Effect of homogenisation in foam and emulsion mix beverage colloidal system: A case in Teh Tarik

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A B S T R A C T
Teh Tarik is a frothed milk tea consisting of Ceylon Tea, condensed milk, sugar, where it is traditionally prepared by pulling motion to get aerated. High-shear homogenisation through rotor-stator homogeniser was explored in this study as an alternative method to produce Teh Tarik at a larger scale and at the same time enhancing the stability of the Teh Tarik emulsion and foam. Varying speeds (11,000 rpm, 18,000 rpm and 25,000 rpm) of homogenisation resulted in size reduction of milk fat globules to various degrees. This reduction in particle size by at least 0.4 μm consequently increased the stability of the milk tea emulsion, which is the most significant (α = 0.05) at the speed of 18,000 rpm. At the same time, increasing speed of homogenisation from 11,000 rpm to 18,000 rpm and 25,000 rpm also reduces dynamic surface tension through the increased protein adsorption rate at the water-air interphase and ultimately reducing foam drainage. Subsequently, the improved physical stability of emulsion and foam could be made use to develop satiety- and satiation-enhanced beverage as a modus operandi to reduce calorie intake among Malaysians.

1. Introduction
Homogenisation is a common unit operation applied in the food industry, typically in the dairy industry to stabilise the fat phase in dairy products and thus, prevent creaming. Stabilisation of the fat particles in dairy products via homogenisation is achieved primarily through the reduction of milk fat globule sizes. During homogenisation, larger milk fat globules are broken down into smaller particles, at the same time, the original milk fat globule membranes will be disrupted and readsobered into the smaller globules with milk caseins and whey proteins originally found in the milk serum (Truong et al., 2015). According to the Stokes’ Law, this reduction of particle size could also reduce the effect of gravity on the movement of the dispersed particles (Yildirim et al., 2016), thus preventing phase separation. Viscosity could be increased via homogenisation contributing to the reduction of the fat particles’ movement. It is established that the reduction of the particle size of these milk fat globules down to 0.4 μm is sufficiently stable against creaming of the colloidal system. However, the particle size of commercial drinking milk is generally around 1 μm (Truong et al., 2015).

Other than that, the reduction of milk fat particles could also increase the palatability of a dairy product due to the increased viscosity and perception of creaminess. Reduction of particle size increases interparticle interactions due to the increase of total surface area, thus increasing the viscosity of the system. In addition, according to the ball-bearing hypothesis (Liu et al., 2016; Anvari and Melito, 2017), the decrease in particle size also creates smoothness in beverages as the particles glide against each other. Controlling particle size below 10 μm thus yields a smooth and creamy texture due to the reduced friction in the small ball-like emulsion droplets structure. These preferred attributes are associated with the texture of a high-fat product, hence reduction in particle size is often made use to formulate reduced-fat food product (Lett et al., 2016a).

Numerous kinds of mechanical devices can be used to stabilise emulsions, including high-shear mixers, colloid mills, high-pressure valve homogenisers, microfluidisers, and sonicators (McClements, Newman and McClements, 2019). High-shear mixers such as a rotor-stator homogeniser make use of the turbulent energy created at the tiny gap between the inner rotating shaft and outer stationary shaft to break down particles. Other than homogenisation, rotor-stator homogenisers are often used in dairy products for whipping purposes. Due to

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the high mechanical force and turbulence, air is whipped into the aqueous phase and then further broken down into tiny air cells through the tiny gaps of the stator. As a result, a matrix containing air bubbles and oil droplets dispersed in the aqueous phase is formed. Although the presence of fat is classically believed to suppress foaming (Rio et al., 2014), there are also systems where emulsion and foam coexist, such as Teh Tarik (pulled milk tea).

In this study, Teh Tarik is being selected as the study model due to its dual texture of having emulsion (milk tea) and foam from the same base. Teh Tarik is essentially a frothed Ceylon milk tea, made up of Ceylon tea, sugar, and condensed milk or non-dairy creamer, traditionally aerated by pulling motion. Because of the frothy foam that adds an extra layer of texture to the already silky milk tea body, it is undoubtedly that Teh Tarik is being crowned as the national drink (New Sabah Times, 2012). According to the Malaysia Food Barometer (2014), Teh Tarik is Malaysia’s third most commonly enjoyed beverage after tea and coffee throughout the day, and the highest consumed beverage during supper.

Since the creaminess and frothiness of Teh Tarik are very much related to the emulsifying properties and stability, as well as the foaming properties and stability, research has been focused to formulate ingredients such as non-dairy creamer in order to improve emulsifying and foaming properties. Studies on a new technique of preparing Teh Tarik, i.e., via homogenisation, would welcome potential to scale up production of the beverage. High-shear homogenisation could also potentially produce Teh Tarik with a high satiety (fullness sustainability) and satiation (fillingness of a food product) capacity (Bellisle and Blundell, 2013) through stabilisation of the milk tea foam and emulsion particle size (Chan et al., 2017; Lett et al., 2016b).

Therefore, in this study, we aim to find out the effect of high-shear homogenisation on foam and emulsion stability of Teh Tarik. We hypothesised that at the right homogenisation speed, the particle size of milk fat droplets could be reduced, thus increasing viscosity, reducing surface tension, and ultimately stabilise the emulsion and foam.

2. Materials & methods

2.1. Materials

The ingredients used in milk tea were all food grade. BOH Teh Harimau black tea dust (BOH Plantations Sdn. Bhd, Cameron Highlands, Malaysia), Promex Instant Full Cream Milk Powder (24% protein, 28.4% fat) (Promac Enterprises Sdn. Bhd, Kepong, Malaysia), and sucrose (cane) (Central Sugars Refinery Sdn. Bhd, Shah Alam, Malaysia), were procured from local grocery stores. Distilled water was used to prepare the milk tea samples.

2.2. Preparation of samples

Tea dust, 3.6 g, was infused with 225 g of hot water at an initial temperature of 80 °C for 15 min. Tea dust was then filtered off with Whatman No.1 filter paper and tea was left to cool down to room temperature. Consequently, whole milk powder (15 g) and sugar (5 g) were dispersed in water (45 g) with the aid of a magnetic stirrer (350 rpm) at room temperature until fully dissolved. The milk tea was then constituted by mixing milk mixture and tea at a ratio of 1:3 by weight. This mixture served as the control sample. Milk tea underwent homogenisation using a rotor-stator homogeniser (IKA Ultra-Turrax T25, Ika Works, Selangor, Malaysia) of rotor diameter of 18 mm and 0.5 mm gap between the rotor and stator. Samples were homogenised at speeds 11,000 rpm, 18,000 rpm and 25,000 rpm for 2 min, respectively.

2.3. Characterisation of the emulsion sample

2.3.1. Particle size analysis

Particle size analysis was conducted as described by Wu et al. (2020) with modifications. The particle size of the emulsion was analysed using a laser diffraction particle size analyser (Anton Paar PSA 1190, Anton Paar Malaysia Sdn Bhd, Petaling Jaya, Malaysia). Fresh emulsion samples (0 min) were extracted from the bottle of the beakers 30 s after homogenisation and loaded into the circulation tank filled with deionised water until an obscuration level of 12–14% was achieved. The samples were then subjected to 30 s of ultrasound to prevent agglomeration. The average of 5 readings was calculated and the tests were conducted in triplicates. Samples were measured again at 60 min and 120 min after homogenisation. Results were interpreted in terms of a distribution using the equation below:

\[ \text{Polydispersity index} = \frac{D_{90} - D_{10}}{D_{90}} \]

Where, \( D_{90} = \text{mean particle size at the 90th percentile, } \)
\( D_{10} = \text{mean particle size at the 10th percentile, } \)
\( D_{50} = \text{the mean particle size at the median. } \)

2.3.2. Flow behaviour of the emulsion

Samples of milk tea emulsion (0.9 mL) were extracted from the bottom of the beaker 30 s after homogenisation. Flow behaviour, shear stress, \( \tau \), and apparent viscosity, \( \eta \), of the beverage emulsion were determined using Thermo Scientific™ HAAKE™ MARS™ Rheometer (Thermo Electron GmbH, Germany). The linear viscoelastic region of the sample was first determined using frequency sweep using a parallel-plates sensor system (6 mm diameter and 1 mm gap) over a range of 0.01–10 Hz at 25 °C. The shear stress and apparent viscosity of the beverage model within the linear viscoelastic region were then determined at a linearly increasing shear rate from 0/s to 1000/s within 180 s, and the temperature kept at 25 °C (Morell et al., 2014).

Flow behaviour (shear stress \( \tau \) vs shear rate) were then fitted using power law to determine the flow behaviour index, \( n \).

\[ \tau = K\gamma^n \]

Where, \( \tau = \text{shear stress (Pa); } \) \( \gamma = \text{shear rate (s)}; K = \text{flow consistency index (Pa.s}^n) \) \( n = \text{flow behaviour index. } \)

2.4. Characterisation of the foam sample

2.4.1. Physical characteristics

2.4.1.1. Foaming stability & ability. Milk tea sample (50 mL) were homogenised with a rotor-stator homogeniser (IKA Ultra-Turrax T25, IKA Works, Selangor, Malaysia) at speeds of 11,000 rpm, 18,000 rpm and 25,000 rpm respectively, in a 100 mL measuring cylinder for 2 min. Immediately after homogenisation the total volume of the foam formed was immediately taken. The time taken for foams to disappear was recorded. Time taken for the bubbles to totally collapse (overrun to drainage ratio) was used to estimate the overall foaming ability and stability. These measurements were calculated by using the formula below:

\[ \text{Overrun} = \frac{V_f - V_i}{V_i} \times 100\% \]

Where, \( V_f = \text{Volume after homogenisation; } V_i = \text{Volume before homogenisation} \)

\[ \text{Drainage} = \frac{\text{Overrun}(\%)}{t} \]

Where Drainage = rate of volume loss (% per min); \( t = \text{time taken for the foam to collapse (min) } \)

\[ \text{Foam stability} = \frac{\text{Overrun}}{\text{Drainage}} \approx \text{Time taken for the foam to collapse} \]
2.4.1.2. Microscopy. Methods described by Hao et al. (2016) was applied with modifications. Milk tea foam (45 μL) prepared as previously described was scooped using a spatula from the surface 30 s after homogenisation and loaded onto a concave microscope slide and covered with a glass slide. Excess liquid was absorbed from the side of the cover slide.

Bubble distribution and changes of bubble size of foam was observed through an upright optical light microscope (Nikon Eclipse Ni-U, Nikon Corporation, Tokyo, Japan) at 4× magnification and captured using Nikon DS-Fi2 camera (Nikon Instruments Inc, NY, USA). Photomicrographs of the samples were processed and fitted with square grids of 50 μm length. using imaging software NIS-Elements Br ver. 4.30.01 (Nikon Laboratory Imaging, NY, USA). These photomicrographs were then cropped to an area of 0.36 mm².

2.4.2. Dynamic surface tension

The dynamic surface tension of the foam was determined using attention Theta lite Optical tensiometer (Biolin Scientific Oy, Espoo, Finland) using the pendant drop test (Drapala et al., 2018). Each milk tea samples were injected manually into a drop of 7.5 μL from a precision syringe with steel needle (Biolin Scientific Oy, Espoo, Finland). Measurements were taken at a rate of 2 measurements per second for 180s. Readings were then analysed with the software One Attension (Biolin Scientific) using the Young-Laplace curve-fitting method. Each sample was run for triplicates and a graph of surface tension against time was plotted. The standard deviation of the triplicates was roughly 0.1 mN/m. The data obtained were then fitted into a Joos-Hansen model by plotting surface tension, γ, against the reciprocal of root of time, t⁻¹/² to derive the long-time gradient, λ (Daniel and Berg, 2001).

2.4.3. Flow behaviour of the foam

Samples of milk tea foam (0.9 μL) were scooped from the surface 30 s after homogenisation. Steps described in section 2.3.2 was repeated to determine the flow behaviour, shear stress, τ, and apparent viscosity, ηa, of the beverage foam at a linearly increasing shear stress from 0 Pa to 4 Pa within 180s and the temperature kept at 25 °C (Morell et al., 2014). Results were represented as shear stress and viscosity against shear rate, while yield stress was later determined using the tangent intersection point method (Willenbacher and Lexis, 2019).

2.5. Statistical analysis

Samples were prepared in triplicates and measurements of each triplicate were taken thrice. Then, data collected were analysed using one-way ANOVA in IBM SPSS statistics (ver 25, IBM Corp., USA) to determine the significance of differences between the mean values at a confidence level of 95% (α = 0.05). Correlation and multiple linear regression were also used to analyse the impact of the testing parameters (homogenisation speed and the resultant parameters, i.e., particle size, dynamic surface tension, and overrun) on the outcome, which is the stability of milk tea emulsion and foam samples.

3. Results & discussion

3.1. Properties of milk tea emulsions

3.1.1. Effect of homogenisation speed on particle size and particle size distribution

Particle size and particle size distribution are important parameters in defining the rheological profile of emulsions. The smaller the particle size of the dispersed phase, the lower the tendency for fat droplets to be disrupted under high shear. Furthermore, as the particle size reduces, the number density of fat droplets increases, increasing total surface area, exposing more sites for inter-particle interactions such as van der Waals forces, hydrophobic interactions and formation of hydrogen bonding as the particles interact. These interactions increase the resistance to flow, hence increasing the viscosity of the emulsion (Hussain et al., 2017).

Particle size distribution, expressed in terms of polydispersity, could be treated as an indication for emulsion destabilisation such as flocculation, agglomeration, or coalescence of the dispersed phase. A high polydispersity index indicates a wider range of particle sizes as compared to a low polydispersity index. In other words, samples with high polydispersity index have less uniform particle size distribution due to destabilisation of emulsions. Hence, in addition to the mean particle size, a higher polydispersity index also indicated lower emulsion stability (Loi et al., 2019).

Based on the results obtained in Table 1, it was observed that the particle size had significantly reduced (P < 0.05) upon homogenisation. There were no significant differences (P > 0.05) between the samples homogenised at the speed of 11,000 rpm and 18,000, as well as 11,000 rpm and 25,000 rpm, respectively. However, samples homogenised at 18,000 rpm had the smallest D₅₀ and was significantly different (P < 0.05) compared with that of control and samples homogenised at 25,000 rpm.

Referring to Fig. 1, the mean particle size of the control set grew upon storage, whereas that of homogenised samples remained consistent (P > 0.05) at 1.17 μm (11,000 rpm) 1.12 μm (18,000 rpm) and 1.20 μm (25,000 rpm) throughout the 2-h storage. The growth of particle size is an indicator for destabilisation of milk fat globules. Therefore, the controlled particle size during storage in the homogenised samples showed that homogenisation could effectively control the destabilisation of milk tea emulsion.

Besides, the stability of the milk tea emulsion was also reflected in the polydispersity indices of the samples. As mentioned earlier, a high polydispersity index is a result of destabilisation of emulsion where coalescence, flocculation, and agglomeration of fat droplets lead to a disproportion of the particle size. According to Fig. 1, all the homogenised samples have significantly lower (P < 0.05) polydispersity index than the control set. The particle size distribution of the fat droplets in homogenised samples were concentrated around the median particle size (high uniformity, low polydispersity index), whereas the distribution was more widespread in the control set. The subsequent increase of the polydispersity index of the control set in the first hour indicated that destabilisation of fat globules occurred at different rate contributing to various particle sizes ranging from 0.3 μm to 20.6 μm. The higher mean particle size and uniformity of the control set in the second hour suggested that the smaller fat droplets have thus coalesced during storage, narrowing and heightening the particle distribution peak. A similar scenario was also observed in samples that were homogenised at 25,000 rpm during the second hour of storage but not in samples that were homogenised at 11,000 rpm and 18,000 rpm. This showed that homogenisation speed of 25,000 rpm yielded a less stable emulsion as compared to 11,000 rpm and 18,000 rpm.

3.1.2. Effect of homogenisation speed and particle size on flow behaviour

All milk tea samples exhibited shear-thinning properties (Table 1) upon increasing shear rates. It is speculated that the decrease in viscosity at high shear rates was caused by the deformation of oil droplets leading to droplet coalescence and subsequently weakens the interparticle interactions due to the increase particle-to-particle distance. The change in viscosity could also be observed through the consistency index, K and flow behaviour index, n. A higher K value indicates a higher viscosity while an n value lower than 1 indicates a shear thinning behaviour. The smaller the value of n, the more pronounced is the shear thinning behaviour.

Based on the results, although the effect on viscosity was not significant (P > 0.05), it could be observed that the values of K increased as the speed of homogenisation increased. In other words, the viscosity of the milk tea samples increases as the homogenisation speed increases. Although particle size was lowest in samples homogenised at 18,000
rpm (P < 0.05), viscosity was the highest in the samples homogenised at 25,000 rpm. The increase in viscosity in samples homogenised at 18,000 rpm was due to reduction of particle size, whereas the increase in viscosity of samples homogenised at 25,000 rpm could be explained through partial coalescence of fat globules. The shear rate from homogenisation at 25,000 rpm was too high that the disrupted native milk fat globule membrane was unable to completely readorb onto the broken-down droplets, exposing unadsorbed surface on the fat globules for coalescence to occur. This clustering of fat droplets was reported to be encouraged through single homogenisation and could lead to increased viscosity and firmer body in cream and cultured cream (Narvhus et al., 2019). This also explains the lowest \( n \) value in samples homogenised at 25,000 rpm, as coalesced fat droplets are less stable (Narvhus et al., 2019; Schröder et al., 2018), hence the resulting in the more pronounced shear-thinning behaviour.

3.2. Foaming properties of milk tea foam

The ability to increase in volume and maintaining volume are indicators of foaming ability and stability, respectively. Foaming ability increases when a continuous milk tea emulsion phase can trap more air in the system, while stability increases when the ability to retain the trapped air increases without breaking the air bubbles. Foaming properties could be affected by viscosity and surface tension of the liquid continuous phase. In the previous part of this study (3.1.2), we found that change in homogenisation speed did not significantly change the viscosity of the liquid emulsion phase. Therefore, the relationship between surface tension and foaming properties due to homogenisation is studied.

3.2.1. Dynamic surface tension

Dynamic surface tension is a determining factor for foaming properties. The stability of the foam formed from the milk tea emulsion
model in this study is contributed by the milk fats, sugar, and milk protein. Surface tension reduces as the milk proteins and sugar start to adsorb onto the water-air interface until it reaches an equilibrium. The higher the rate of adsorption of protein and sugar into the interfacial layer, the sooner a protective layer is formed, thus, the more stable is the foam. On the other hand, it is suggested that milk fats globules also play a part in stabilising the foam structure, where partially coalesced liquid fat would also partly adsorb onto the surface of the bubbles (Borchardt et al., 2008), forming a 3-D fat network covering and protecting the surface of air bubbles (Eisner et al., 2005).

Based on the results obtained (Fig. 2A), the surface tension of samples homogenised at 18,000 rpm and 25,000 rpm reduced at a higher rate as compared to control and samples at 11,000 rpm. The readings of surface tension, \( \gamma \) at \( t = 100s \) were also lower in 18,000 rpm (\( \gamma_{100} = 44.1 \) mN/m) and 25,000 rpm (\( \gamma_{100} = 44.1 \) mN/m) than control (\( \gamma_{100} = 44.6 \) mN/m) and 11,000 rpm (\( \gamma_{100} = 44.5 \) mN/m). Correlation study between homogenisation speed and surface tension at \( t = 100s \) showed that surface tension was negatively correlated with speed (\( P < 0.05 \), Pearson’s correlation = 0.804). This indicates that the increase in homogenisation speed reduces the surface tension of the samples.

The graph of surface tension against time \( t^{-1/2} \) was then plotted to fit the Joos-Hansen model and extrapolated to derive the long-time gradient, \( \lambda \). According to Fig. 2B and Table 1 the long-time gradient, \( \lambda \), was reduced through homogenisation at 18,000 rpm, but increased after being homogenised at 25,000 rpm and 11,000 rpm. Long-time gradient is a derivative of the function of surface tension against time \( t^{-1/2} \) based on the Ward-Tordai equation, limiting the time as it approaches infinity.

\[
\lambda = \lim_{t \to \infty} \frac{d\gamma}{dt} \left( \frac{1}{2} \right) = \frac{RT^2}{\pi \Gamma c_0} \sqrt{\frac{\pi}{4D}}
\]

Where, \( \gamma \) is the dynamic surface tension, \( t \) is the time, \( R \) is the gas constant, \( T \) is the temperature, \( \Gamma \) is the adsorption, \( c_0 \) is the bulk surfactant concentration, \( \pi = 3.142 \) and \( D \) is the diffusion coefficient. Lower long-time gradient represents a more effective reduction of diffusion coefficient. Diffusion coefficient is a measure of the rate of adsorption of surfactants at the interface, which is a factor for foam stability (Daniel and Berg, 2001). In other words, the lower long-time gradient in samples homogenised at 18,000 rpm indicated the higher rate of adsorption, contributing to the stability of milk tea foam.

As discussed previously, high shear from homogenisation could disrupt the milk fat globule membrane releasing milk proteins to the

Fig. 2. Changes in surface tension over (A) 180 s after homogenisation; and (B) against \( t^{-1/2} \). Samples homogenised at 18,000 rpm and 25,000 rpm reached equilibrium at a higher rate than control samples and that of 11,000 rpm and the respective long-time gradients, \( \lambda \), were 9.4 mN/m.s\(^{-1/2} \) (\( R^2 = 0.998 \)); 10.2 mN/m.s\(^{-1/2} \) (\( R^2 = 0.994 \)); 9.7 mN/m.s\(^{-1/2} \) (\( R^2 = 0.978 \)); 10.5 mN/m.s\(^{-1/2} \) (\( R^2 = 0.989 \)).
aqueous phase. Since the surface-active molecules in the milk fat membrane have a higher affinity to air than fats (Eisner et al., 2007), it adsorbs much quicker to the air-water interface, thus reducing surface tension at a higher rate. Therefore, the higher the homogenisation speed, the higher the rate of surface tension reaches its equilibrium. However, the increase in stabilisation time in the sample homogenised at 25,000 rpm could be due to over-shearing that led to separation.

3.2.2. Physical characteristics of milk tea foam

Based on the results obtained in Fig. 3 overrun of the foam was significantly improved ($P < 0.05$) with the increase of homogenisation speed. Correlation study between homogenisation speed and overrun shows that it is strongly and positively correlated ($P < 0.05$; Pearson’s correlation $= 0.881$). In other words, an increase in homogenisation speed could greatly increase the overrun. However, overrun was not correlated to surface tension ($P > 0.05$). This increase in volume along with the increase of speed was essentially due to the increase of mechanical agitation, resulting in more air incorporation. Hanselmann and Windhab (1998) reported that mechanical energy input is the most impactful parameter for foam dispersion by rotor-stator homogenisation.

The correlation between homogenisation speed and overrun, on the other hand, did not translate into the drainage of the milk tea foams. There was no significant correlation between homogenisation speed and drainage ($P > 0.05$; Pearson’s correlation $= -0.139$). Drainage was the lowest in the samples homogenised at 18,000 rpm, which is significantly lower than the samples prepared at 11,000 rpm ($P < 0.05$) but not that of 25,000 rpm ($P > 0.05$). Although there is no correlation between homogenisation speed and drainage, a positive correlation was found between surface tension and drainage ($P < 0.05$, Pearson’s correlation $= 0.708$). This reflected that bubbles are less prone to deformation at lower surface tension.

Consequently, by considering the two parameters (overrun and drainage) together, we derived that the physical stability of milk tea foam was significantly lower ($P < 0.05$) at 11,000 rpm, while there is no significant difference between the stability of milk tea foam produced at 18,000 rpm and 25,000 rpm, despite the significantly high overrun produced at 25,000 rpm. Therefore, we conclude that 18,000 rpm was the optimal speed among the studied speeds to produce the most stable foam.

3.2.3. Effect of the particle size and surface tension on foaming properties

A similar trend was noticed (Figs. 1 and 3) between particle size and drainage against homogenisation speed, where both parameters had the lowest values when speed is at 18,000 rpm, followed by 25,000 rpm and the highest when speed is at 11,000 rpm. Besides, it is also noted that the surface tension of the milk tea samples was positively correlated to drainage. Therefore, the impact of particle size and surface tension on foam stability was investigated through multiple-linear regression model.

Multiple collinearity analysis was run between particle size and surface tension to examine the correlation between these two variable (Hoffman and Hoffman, 2015). Through this test, it is found that both particle size and surface tension were independent against each other (Variable inflation factor, VIF = 1.068; VIF = 1 indicates the variables are independent against each other, and VIF > 5 suggests the presence of multiple collinearity). The impact of particle size on foam stability and drainage was insignificant ($P > 0.05$). This finding also agrees with the findings of Borchering et al. (2008), where fat globule size “had only a marginal effect on the formation and stability of foam” at unfavourable foaming temperatures of 20–30 °C. Milk proteins and surface-active component released during homogenisation are the major components that adsorb on the interface (Borchering et al., 2008), resulting in the reduction of surface tension. Therefore, the change in surface tension was the factor that contributed to the change of drainage, and subsequently the change of foam stability ($P < 0.05$). It was postulated that foam stability was improved by the reduction of surface tension leading to the reduction of pressure gradient across the bubble interface, thus minimising thinning of foam films (Jaensson and Vermant, 2018).

3.2.4. Microstructure: bubble size & structure

The foam layer of the milk tea sample is a liquid foam where air is dispersed in the liquid emulsion phase of the milk tea. The foam is characterised by small spherical bubbles with higher surface tension and lower gas fraction, $\phi$ as compared to dry foams. The gas fraction of the milk tea foam samples ranged from 0.20 to 0.36, averaging at 0.28
The foam undergoes ageing in terms of drainage, coalescence and coarsening or disproportionation due to its thermodynamically unstable nature. This phenomenon could be observed through microscopy in terms of foam density (number of bubbles per unit volume) and bubble size.

From the photomicrographs (Fig. 4), it is seen that bubble size grew upon time while density decreased. The increase in bubble size and decrease in bubble count were indicators of destabilisation of bubbles through coalescence and drainage. Drainage occurs when i) the liquid in between the plateau borders is lost due to gravity, resulting in thinner foam walls (Weaire and Phelan, 1996) and ii) when the pressure gradient at the interface forces bubbles to coalesce squeezing fluid out between the foam films (Jaensson and Vermant, 2018). This thinning of foam wall is observed in foams prepared at 25,000 rpm on the 30th minute. On the other hand, coalescence occurs when bubbles merge due to strong interparticle attractions such as van der Waals forces, while disproportionation occurs when gas diffuses from smaller bubbles into larger bubbles due to pressure differences, resulting in great differences of bubble sizes. Bubble sizes were more uniform in speed 18,000 rpm, followed by 11,000 rpm then finally 25,000 rpm. Uniformity of the bubble size suggested that coalescence and disproportion were less apparent in speed 18,000 rpm, thus foam prepared at this speed was the most stable.

3.2.5. Rheology of foam

Results from the flow behaviour and viscosity (Fig. 5) showed that 18,000 rpm is the most optimal speed among the studied speeds to produce a viscous and resistant foam. Yield stress, $\tau_y$, of the foam from 18,000 rpm was the highest ($\tau_y = 10.2$ Pa) followed by foam formed at 11,000 rpm ($\tau_y = 9.7$ Pa), and finally 25,000 rpm ($\tau_y = 3.3$ Pa), the foam quickly lost its shear stress at the region of shear rate $> 100/s$. This explained the fragility of foam produced from 25,000 rpm as described previously. The higher yield stress of the foam from 18,000 rpm indicated that the foam exhibits a more elastic behaviour where the bubbles would rearrange and initiate foam flow, hence more resistant to deformation (Völpi et al., 2021). In other words, foam from 18,000 rpm was the most resistant to stress followed by that of 11,000 rpm.

In terms of flow behaviour, the foam exhibited a shear thickening behaviour at lower shear rates up to a shear rate of 20/s. The effect was most apparent when the homogenisation speed was 18,000 rpm, while foam of 11,000 rpm experienced a less sharp decline in viscosity after the peak, suggesting that the foam is more resistant to destruction. This showed the potential of satiation and satiety inducing capacity of foam-stabilised beverages, as increased bulk volume and are signals for

<table>
<thead>
<tr>
<th>Speed</th>
<th>Time</th>
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<tbody>
<tr>
<td>11,000 rpm</td>
<td>0 min</td>
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<tr>
<td>18,000 rpm</td>
<td>15 min</td>
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<tr>
<td>25,000 rpm</td>
<td>30 min</td>
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Fig. 4. Changes of bubble sizes and distribution of milk tea foam at 0, 10, 20, 30 min after homogenisation at speeds 11,000, 18,000 and 25,000 rpm under 4× magnification. Scale: 1 square = 50 μm. Disproportionation of bubbles (A) was observed in foams formed at 25,000 rpm starting at the 15th minute while thinning of bubble walls (B) was observed at the 30th minute in the foams formed at 25,000 rpm.
increased expected satiety (Arboleya et al., 2014) and resilient foam delayed stomach emptying (Murray et al., 2015).

4. Conclusion

Homogenisation has significantly reduced the particle size of milk fat globules and controlled the growth of the particles up to 2 h. This reduction of particle size was not significant enough to increase the viscosity of the milk tea emulsion, hence external aid such as hydrocolloids could be applied to further improve the stability of the emulsion. In addition, the reduction of particle size was not directly related to the reduction of surface tension in the homogenised samples. We speculated that the reduction of surface tension was due to the release of surface-active components in the milk fat globule membrane, which is broken down during homogenisation. However, it is clear that the foam stability in terms of drainage has significantly improved after homogenisation. Overrun is positively correlated to homogenisation speed, as the energy input was the most important factor in dispersing air bubbles in the foam.

Optimal speed to produce a stable Teh Tarik system is 18,000 rpm, where the particle size was the smallest and could be maintained for at least 2 h. The drainage value was also lowest at 18,000 rpm suggesting that the foam is the most stable at this stage. These findings confirm that high-shear homogenisation could be a one-stop solution to produce a stable milk tea system with stable foam. These physical advantages of a stabilised foamed milk tea could be made use to develop satiety- and satiation-enhancing food.

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Authorship statement

W.D.Y. GOH: Conceptualization, Investigation, Formal analysis, Data curation and Writing- Original draft, L.C. CHONG: Supervision, Conceptualization; Validation, Writing-Review & Editing Project Administration, Y.H. KUAN: Validation, Writing – Review & Editing, M. N. ISMAIL: Funding acquisition.

Implications for gastronomy

The study showed that through high-speed homogenisation, the reduction of particle size of milk fat globules by at least 0.4 μm increases the emulsion stability of milk tea emulsion and at the same time increases the surface tension of the milk tea foam. This is significant because the improved physical stability of emulsion and foam as demonstrated in the milk tea model could be applied to satiation-enhancing products, thus creating a modus operandi to reduce calorie intake among Malaysians. We believe that this manuscript is appropriate for publication by IJGFS because it investigates a complex system of aerated emulsion in Teh Tarik which is lesser studied. On top of that, the scientific validation in this study provided insights on innovative ways to improve the preparation of a traditional beverage and suggested the potential for scale-up manufacturing.

Declaration of competing interest

The authors declare that there is no conflict of interests.

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