28^{aB}
b^* value	24.28 ± 2.65^{bB}	25.34 ± 1.00^{bB}	51.57 ± 2.05^{aB}	55.13 ± 4.41^{aA}
Vol. weighted mean D [4,3] (µm)	501.34 ± 55.92^{aA}	504.45 ± 58.12^{aB}	448.95 ± 47.84^{aB}	515.61 ± 34.98^{aB}
Separated oil portion (%)	0.00 ± 0.00^{aB}	1.83 ± 2.70^{abB}	1.19 ± 1.75^{abB}	0.44 ± 0.27^{bB}

Values are mean ± SD ($n = 6$). Mayonnaises labelled as H-SBO and M-SBO contain 100% (w/w) soybean oil as the fat portion, while other mayonnaises contain 0% (H-0, M-0), 25% (H-25, M-25), and 50% (H-50, M-50) red palm olein blended with palm olein as the fat portion. Means in the same row followed by different lowercase superscripts are significantly different ($p < 0.05$) based on One-way ANOVA and Tukey's Multiple Comparison Test. Means for each property followed by different uppercase superscripts are significantly different ($p < 0.05$) based on two-sample *t*-test.

According to Gómez and Fernández-Salguero (1992), sodium chloride (NaCl) was the main depressing agent in products including mayonnaise, butter, and margarine; samples with highest NaCl in the aqueous phase would have the lowest a_w and vice versa. In the present work, similar NaCl (salt) amount was used in all samples. However, the different mixing and homogenising methods had most likely affected the NaCl distribution in the oil and aqueous phases, thus resulting in the apparent differences. On the other hand, these values were lower than mayonnaises formulated using soybean oil (0.95) (Su *et al.*, 2010), and blends of soybean and sunflower oil (0.89 - 0.94) (Amin *et al.*, 2014). These disparities might be explained by the different formulations used since the composition of the soluble compounds in the water phase might affect the a_w of mayonnaises (Chirife *et al.*, 1989). Only the vinegar solution had a water portion in the present work, and no water was added (Table 1). The formulation might have contributed to the lower a_w of the mayonnaise samples. Meanwhile, there was also no significant difference ($p > 0.05$) in a_w between M- and H-mayonnaise samples. These findings reinstated the influence of different formulations on the a_w of mayonnaises. However, the alteration in the a_w of mayonnaises depended on the formulations used, but did not vary with the mixing mechanisms.

Colour properties, droplet size distribution, microstructure, and oil phase separation

Table 2 shows the colour properties of mayonnaise samples, whereas their images are displayed in Figure 1a.

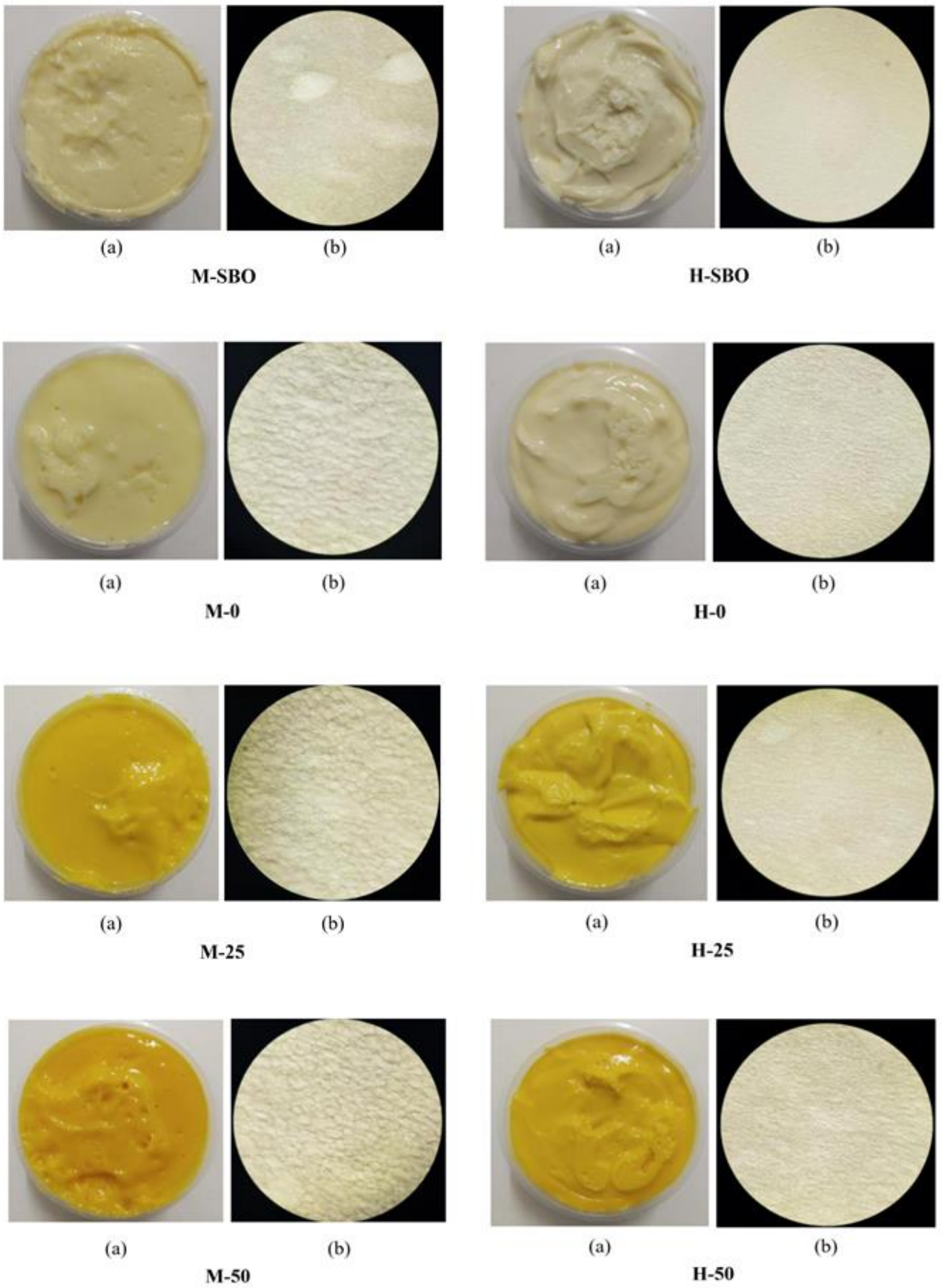

Figure 1. (a) Colour and **(b)** microstructure of mayonnaises with different fat portions prepared using a lab-scale mixer (M) and a high-shear homogeniser (H). M-SBO and H-SBO are mayonnaises containing 100% (w/w) soybean oil as the fat portion, while other mayonnaises contain 0% (M-0, H-0), 25% (M-25, H-25), and 50% (M-50, H-50) red palm olein blended with palm olein as the fat portion.

For the M-mayonnaise samples, the *L** values (lightness) significantly decreased ($p < 0.05$) from M-SBO to M-0, M-25, and M-50. There was a corresponding significant ($p < 0.05$) increase in *a** (redness) and *b** (yellowness) values in both M-25 and M-50 as compared to M-SBO and M-0. Similar trends were observed in H-mayonnaise samples in all cases. These results corroborated the reports from previous studies, where RPOL had significant effects in decreasing the lightness and increasing the mayonnaise samples' redness and yellowness (Riyadi *et al.,* 2016; Loganathan *et al.,* 2017). The capacity to induce these changes was attributed to the high carotene content in RPOL, which is estimated to be 500 - 800 mg/kg (Riyadi *et al.,* 2016; Loganathan *et al.,* 2017).

All palm-based H-mayonnaise samples recorded significantly higher ($p < 0.05$) *L** values than those of M-mayonnaise samples (Table 2). M-25 and M-50 exhibited significantly higher ($p < 0.05$) *a** values as compared to H-25 and H-50, respectively. Similar trends were observed for *b** values where all M-mayonnaise samples had significantly higher ($p < 0.05$) values than those of H-mayonnaise samples, except for M-50 and H-50. Hence, H-mayonnaise samples indicated higher lightness, and lower redness and yellowness as compared to M-mayonnaise samples. The smaller droplet size of the H-mayonnaise samples as compared to M-mayonnaise samples might have been responsible for these findings. In developing an emulsion, an increase in the mixing speed results in decreasing the droplet size and the production of smaller emulsion droplets. The process enhances light dispersion, and increases the emulsion's lightness (Su *et al.,* 2010; Ng *et al.,* 2014). Wendin *et al.* (2000) also reported a similar finding based on the positive correlation between the whiteness of mayonnaise and the droplet size, whereas a negative association was observed between the yellowness of cream cheese and homogenisation speed (Wendin *et al.,* 2000).

M-SBO exhibited a significantly smaller ($p < 0.05$) droplet size relative to that of palm-based M-mayonnaise samples (Table 2). According to Wan Rosnani *et al.* (2015), SBO contributed to small droplet size in a mayonnaise formulation. In another study, the substitution of SBO with an increasing amount of palm kernel oil resulted in mayonnaise with increasing droplet size diameter (Hayati *et al.,* 2007). Muhialdin *et al.* (2019) also reported the smallest droplet size of mayonnaise samples formulated with SBO blended with virgin coconut oil, followed by SBO and virgin coconut oil individually.

In contrast to these studies, the droplet sizes of H-mayonnaise samples were not significantly different ($p > 0.05$) from each other in the present work. Moreover, all H-mayonnaise samples had significantly smaller ($p < 0.05$) droplet sizes than those of M-mayonnaise samples. These differences were mainly due to the different probes and operational mechanisms of both lab-scale mixer and high-shear homogeniser. For instance, as the rotor in the homogeniser rotated at a higher speed, the mixture was drawn and expelled through the openings at the stator at high velocity. This homogenising mechanism led to the formation of small emulsion droplets, which improved the emulsion stability (Banaszek, 2011; Di Matia *et al.,* 2015). Increased shear rates during homogenisation also resulted in the formation of smaller emulsion droplet sizes (Winderström and Öhman, 2017). In contrast, a lab-scale mixer employs common rotational forces from the whisk/blade, and creates an emulsion with a larger droplet size (Table 2).

Another indication of the smaller droplet size in H-mayonnaise samples was their microstructures. As shown in Figure 1, H-mayonnaise samples had closely packed and spherical oil droplets of smaller diameter as compared to M-mayonnaise samples. Nevertheless, the microstructures of palm-based M- and H-mayonnaise samples changed gradually, and became less closely packed as the amount of RPOL increased. The process led to the formation of aggregates in the M-mayonnaise samples besides exhibiting coarser, open, and looser structure as compared to the H-mayonnaise samples. According to Ng *et al.* (2014), the formation of aggregates may enhance the merging of two or more droplets, thus leading to the formation of a single larger droplet. The larger droplets are further separated as an oil layer on top of the mixture. This phenomenon is known as oiling-off, and described as coalescence phenomena, which may subsequently decrease the stability of the emulsion.

As presented in Table 2, the oiling-off was observed in M-mayonnaise samples (separated oil portion, 16.83 - 42.68%), which indicated their lower stability as compared to H-mayonnaise samples (separated oil portion, 0.00 - 1.83%). However, the oil separation was not affected by the type of oil used, except for H-SBO, which showed no oil separation. This outcome might have been due to the similar chemical compositions of SBO, RPOL, and palm olein. As reported in previous studies, SBO contained the highest amount of linoleic acid (C18:2; 49.5%, w/w) (Kostik *et al.*, 2013), while oleic acid (C18:1) made up 42.3% (w/w) and 39.8% (w/w) of RPOL and palm olein, respectively (Kumar and Krishna, 2014; Tang and Pantzaris, 2017). Oleic and linoleic acids are classified as polyunsaturated fatty acids, which contribute to their liquid property at room temperature. Hence, the similar chemical properties in the oils might have been responsible for the lack of significant differences in the amount of oil separated.

Rheological properties

Besides complex modulus, viscoelastic moduli, elastic or storage modulus (*G'*) and viscous or loss modulus (*G''*) are widely applied to determine the rheological properties of mayonnaise as a semi-solid product (Zheng, 2019). The solid-like property of a product is indicated by the *G'*, which is the energy metric stored in an oscillation cycle. On the other hand, the liquid-like property is indicated by the *G''*, which is the measure of energy dissipated as a viscous liquid in an oscillation cycle (Zheng, 2019). In the present work, *G'* values were higher than *G''* for all mayonnaise samples (Figure 2), which indicated their elastic or semi-solid behaviour upon the exerted stress.

In Figure 2a, M-SBO showed the highest *G'* values, followed by M-0, M-50, and M-25. This was a reflection of the lower emulsifying capability of the lab-scale mixer as compared to the high-shear homogeniser. In addition to the presence of RPOL, this situation might have resulted in M-mayonnaise samples exhibiting less mechanical rigidity and, therefore, less solid-like property. Evidently, lower *G'* values and yield stress were observed in all M-mayonnaise samples (Figure 2a) as compared to those of H-mayonnaise samples (Figure 2b). As described by Zheng (2019), a decrease in the G' beyond the linear viscoelastic region indicates structural disruption, while an additional crossover of G' and *G''* indicates the possibility of the material to flow (Zheng, 2019).

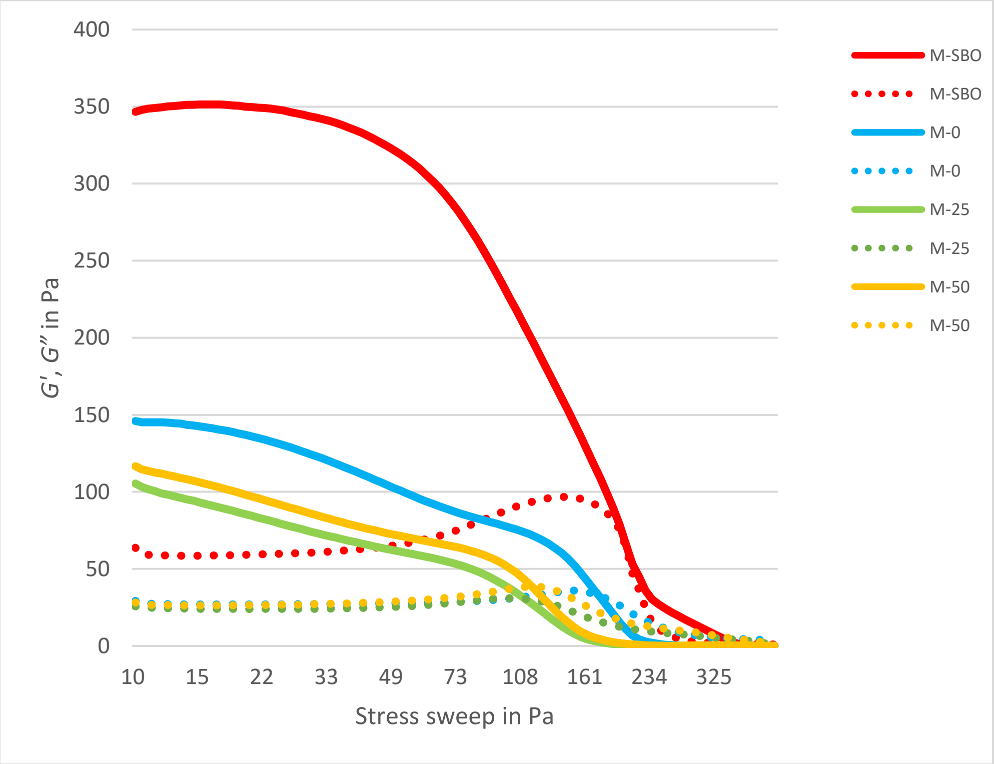

Figure 2a. Dynamic mechanical properties of mayonnaises with different fat portions prepared using a lab-scale mixer (M-). Mayonnaises labelled as M-SBO contain 100% (w/w) soybean oil as the fat portion, while other mayonnaises contain 0% (M-0), 25% (M-25), and 50% (M-50) red palm olein blended with palm olein as the fat portion. Lines and dotted lines indicate storage modulus (*G'*) and loss modulus (*G''*) of the mayonnaises, respectively.

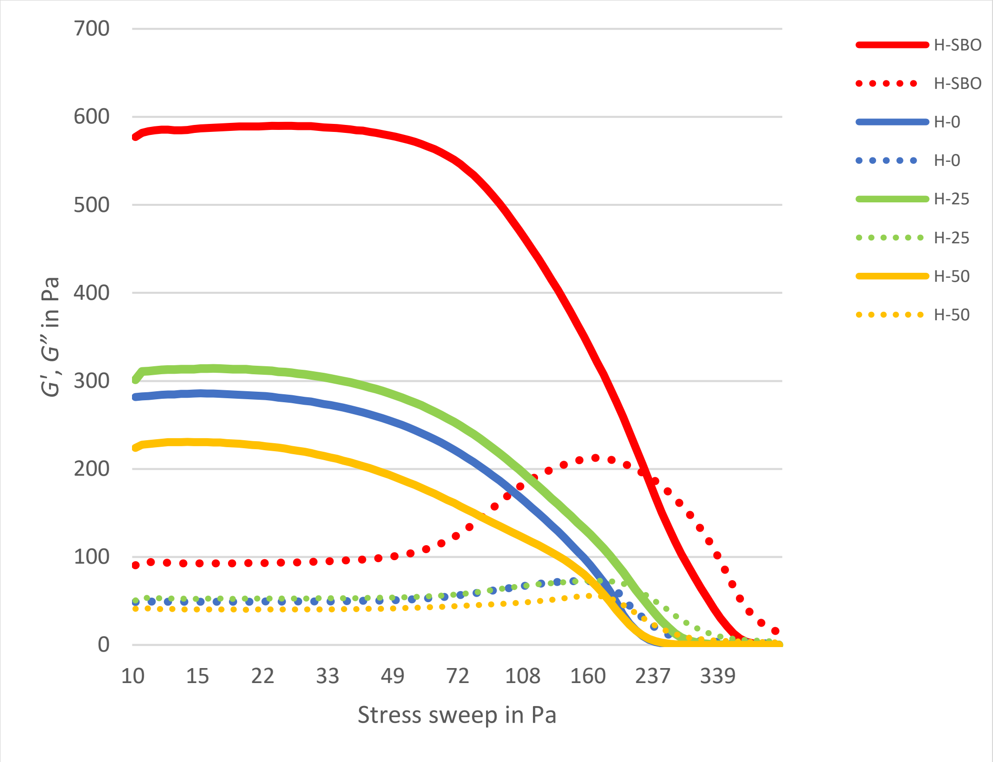

Figure 2b. Dynamic mechanical properties of mayonnaises with different fat portions prepared using a high-shear homogeniser (H-). Mayonnaises labelled as H-SBO contain 100% (w/w) soybean oil as the fat portion, while other mayonnaises contain 0% (H-0), 25% (H-25), and 50% (H-50) red palm olein blended with palm olein as the fat portion. Lines and dotted lines indicate storage modulus (*G'*) and loss modulus (*G''*) of the mayonnaises, respectively.

In the case of H-mayonnaise samples, Figure 2b shows the highest *G'* values (*i.e.* a greater solid-like property in H-SBO), followed by H-25, H-0, and H-50. Tiefenbacher (2017) reported that oils having iodine value higher than 115 were susceptible to hardening; becoming tough and firm due to polymerisation before exposition to the air. In the present work, the SBO with an iodine value of 129 - 140 (Behic *et al.*, 2013; Muhialdin *et al.*, 2019) had possibly undergone polymerisation during the emulsion formation. In the process, air participation was induced during homogenisation. Therefore, H-SBO exhibited greater solid-like property as compared to both H-25 and H-50. On the other hand, it was assumed that 25% (w/w) RPOL in the H-25 fat portion had effectively emulsified with palm olein, and blended well with other ingredients, thus resulting in mayonnaise with greater solid-like behaviour as compared to H-0 and H-50.

Sensory evaluation

H-mayonnaise samples exhibited greater physical properties and structural stability than M-mayonnaise samples. Therefore, the H-mayonnaise samples were further used to determine the sensory acceptance of consumers. As presented in Table 3, H-SBO was more accepted ($p < 0.05$) in their colours than palm-based mayonnaise samples. This indicated that mayonnaise's colour was significant in influencing the consumer's acceptance.

Palm-based mayonnaise samples, particularly those containing RPOL, were higher in redness and yellowness (Table 2). The physical appearance might be unappealing to certain consumers. Aside from the physical appearance, some panellists mentioned that the mayonnaise's yellow colour might be confusing because the colour was similar to that of mustard. Nevertheless, no significant difference ($p > 0.05$) was observed in the creaminess, odour, and taste between the H-SBO and palm-based mayonnaise samples as well as the overall acceptance between H-SBO, H-0, and H-50. However, the overall acceptability score was lowest for H-25 ($p < 0.05$); the score was not significantly different ($p > 0.05$) from that of H-0 and H-50.

Table 3. Sensory acceptability score of mayonnaises with different fat portions prepared using a high-shear homogeniser.

Sensory property	**Mayonnaise**			
	H-SO	**H-0**	**H-25**	**H-50**
Creaminess	5.44 ± 1.84^{a}	5.08 ± 1.87^{a}	4.90 ± 1.78^{a}	5.06 ± 1.91^{a}
Colour	6.08 ± 1.63^{a}	4.94 ± 1.87^{b}	4.80 ± 2.05^{b}	4.12 ± 2.04^{b}
Odour	5.18 ± 1.85^{a}	4.90 ± 1.81^{a}	4.82 ± 1.75^{a}	4.54 ± 1.88^{a}
Taste	5.28 ± 2.09^{a}	4.78 ± 2.05^{a}	4.22 ± 2.02^{a}	4.78 ± 2.04^{a}
Overall acceptability	5.56 ± 1.98^{a}	4.94 ± 1.94^{ab}	4.50 ± 1.80^{b}	4.58 ± 1.93^{ab}

Values are mean ± SD (n = 50). Different lowercase superscripts in the same row indicate significant difference ($p < 0.05$) based on one-way ANOVA and Tukey's Multiple Comparison Test. H-0, H-25, and H-50 contain 0% (w/w), 25% (w/w), and 50% (w/w) red palm olein, respectively.

Conclusion

The redness and yellowness of mayonnaises increased upon higher RPOL content, yet the lightness decreased, while the a_w, droplet size, and separated oil phase did not change significantly. The use of high-shear homogeniser resulted in mayonnaises with better physical properties and structural stability based on droplet size, microstructure, oil phase separation, and viscoelastic properties as compared to the use of the lab-scale mixer. The overall sensory acceptability scores were not different between the H-mayonnaises, except for the lower scores of the colour properties. Nevertheless, this newly developed RPOL-based product could be a healthier choice of mayonnaise which should further be explored for commercialisation purposes.

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