Original Article
Food Science and Technology

ISSN 0101-2061 (Print)
ISSN 1678-457X (Online)

DOI: https://doi.org/10.1590/fst.05522

One-step method for improving the stability of coconut milk emulsion and keeping its flavor based on dynamic high-pressure microfluidization

Limei DENG[1,2], Yujia LIU[2], Shuyan ZHANG[2], Lin LI[2], Jie ZHU[2*], Hongpeng YU[1*]

Abstract

Coconut milk is a traditional subtropical food, but its quality and flavor stability are the biggest challenge for promotion and commercialization. In this study, the effect of dynamic high-pressure microfluidization (DHPM) on texture and flavor properties of coconut milk was investigated under different pressures. The mean particle size decreased from 24.04 ± 1.17 μm (blank sample) to 8.21 ± 0.11 μm, reaching the minimum at 18000 psi. Microfluidization technique has positive effect on the taste of coconut milk, reducing the bitterness value from 13.39 ± 0.23 to 11.50 ± 0.20 ($p > 0.05$) using electronic tongue; simultaneously, the other tastes were retained. The flavor of coconut milk is less affected by pressure, and the flavor is essentially not lost in the appropriate pressure range. This work provides a new understanding of quality and flavor changes of coconut milk using DHPM in the future processing process.

Keywords: coconut milk; dynamic high-pressure microfluidization; stability; taste; flavor.

Practical Application: This work will help us using the dynamic high-pressure microfluidization technique to improve the quality and flavor of coconut milk in practical production.

1 Introduction

Coconut (*Cocos nucifera* L.) milk is a kind of milky white protein-stabilized oil-in-water natural emulsion that is extracted from mature coconut endosperm. Coconut milk is rich in protein, fat, minerals, vitamins, etc. The fat content of coconut milk can reach 35-37%, and protein can reach 2-5% (Su'i et al., 2020; Lad & Murthy, 2012). Because it is rich nutrition and it has a unique flavor, it is often used in cooking, especially in Thailand and Southeast Asian cuisine (Schiassi et al., 2020; Tansakul & Chaisawang, 2006). In addition, it is often used in desserts, ice cream, and yoghurt (Góral et al., 2018; Patil & Benjakul, 2018). However, coconut milk is thermodynamically unstable and readily flocculates and separates into layers.

The most commonly used methods to improve the stability of coconut milk are using emulsifying agents and surface-active stabilizers such as protein, sucrose esters, Tween, sodium carboxymethyl cellulose, and sodium dodecyl sulfate (Ariyaprakai et al., 2013; Thanatrungrueang & Harnsilawat, 2019; Tangsuphoom & Coupland, 2008). At present, there are some reports on the use of starch to stabilize coconut milk (Lu et al., 2019b). Additives may improve the stability of coconut milk to some extent. However, most additives are not completely safe and cannot be used at more than a specific value. There are many studies on the use of protein, starch, and other absolutely safe substances to stabilize oil-in-water emulsions, but additives have an effect on the flavor and taste of coconut milk to some extent. The sensory properties of coconut milk largely depend on the relative balance of flavor compounds that are derived from its fats, proteins, and carbohydrates (Wang et al., 2020). Using one method alone does not maintain good stability of coconut milk within its shelf life. Thus, methods that combine chemistry and physics are usually chosen.

The physical methods reported to improve the stability of oil-in-water emulsions are heating, homogenization, ultrasound, etc. (Martins et al., 2020; Chiewchan et al., 2006; Lu et al., 2019a; Tangsuphoom & Coupland, 2009). Homogenization and heating are the most widely reported methods for the processing of coconut milk. However, according to research, coconut milk is also prone to stratification after multiple homogenization and thermal treatment, which increases the degree of flocculation (Tangsuphoom & Coupland, 2005). Microfluidization, also known as dynamic high-pressure microfluidization (DHPM) technology, is a kind of high-pressure homogenization technology that integrates transportation, mixing, ultrafine grinding, expansion, and so forth (Guo et al., 2020). It can create strong shear, high-speed impact, instantaneous pressure drop, high-frequency oscillation, and cavitation of fluid materials (Wei et al., 2009). Microfluidization not only makes food particles reach very small particle size and improves food stability, but it also retains nutrients in food and maintain its good taste and color. According to reports, the total antioxidant activity of peach juice increases up to 16% with DHPM treatment (2900 psi, one pass) since DHPM induces active ingredient release in fruits (Wang et al., 2019). Treatment of strawberry juice under pressure at 14503 psi, significantly increases the antioxidant properties of strawberry juice because of inactivation of polyphenol

Received 01 Jan., 2022
Accepted 30 Jan., 2022
[1] *School of Chemical Engineering and Light Industry, Guangdong University of Technology, Guangzhou, China*
[2] *Key Laboratory of Healthy Food Development and Nutrition Regulation of China National Light Industry, School of Chemical Engineering and Energy Technology, Dongguan University of Technology, Dongguan, China*
*Corresponding author: zhujie@dgut.edu.cn; yuhpeng@163.com

oxidase and peroxides (Karacam et al., 2015). Appropriate treatment pressure is beneficial to the preservation of vitamin C and carotenoids of juice (Abliz et al., 2021; Koley et al., 2020). Therefore, microfluidic technology has a broad prospect for coconut milk. The application of microfluidization technology in coconut milk products has not been reported.

In this study, changes in the particle size, color difference, differential scanning calorimetry (DSC), texture, static and dynamic rheological properties, as well as flavor and taste characteristics of a coconut milk treated with DHPM, were studied. The aims of this study were to improve the stability of coconut milk through DHPM technology and to study the effect of different treatment pressures on the rheological properties, taste, and flavor of coconut milk.

2 Materials and methods

2.1 Materials

Coconut (*Cocos nucifera* L.) was purchased from the local market, and anhydrous ethanol was obtained from Chinese Medicine Group Chemical Reagent Co., Ltd.

2.2 Microfluidization of coconut milk

Coconut milk was obtained by traditional methods: coconut meat was ground using a high-speed mixer (MJ-BL1036A; Midea Co., Ltd, China) and then filtered by 400 mesh sieves. The microfluidization process was as follows. Coconut milk was diluted once with ultrapure water. After dilution, the milk was processed in a DHPM (M-110EH30; Microfluidic Corporation, Newton, MS, USA) at different homogenization pressures (15000, 18000, 21000, 24000, and 27000 psi) for one pass at room temperature. The microfluidizer have two interaction chambers: a Y main interaction chamber (diamond, 75 μm) and a Z auxiliary interaction chamber (pottery and porcelain, 200 μm). Untreated sample was used as a control (0 psi). All samples were stored in refrigerator at 4 °C, and physical and chemical analyses were conducted.

2.3 Color and pH

Color measurements were performed by using a CM-5 spectrophotometer (Konica Minolta, Inc., Japan). White and black calibration was used for the instrument standardization. The samples were placed in glass cells, and the measurement was performed. The $L^*/a^*/b^*$ color space was used for the measurement. Here, the L^* value is a measure of the lightness, the a^* value is the greenness to redness, and the b^* value is the blueness to yellowness of the sample. Unprocessed coconut milk (L^*_0 = 62.24, a^*_0 = 1.65, b^*_0 = 9.43) was used as the reference. The color of the samples was measured in triplicate at ambient temperature. The total color change (ΔE) was calculated using the following Formula 1:

$$\Delta E = \sqrt{\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right)^2 + \left(b^* - b_0^*\right)^2} \quad (1)$$

where the subscript 0 indicates the initial color of the coconut milk without microfluidization.

The pH of the coconut milk was measured by a pH meter (PHS-3C; Shanghai Precision Instrument Co. Ltd., China).

2.4 Stability analysis

Particle size distribution (PSD)

The PSD of the coconut milk was measured using an LS-13-320 Laser Diffraction Particle Size Analyzer (Beckman Coulter Co., Ltd., Miami, USA) at room temperature (Gul et al., 2017). The wavelength was 780 nm, the refractive index of dispersed phase was 1.471, and the dispersant was 1.333. Samples of coconut milk were slowly placed in the test chamber, which was filled with distilled water in order to prevent multiple light-scattering effects, until obscuration was 8%. The PSD results were main expressed as the volume-weighted mean diameter D[4,3] calculated using the following Formula 2:

$$D[4,3] = \frac{\sum_i n_i d_i^4}{\sum_i n_i d_i^3} \quad (2)$$

where n_i is the number of droplets of diameter d_i.

Centrifugal sedimentation rate

The samples of coconut milk were centrifuged (Sigma, Model 3-30KS, Germany) at 2500 × *g* for 5 min at 4 °C. After centrifugation, the upper liquid was sucked by suction tube, the sediment was weighed, and the centrifugal precipitation rate was calculated according to Formula 3. A smaller sedimentation rate means better stability.

$$\text{Centrifugal sedimentation rate (\%)} = \frac{\text{Sediment weight (g)}}{\text{Sample weight (g)}} \times 100\% \quad (3)$$

Thermodynamic property analysis

The thermodynamic stability property of coconut milk was measured using a differential scanning calorimeter (Mettler-Toledo AG, Switzerland). All liquid samples (about 10 mg) were injected into aluminum pans and sealed. An empty pan was used as a reference. The samples were heated from 10 to 100 °C at a heating rate of 5 K/min. The nitrogen flow rate remained at 40 mL/min throughout the DSC analysis.

2.5 Textural properties

The physical textural properties of coconut milk were measured by a texture meter (TA XT Plus; SMS, UK) with F04C03 A/BE back extrusion device. Coconut milk (25.0 mL) was accurately transferred to standard test cup with a diameter of 50 mm, and a disc probe with a diameter of 35 mm was used for back-extrusion experiments. Test conditions were set as follows: 5.0 g trigger force, 10.00 mm target distance, and 2.00 mm/s test speed. All tests were done with three parallel experiments.

2.6 Rheological behaviors

Steady rheological measurements

The rheological properties of the coconut milk were assessed using a rotational rheometer (MCR 702 MultiDrive; Anton Paar, Austria) with parallel plates (40 mm upper diameter, 60 mm bottom diameter, 1 mm gap) at 25 °C. All plates were both pasted with sandpaper (P240, 58 μm roughness) to avoid slipping of the coconut milk. The measurement of shear rate was performed in the range of 1-100 s^{-1}. The experimental data of the flow curve were obtained and fitted using the power law model (Equation 4):

$$\eta = K\gamma'^{(n-1)} \tag{4}$$

where η is the apparent shear viscosity, γ is the shear rate (s^{-1}), K is the consistency coefficient ($Pa{\cdot}s^{N}$), and n is the flow behavior index.

Dynamic rheology measurements

The strain sweep mode was applied to obtain the linear viscoelastic regime (1% strain) followed by the dynamic oscillatory frequency procedure over the frequency range of 0.1-2 Hz to obtain the storage modulus (G') and loss modulus (G'').

2.7 Taste and flavor analysis

Taste analysis

Taste analysis was performed using an SA402B electronic tongue (Insent Company, Japan). It is necessary to activate the sensor and reference sensor 24 h in advance of any determination. Coconut milk was treated by DHPM, and the control sample was diluted with ultrapure water for 2000 times. After dilution, a 15 mL sample was transferred into 50 mL sample cups for detection (Dang et al., 2019). In this experiment, distilled water was used as the cleaning solvent, and comparison with a reference solution was performed (30 mmol/L KCl and 0.3 mmol/L tartaric acid).

Five parallel measurements were run for each sample, and the average value of each sensor with three similar measurements was taken as one sample datum for subsequent data analysis.

Flavor analysis

Flavor analysis was performed by gas chromatography-ion mobility spectrometry (GC-IMS). The instrument consists of a gas chromatograph (Agilent Technologies, Palo Alto, CA, USA) and an ion migration chromatograph (FlavourSpec®; Gesellschaft für Analytische Sensorsysteme mbH, Dortmund, Germany) equipped with a PAL3 automatic sampling unit (CTC Analytics AG, Zwingen, Switzerland) that can be directly sampled from the headspace.

For analysis, 2.0 mL of coconut milk sample (0, 15000, 18000, 21000, 24000, and 27000 psi) was transferred to a 20 mL headspace glass sampling vial. and the bottle mouth was sealed. Subsequently, it was inserted into the sampling tank of the automatic sampler. Samples were incubated at 60 °C for 20 min at incubation speed of 500 revolutions per minute. After incubation, 100 μL of sample headspace was automatically injected by means of an injection needle (85 °C). After injection, nitrogen gas was used as carrier gas, and the sample was loaded into an FS-SE-54-CB-1 capillary column (15 m×0. 53 mm, 1 μm, 60 °C). Nitrogen at a programmed flow was as follows: 2 mL/min for 2 min, 10 mL/min for 8 min, 100 mL/min for 10 min, and 150 mL/min for 5 min. After preliminary separation by gas chromatography, the analytes were driven into the ionization chamber for ionization. Finally, ions reached the drift tube (45 °C) to be separated. The drift gas was N_2.

Experimental results were analyzed using LAV software (Laboratory Analytical Viewer) and three plug-ins (Reporter, Gallery Plot, and Dynamic PCA), as well as NIST2014 and IMS databases.

2.8 Statistical analysis

Except for GC-IMS data, all data were presented as mean ± standard deviation (SD), and statistical analysis of variance was performed using SPSS 23 data analysis software. The means were compared with Duncan's multiple range test ($p < 0.05$). In the tables, different letters in the same column mean significant differences.

3 Results and discussion

3.1 Color and pH

The effects of DHPM treatment on color and pH value of coconut milk are summarized in Table 1. Color is an important parameter of food quality. Because of the bright nature of coconut milk, the L value is the main parameter of color of coconut milk (Wang et al., 2020). Statistical analysis of color parameters showed that there was significant difference in L^* values between the control and homogenized samples ($p < 0.05$), and the lightness decreased with the increase in pressure, which dropped from 62.24 to 49.39. When the pressure exceeded 21000 psi, L^* increased slightly with the increase in pressure, but it was still smaller than the control. Homogenization also had a significant effect on a^* and b^*, but the effect was not as large as that for L^*. The a^* and b^* values of the coconut milk increased for all treatments compared with the control sample, but there was no significant difference in different pressure. The literature reported similar results when treating Ottoman strawberry (*F. Ananassa* Duck) juice with microfluidization at 8702 and 14503 psi; this is mainly attributed to the degradation of anthocyanins and the Maillard reaction (Karacam et al., 2015). For coconut milk, the increase in a^* and b^* may be due to the Maillard reaction, and L^* is due to the change in the particle size. According to a study by McClements, L^* is related to the droplet size; a larger particle size produces greater light scattering and a larger L^* value. In contrast, the smaller particles scatter less light and have lower L^* values (McClements, 2002). The measurement of particle size also showed that the change trend of coconut milk is the same as that for the particle size, and that the color of coconut milk is related to the change in particle size.

As Table 1 shows, the pH of all experimental samples was between 6.57 and 6.65, and the pH significantly decreased after DHPM treatment ($p < 0.05$), but there was no significant difference between different pressures. According to research reports, freshly extracted coconut milk has a pH of 6; at this pH, the stability is high (Raghavendra & Raghavarao, 2010). Hence, to some extent, DHPM treatment improved the stability of coconut milk. Changes in pH after homogenization have been reported in the literature. The pH value of sea buckthorn juice was increased significantly when the pressure exceeded 10877 psi (Abliz et al., 2021) probably because of the decrease in concentration of hydrogen ions caused by the dissolution of cellular materials such as peptide or proteins from DHPM treatment (Chen et al., 2012).

3.2 Stability study

Physical stability

According to the law of Stokes, the particle size of an emulsion may be considered as an important parameter for assessing stability against sedimentation. The mean particle sizes of coconut milk samples at different homogenize pressures are shown in Table 1. The average particle size of coconut milk decreased significantly upon DHPM treatment, and the smallest mean particle size (8.209 ± 0.106 μm) was achieved at pressure of 18000 psi ($p < 0.05$). The droplet morphology changes of the coconut milk sample were more intuitively observed by microscopy; the results are shown in Figure 1. Large droplets

Table 1. Effect of microfluidization on color, pH, and particle size of coconut milk.

Pressure (psi)	L	a*	b*	ΔE	pH	D [4,3] (μm)
0	62.24 ± 0.08[a]	1.65 ± 0.01[c]	9.43 ± 0.06[b]	-	6.65 ± 0.07[a]	24.04 ± 1.17[a]
15000	49.99 ± 0.08[b]	1.85 ± 0.01[b]	10.57 ± 0.01[a]	13.59 ± 0.01[bc]	6.60 ± 0.04[b]	12.50 ± 0.51[b]
18000	49.66 ± 0.05[c]	1.88 ± 0.01[a]	10.66 ± 0.08[a]	14.17 ± 0.35[ab]	6.57 ± 0.01[b]	8.21 ± 0.11[d]
21000	49.39 ± 0.07[d]	1.88 ± 0.01[a]	10.73 ± 0.07[a]	14.60 ± 0.35[a]	6.57 ± 0.01[b]	8.89 ± 0.27[cd]
24000	50.19 ± 0.06[e]	1.90 ± 0.01[a]	10.66 ± 0.05[a]	13.86 ± 0.43[ab]	6.57 ± 0.02[b]	9.23 ± 0.29[cd]
27000	50.80 ± 0.03[f]	1.88 ± 0.01[a]	10.64 ± 0.11[a]	12.98 ± 0.39c	6.57 ± 0.01[b]	9.67 ± 0.29[c]

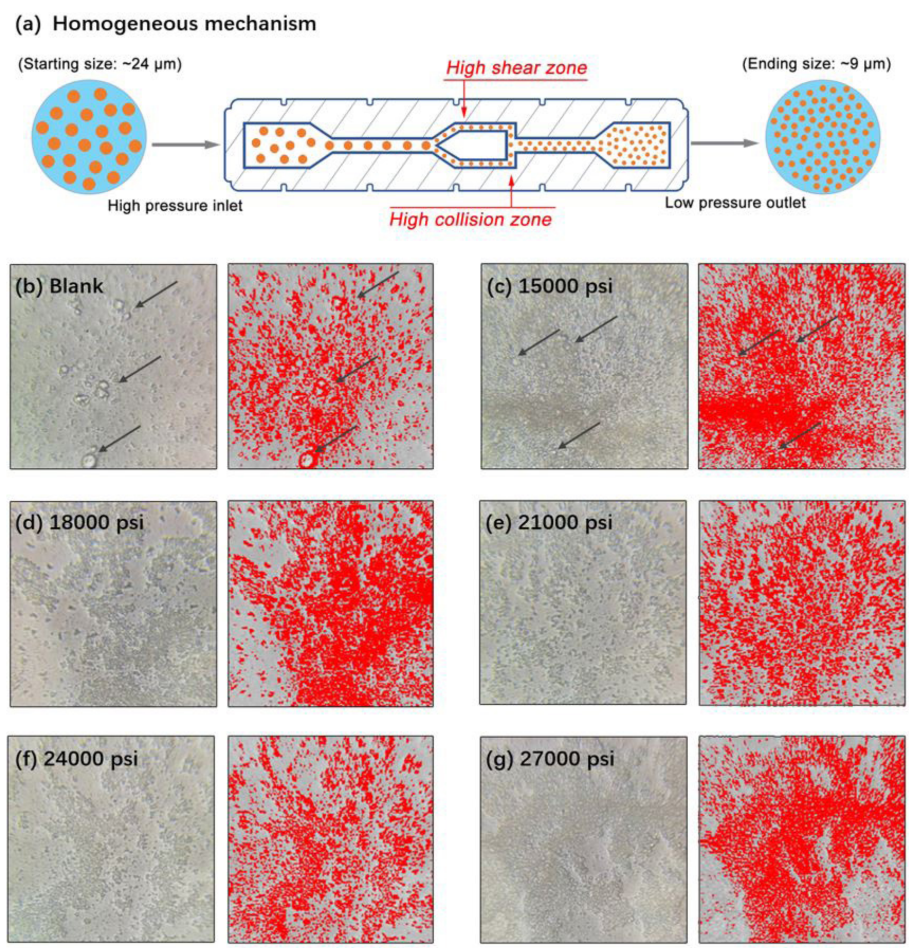

Figure 1. (a) the homogeneous mechanism of DHPM for coconut milk; (b~g) Images from microscopy of the coconut milk (×100 magnification) at different homogeneous pressures.

were observed in the control sample. Individual larger droplets were present in a sample treated at a pressure of 15000 psi, and the particle size of the coconut milk became more uniform when the pressure further increased. When the pressure exceeded 18000 psi, the mean particle size increased with the increase in pressure. Some scholars also reported that when the pressure continuously increases, the particle size increases (Tu et al., 2013).

The particle size distribution curve (Figure S1) further confirms this result. The particle sizes of samples after DHPM-treated were less than 100 μm, and the particle size distribution became obviously narrowed. Samples treated by DHPM at pressures of 15000, 18000, and 21000 psi showed a unimodal distribution, while other samples presented a multimodal distribution. However, it is noteworthy that the peak of particle size distribution curve progressively shifted toward the left when the pressure exceeded 21000 psi. This is because that the particles combined with weaker forces that break at high pressure. After homogenization, coconut milk samples were placed in a glass test tube for 24 h at room temperature, and the stratification condition was investigated. The result can be seen in the photograph in Figure S1a: there was obvious stratification of the untreated coconut milk, and stratification was absent in the homogeneous coconut milk during the observation period.

At the same time, centrifugal sedimentation rate of all samples was measured to evaluate the stability of the long-term storage. Centrifugal sedimentation accelerates the process of storage and statics, which is an intuitive manifestation of the stability of microscopic particle size. In the absence of an expensive laser particle size meter, a centrifuge can effectively predict the stability. The results of centrifugal sedimentation rate (Figure S2) show that the centrifugal sedimentation rate of coconut milk decreased significantly after homogenization. The change is consistent with the particle size; the centrifugal sedimentation rate decreases with the increase in pressure, which is the smallest at 18000 psi. When the pressure continues to increase, the centrifugal precipitation rate begins to increase slightly. According to the above results, we can see that when the treatment pressure was 18000 psi, the stability of coconut milk was the best.

Thermodynamic stability

The thermal property is an important indicator of food processing. In this study, the thermodynamic stability of coconut milk without DHPM treatment as well as treatment by DHPM was investigated by DSC analysis; the results are shown in Figure 2. There were two overlapping endothermic peaks for all samples. Untreated coconut milk exhibited a melting endotherm on heating and a peak at 19.83 °C, ending at 22.83 °C. The position of the melting endotherm peak of coconut milk treated by DHPM not has markedly changed, indicating that crystal did not change. The crystal structure of coconut milk mainly comes from coconut oil. Although homogenization changes the particle size of coconut milk, the amorphous crystal structure of coconut oil does not change. However, the integral area of the DSC curve shows that the enthalpy value decreases with the increase in the treatment pressure, which may be caused by the destruction of the protein structure and the decrease in the fat particle size after homogenization. It is further speculated that microfluidization makes the coconut milk system more uniform.

3.3 Effect on textural and rheological properties of coconut milk

Textural properties of coconut milk

Texture is a very important attribute of food quality; for liquid substrates, it depends mainly on viscosity, but other properties are also important. In this study, we studied the liquidity, firmness, uniformity, cohesiveness, viscosity, and subsidiary of coconut milk by a texture meter; the results are shown in Table S1. The viscosity of coconut milk decreases after microfluidization treatment and reaches minimum viscosity at a pressure of 18000 psi, but there is little difference between different treatment pressures.

For liquidity, the smaller were the values, the better was the fluidity of the sample. The fluidity of DHPM-treated samples is better than that of untreated samples, and the fluidity is the best at a pressure of 18000 psi. The maximum positive peak force on the curve indicates the firmness of the sample. The firmness of the sample became worse after DHPM treatment, there was little change between the different treatment pressures, and the firmness was a minimum at a pressure of 27000 psi. Uniformity represents the smoothness of the sample: the smaller is the value, the better is the internal uniformity of the sample. The change in uniformity is consistent with the change in particle size. The uniformity of the sample increases with pressure and has the best uniformity at 18000 psi. When the pressure exceeds 18000 psi, the uniformity begins to deteriorate with the increase in pressure, but it is better than that at 15000 psi. The cohesiveness reflects the strength of the intermolecular binding of the sample: the greater is the value, the greater is the cohesiveness. The change in cohesion is not as obvious as other properties even though the uniformity of DHPM treated samples is better than that of untreated samples, and the uniformity is the best at a pressure of 18000 psi. Subsidiary indicates the difficulty of dispersing the sample in the mouth. We can be seen that the subsidiary of coconut milk after homogeneous treatment is obviously better than that of the control sample. The texture results show that the coconut milk become silkier after homogenization.

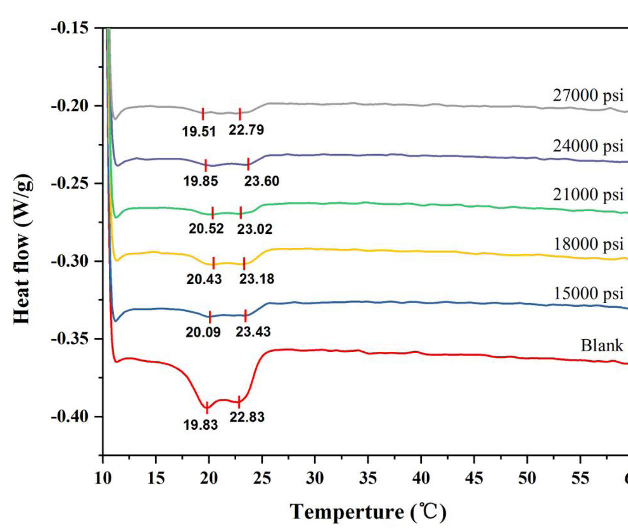

Figure 2. Effect of DHPM pressure on the thermal stability of coconut milk.

Rheological properties

Steady rheological properties of coconut milk

Static rheological properties are typically used to describe and predict the structural changes of foods during processing. The effect of microfluidization on the apparent viscosity of the coconut milk before and after homogenization is shown in Figure 3a. In contrast to texture analysis, rheology technology measures the apparent viscosity of the sample through shear action, which can better reflect the liquid properties. Microfluidization had a significant effect on the viscosity of the coconut milk. The apparent viscosity of all samples decreases with shear rate, indicating that all samples exhibited a shear-thinning behavior. On the early period of measurement, viscosity sharply decreased with shear rate. The viscosity of samples at different homogeneous pressures is quite different except for samples treat at pressures of 15000 and 18000 psi, as well as other pressures. When the shear rate became higher, the apparent viscosity changed slightly and tended to steady, and there was no difference in apparent viscosity of the coconut milk at different homogeneous pressures. The decrease in apparent viscosity with shear rate could be attributed to the deformation and disruption of clusters or aggregates of emulsion droplets and their ordering within the flow field (Walstra, 1999).

As shown in Figure 3b, the shear stress of all samples increased with the shear rate, suggesting that coconut milk is a pseudoplastic fluid. The shear stress in the sample treated by homogenization was obviously smaller than that of the control sample, indicating that the pseudoplasticity of coconut milk was enhanced after homogenization. The parameters of consistency coefficient (*K*) and flow behavior index (*n*) were determined by the power-law model (Table S2). In this study, all flow behavior indices were less than 1.0, further proving that coconut milk was a pseudoplastic fluid. The lower is the *n* value, the stronger is the pseudoplasticity (Zhou et al., 2017). The flow behavior index indicates that the pseudoplasticity of coconut milk increases with pressure at the lower treatment pressure; the pseudoplasticity is the strongest when the pressure at 18000 psi, and when the pressure exceeds 18000 psi, the pseudoplasticity of the sample decreases with pressure. *K* represents the viscosity coefficient, an index of the emulsion viscosity; the higher is the *K* value, the higher is the viscosity. With the exception of a slight increase in *K* at 15000 psi of pressure, *K* decreases with the increase in pressure. This indicates that the viscosity of coconut milk decreases with the increase in pressure.

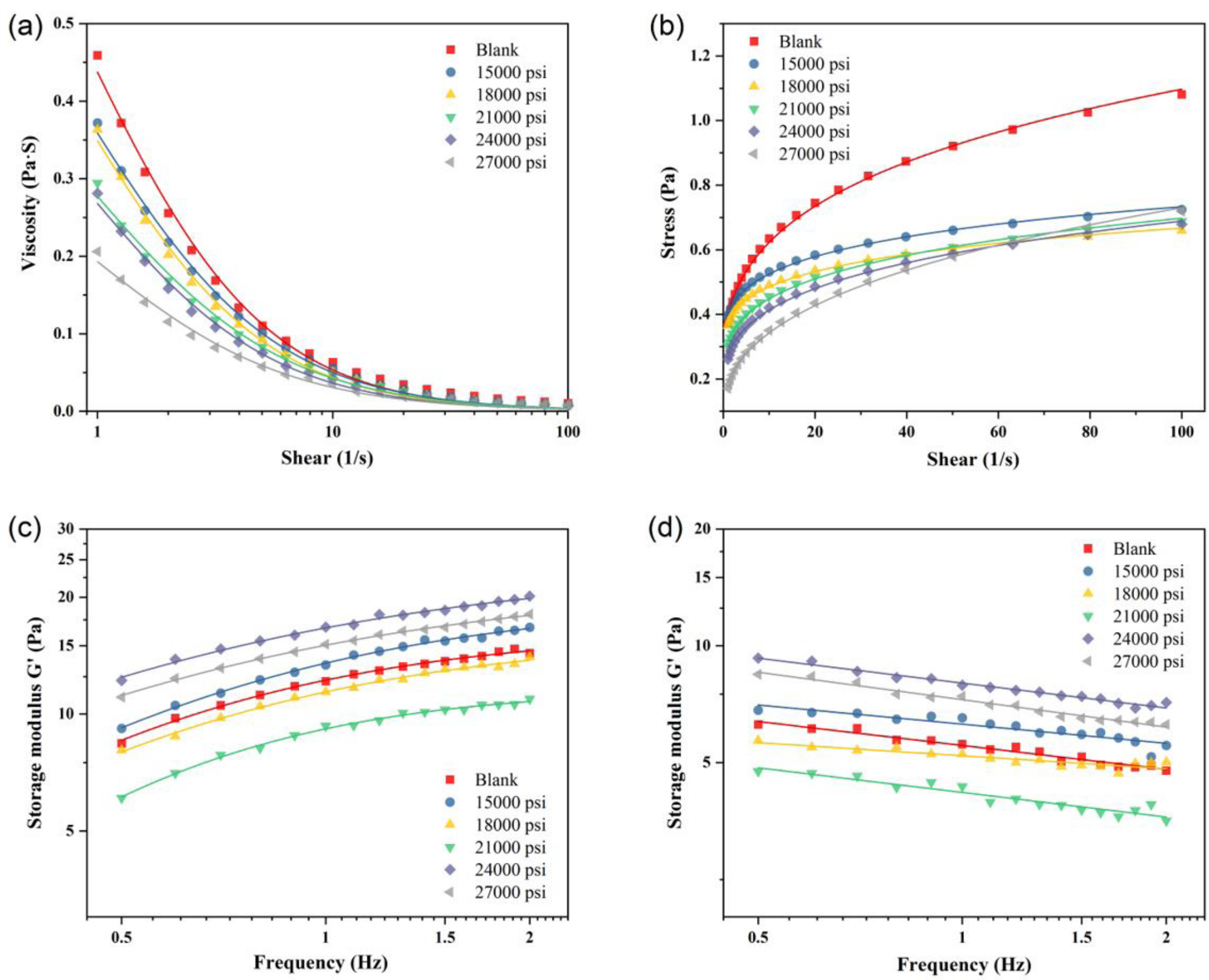

Figure 3. Rheology properties of coconut milk. (a) The apparent viscosity curve and (b) flow curve. (c) *G′* and (d) *G″* as a function of frequency.

Dynamic rheological properties of coconut milk

G′ and *G″* of the coconut milk were dependent on frequency; *G′* increased with an increase in oscillation frequency, whereas *G″* decreased (Figure 3c and d). For all samples of coconut milk, *G′* values were higher than *G″* values in the range of oscillatory frequencies, indicating that coconut milk behaved more like an elastic solid. Overall, the coconut milk showed a weak gel-like behavior. The different DHPM pressure apparently changed *G′* and *G″*. *G′* and *G″* values of all DHPM-treated samples are below the control, suggesting that the gel network structure of the DHPM-treated coconut milk was weaker than that the control sample. After homogenization, *G′* and *G″* are below the control in many emulsions (Gul et al., 2017). The change trends of the *G′* and *G″* with pressure is the same as the particle size, which indicates that the gel network structure of coconut milk can be illustrated by the particle size. When the homogeneous pressure exceeds 18000 psi, *G′* and *G″* values rises with the gel strength possibly because of gel reunion at high pressure.

3.4 Flavor and taste analysis

Electronic tongue

Taste is an important index of food quality. The difference in taste attributes of coconut milk was analyzed using an electronic tongue. The electronic tongue is a kind of detection technology that uses multi-sensor array as the basis to perceive the whole characteristic response signal of the sample. It carries out simulation identification and quantitative qualitative analysis of the sample (Peris & Escuder-Gilabert, 2016). Compared with traditional sensory evaluation, electronic tongue evaluation of samples is more objective and reproducible. Except for bitterness, microfluidization des not have effect on the taste of coconut milk (Table S3). After microfluidization treatment, the bitterness of coconut milk decreased significantly ($p < 0.05$). This suggests that microfluidization has positive effects on the coconut milk taste. The bitterness decrease may be due to partial starch hydrolysis; starch is a food additive in coconut milk.

GC-IMS

After microfluidization treatment, the flavor of coconut milk becomes fresher. Quantitative analysis of flavor substances of coconut milk was done at different homogeneous pressures by using GC-IMS. By comparing the drift time and retention index of the IMS of coconut milk and authentic reference compounds, compounds were characterized. A total of 25 typical target volatile organic compounds were identified using the GC-IMS library: seven aldehydes, seven alcohols, six ketones, two esters, and three alkenes (Table 2). The appreciated visual plots were chosen and listed together by Gallery Plot for intuitive comparison, and the characteristic fingerprints of the different homogeneous pressure were established in Figure 4a. Because

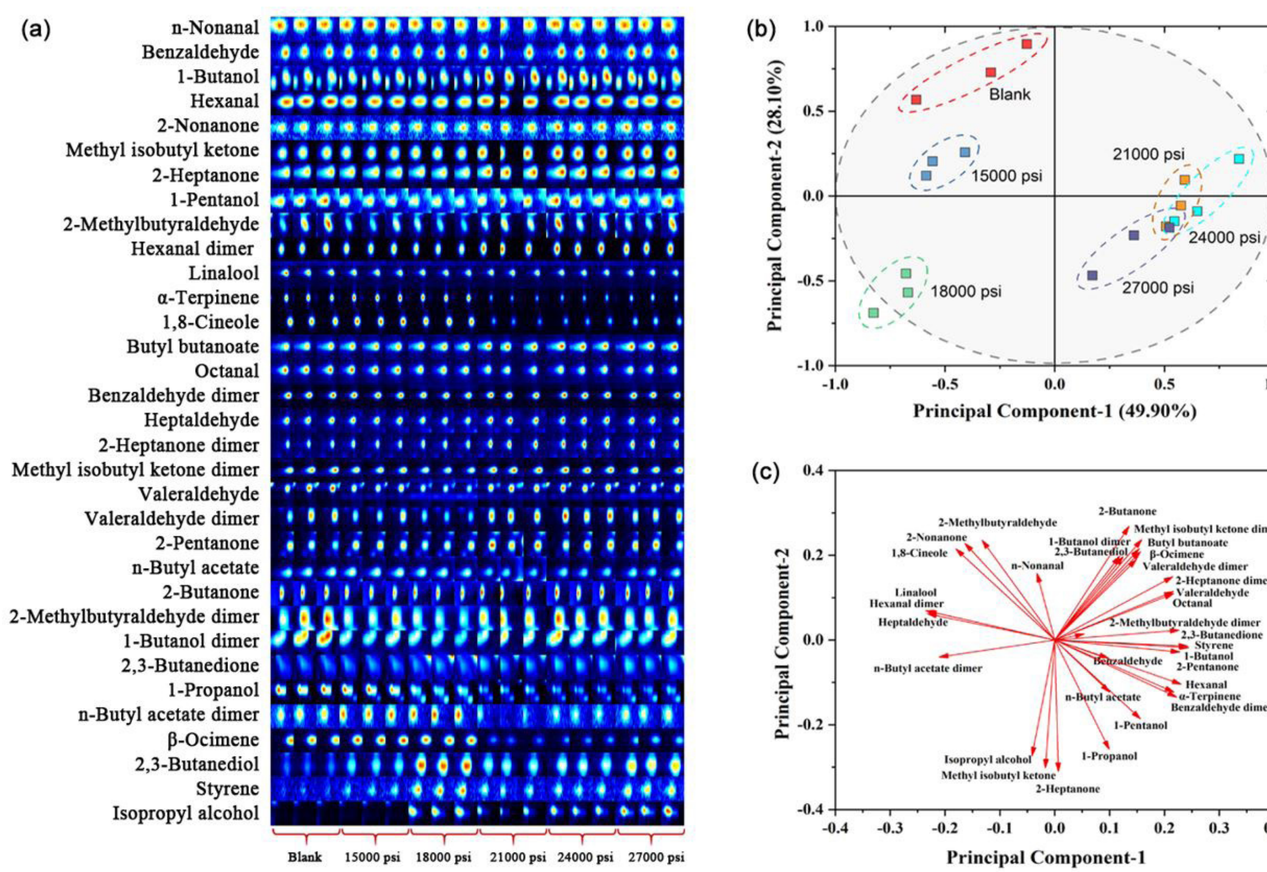

Figure 4. (a) Fingerprints of coconut milk at different homogeneous pressures; (b) Individual-factor PCA (c) and variable-factor PCA.

of the different concentrations, some single compounds may produce multiple signals or spots (dimers or trimers) (Li et al., 2019). Color represented the signal intensity of the substance. White indicated lower intensity and red indicated higher intensity. The darker the color was, the greater was the intensity.

When the pressure exceeds 18000 psi, 1-butanol, 2-heptanone, and methylisobutyl ketone concentrations increase, while α-terpinene, 1,8-cineole, 1-propanol, and β-ocimene concentrations decrease. The concentration of *n*-butyl acetate increases with the pressure, decreases when the pressure exceeds 18000 psi, and is virtually non-existent at 21000 psi. In addition, several new flavor substances were produced after homogenization. All homogeneous samples contain styrene, but untreated samples do not. When the pressure exceeds 15000 psi, two new substances, 2,3-butanediol and isopropyl alcohol, formed. The maximum concentration of 2,3-butanediol was observed at a pressure 18000 psi. The other flavor substances had little change before and after homogenization. Therefore, the proper homogenization pressure can better preserve the flavor of coconut milk.

In order to directly analyze the difference in flavor substances at different homogeneous pressures for the coconut milk samples, the principal component analysis diagram of flavor substances of coconut milk under different homogeneous pressure was established by using the difference in signal intensity of volatile compounds, as shown in Figure 4b and c. It shows a distribution map for the first two major components determined by PCA. It describes the first part PC 49.9%, and the second part PC 28.1% of the accumulative variance contribution rate. Visualization of the data was obtained. The coconut milk samples are distinct in the distribution map, indicating the relationship of flavor compounds under different homogeneous pressure conditions. It is not difficult to see from the diagram that the flavor of coconut pulp under different homogeneous pressures shows a separation trend, which indicates that there are some differences in the composition of flavor. Coconut milk samples at a homogeneous pressure of 18000 psi showed the most significant difference. The samples at a pressure of 15000 psi had flavor similar to those of the control. The samples at pressures of 21000, 24000, and

Table 2. GC-IMS integration parameters of volatile organic compounds of coconut milk.

NO.	Compound	Formula	MW	RI[a]	RT[b]	DT[c]
1	n-Nonanal	$C_9H_{18}O$	142.2	1103.3	825.319	1.4771
2	Octanal	$C_8H_{16}O$	128.2	996.0	646.859	1.2129
3	Heptaldehyde	$C_7H_{14}O$	114.2	890.0	433.664	1.3326
4	2-Methylbutyraldehyde dimer	$C_5H_{10}O$	86.1	653.9	183.733	1.4007
5	2-Methylbutyraldehyde	$C_5H_{10}O$	86.1	655.7	184.728	1.1629
6	Valeraldehyde	$C_5H_{10}O$	86.1	684.7	202.439	1.1871
7	Valeraldehyde dimer	$C_5H_{10}O$	86.1	684.7	202.439	1.4227
8	Benzaldehyde	C_7H_6O	106.1	946.3	543.424	1.149
9	Benzaldehyde dimer	C_7H_6O	106.1	946.4	543.781	1.4692
10	Hexanal	$C_6H_{12}O$	100.2	787.8	298.738	1.2616
11	Hexanal dimer	$C_6H_{12}O$	100.2	786.8	297.654	1.5605
12	1,8-Cineole	$C_{10}H_{18}O$	154.3	1018.3	688.753	1.2964
13	Linalool	$C_{10}H_{18}O$	154.3	1085.8	798.659	1.2129
14	1-Butanol	$C_4H_{10}O$	74.1	649.6	181.412	1.1808
15	1-Butanol dimer	C_4H_10O	74.1	652.1	182.738	1.3758
16	1-Pentanol	$C_5H_{12}O$	88.1	751.5	260.301	1.253
17	1-Propanol	C_3H_8O	60.1	522.2	124.365	1.1149
18	2,3-Butanediol	$C_4H_{10}O_2$	90.1	780.0	290.263	1.3607
19	Isopropyl alcohol	C_3H_8O	60.1	524.7	125.455	1.1775
20	2-Nonanone	$C_9H_{18}O$	142.2	1087.5	801.218	1.4094
21	2-Heptanone dimer	$C_7H_{14}O$	114.2	877.2	412.773	1.6306
22	2-Heptanone	$C_7H_{14}O$	114.2	880.0	417.095	1.2593
23	2,3-Butanedione	$C_4H_6O_2$	86.1	571.4	145.714	1.1712
24	2-Butanone	C_4H_8O	72.1	574.2	146.92	1.2438
25	Methyl isobutyl ketone	$C_6H_{12}O$	100.2	735.6	244.528	1.177
26	Methyl isobutyl ketone dimer	$C_6H_{12}O$	100.2	732.8	241.963	1.4804
27	2-Pentanone	$C_5H_{10}O$	86.1	692.6	208.05	1.3809
28	n-Butyl acetate	$C_6H_{12}O_2$	116.2	797.3	309.088	1.2388
29	n-Butyl acetate dimer	$C_6H_{12}O_2$	116.2	797.3	309.088	1.6216
30	Butyl butanoate	$C_8H_{16}O_2$	144.2	991.4	637.813	1.3404
31	α-Terpinene	$C_{10}H_{16}$	136.2	1018.3	688.753	1.218
32	β-Ocimene	$C_{10}H_{16}$	136.2	1049.6	741.943	1.2181
33	Styrene	C_8H_8	104.2	692.6	208.05	1.3809

[a]Retention index calculated using *n*-ketones. C4-C9 were the external standard for the FS-SE-54-CB-1 column; [b]Retention time in the capillary GC column; [c]The drift time in the drift time.

27000 psi showed significant flavor differences compared with the control, but had similar flavor.

4 Conclusions

This work clearly showed that microfluidization treatment improves the quality of coconut milk. After homogenization, we found no stratification in the observation period; the particle size of coconut milk decreased significantly, and the particle size was the smallest at a pressure of 18000 psi. The results of particle size, pH, and DSC also show that the stability of coconut milk was improved after homogenization. Meanwhile, we found that microfluidization has a positive effect on texture, taste, and flavor of coconut milk. After homogenization, the texture of coconut milk became silkier, the bitter taste decreased, and no effect on the major flavor substances was apparent. This work promotes the development and production of coconut products using DHPM in the future.

Acknowledgments

This work was supported by National Natural Science Foundation of China (No. 31901682), Natural Science Foundation of Guangdong province (No. 2020A1515010833), Foundation for Young Talents in Higher Education of Guangdong, China (No. 2018KQNCX259) and the Special Funds for Research Start-up of DGUT, China (No. GC300501-074). Finally, the authors thanks to Prof. Hang Xiao from University of Massachusetts for his continuous technical advice and beneficial discussions.

References

Abliz, A., Liu, J., Mao, L., Yuan, F., & Gao, Y. (2021). Effect of dynamic high pressure microfluidization treatment on physical stability, microstructure and carotenoids release of sea buckthorn juice. *LWT*, 135, 110277. http://dx.doi.org/10.1016/j.lwt.2020.110277.

Ariyaprakai, S., Limpachoti, T., & Pradipasena, P. (2013). Interfacial and emulsifying properties of sucrose ester in coconut milk emulsions in comparison with Tween. *Food Hydrocolloids*, 30(1), 358-367. http://dx.doi.org/10.1016/j.foodhyd.2012.06.003.

Chen, J., Liang, R.-H., Liu, W., Liu, C.-M., Li, T., Tu, Z.-C., & Wan, J. (2012). Degradation of high-methoxyl pectin by dynamic high pressure microfluidization and its mechanism. *Food Hydrocolloids*, 28(1), 121-129. http://dx.doi.org/10.1016/j.foodhyd.2011.12.018.

Chiewchan, N., Phungamngoen, C., & Siriwattanayothin, S. (2006). Effect of homogenizing pressure and sterilizing condition on quality of canned high fat coconut milk. *Journal of Food Engineering*, 73(1), 38-44. http://dx.doi.org/10.1016/j.jfoodeng.2005.01.003.

Dang, Y., Hao, L., Zhou, T., Cao, J., Sun, Y., & Pan, D. (2019). Establishment of new assessment method for the synergistic effect between umami peptides and monosodium glutamate using electronic tongue. *Food Research International*, 121, 20-27. http://dx.doi.org/10.1016/j.foodres.2019.03.001. PMid:31108741.

Góral, M., Kozłowicz, K., Pankiewicz, U., Góral, D., Kluza, F., & Wójtowicz, A. (2018). Impact of stabilizers on the freezing process, and physicochemical and organoleptic properties of coconut milk-based ice cream. *Lebensmittel-Wissenschaft + Technologie*, 92, 516-522. http://dx.doi.org/10.1016/j.lwt.2018.03.010.

Gul, O., Saricaoglu, F. T., Mortas, M., Atalar, I., & Yazici, F. (2017). Effect of high pressure homogenization (HPH) on microstructure and rheological properties of hazelnut milk. *Innovative Food Science & Emerging Technologies*, 41, 411-420. http://dx.doi.org/10.1016/j.ifset.2017.05.002.

Guo, X., Chen, M., Li, Y., Dai, T., Shuai, X., Chen, J., & Liu, C. (2020). Modification of food macromolecules using dynamic high pressure microfluidization: a review. *Trends in Food Science & Technology*, 100, 223-234. http://dx.doi.org/10.1016/j.tifs.2020.04.004.

Karacam, C. H., Sahin, S., & Oztop, M. H. (2015). Effect of high pressure homogenization (microfluidization) on the quality of Ottoman Strawberry (*F. Ananassa*) juice. *Lebensmittel-Wissenschaft + Technologie*, 64(2), 932-937. http://dx.doi.org/10.1016/j.lwt.2015.06.064.

Koley, T. K., Nishad, J., Kaur, C., Su, Y., Sethi, S., Saha, S., Sen, S., & Bhatt, B. P. (2020). Effect of high-pressure microfluidization on nutritional quality of carrot (*Daucus carota* L.) juice. *Journal of Food Science and Technology*, 57(6), 2159-2168. http://dx.doi.org/10.1007/s13197-020-04251-6. PMid:32431342.

Lad, V. N., & Murthy, Z. V. P. (2012). Enhancing the Stability of Oil-in-Water Emulsions Emulsified by Coconut Milk Protein with the Application of Acoustic Cavitation. *Industrial & Engineering Chemistry Research*, 51(11), 4222-4229. http://dx.doi.org/10.1021/ie202764f.

Li, M., Yang, R., Zhang, H., Wang, S., Chen, D., & Lin, S. (2019). Development of a flavor fingerprint by HS-GC-IMS with PCA for volatile compounds of Tricholoma matsutake Singer. *Food Chemistry*, 290, 32-39. http://dx.doi.org/10.1016/j.foodchem.2019.03.124. PMid:31000053.

Lu, X., Chen, J., Zheng, M., Guo, J., Qi, J., Chen, Y., Miao, S., & Zheng, B. (2019a). Effect of high-intensity ultrasound irradiation on the stability and structural features of coconut-grain milk composite systems utilizing maize kernels and starch with different amylose contents. *Ultrasonics Sonochemistry*, 55, 135-148. http://dx.doi.org/10.1016/j.ultsonch.2019.03.003. PMid:30853534.

Lu, X., Su, H., Guo, J., Tu, J., Lei, Y., Zeng, S., Chen, Y., Miao, S., & Zheng, B. (2019b). Rheological properties and structural features of coconut milk emulsions stabilized with maize kernels and starch. *Food Hydrocolloids*, 96, 385-395. http://dx.doi.org/10.1016/j.foodhyd.2019.05.027.

Martins, M. P., Geremias-Andrade, I. M., Ferreira, L. D. S., Brito-Oliveira, T. C., & Pinho, S. C. D. (2020). Technological and sensory feasibility of enrichment of low-sugar mango jams with curcumin encapsulated in lipid microparticles. *Food Science and Technology*, 41(1-3), 74-81. .

McClements, D. J. (2002). Theoretical prediction of emulsion color. *Advances in Colloid and Interface Science*, 97(1), 63-89. http://dx.doi.org/10.1016/S0001-8686(01)00047-1. PMid:12027025.

Thanatrungrueang, N., & Harnsilawat, T. (2019). Effect of sucrose ester and carboxymethyl cellulose on physical properties of coconut milk. *Journal of Food Science and Technology*, 56(2), 607-613. http://dx.doi.org/10.1007/s13197-018-3515-1. PMid:30906018.

Patil, U., & Benjakul, S. (2018). Coconut milk and coconut oil: their manufacture associated with protein functionality. *Journal of Food Science*, 83(8), 2019-2027. http://dx.doi.org/10.1111/1750-3841.14223. PMid:30004125.

Peris, M., & Escuder-Gilabert, L. (2016). Electronic noses and tongues to assess food authenticity and adulteration. *Trends in Food Science & Technology*, 58, 40-54. http://dx.doi.org/10.1016/j.tifs.2016.10.014.

Raghavendra, S. N., & Raghavarao, K. S. M. S. (2010). Effect of different treatments for the destabilization of coconut milk emulsion. *Journal of Food Engineering*, 97(3), 341-347. http://dx.doi.org/10.1016/j.jfoodeng.2009.10.027.

Schiassi, M. C. E. V., Carvalho, C. D. S., Lago, A. M. T., Curi, P. N., Pio, R., Queiroz, F., Resende, J. V., & Souza, V. R. (2020). Optimization for sensory and nutritional quality of a mixed berry fruit juice elaborated with coconut water. *Food Science and Technology (Campinas)*, 40(4), 985-992. http://dx.doi.org/10.1590/fst.28919.

Su'i, M., Sumaryati, E., Anggraeni, F. D., Utomo, Y., Anggraini, N., & Rofiqoh, N. L. (2020). Monoglyceride biosynthesis from coconut milk with lypase enzyme of sesame seed sprouts as biocatalyst. *Food Science and Technology*, 41, 328-333. http://dx.doi.org/10.1590/fst.08820.

Tangsuphoom, N., & Coupland, J. N. (2005). Effect of heating and homogenization on the stability of coconut milk emulsions. *Journal of Food Science*, 70(8), e466-e470. http://dx.doi.org/10.1111/j.1365-2621.2005.tb11516.x.

Tangsuphoom, N., & Coupland, J. N. (2008). Effect of surface-active stabilizers on the surface properties of coconut milk emulsions. *Food Hydrocolloids*, 23(7), 1801-1809. http://dx.doi.org/10.1016/j.foodhyd.2008.12.002.

Tangsuphoom, N., & Coupland, J. N. (2009). Effect of thermal treatments on the properties of coconut milk emulsions prepared with surface-active stabilizers. *Food Hydrocolloids*, 23(7), 1792-1800. http://dx.doi.org/10.1016/j.foodhyd.2008.12.001.

Tansakul, A., & Chaisawang, P. (2006). Thermophysical properties of coconut milk. *Journal of Food Engineering*, 73(3), 276-280. http://dx.doi.org/10.1016/j.jfoodeng.2005.01.035.

Tu, Z., Yin, Y., Wang, H., Liu, G., Chen, L., Zhang, P., Kou, Y., & Zhang, L. (2013). Effect of dynamic high-pressure microfluidization on the morphology characteristics and physicochemical properties of maize amylose. *Stärke*, 65(5-6), 390-397. http://dx.doi.org/10.1002/star.201200120.

Walstra, P. (1999). Food emulsions: principles, practice, and techniques. *Trends in Food Science & Technology*, 10(6)

Wang, X., Wang, S., Wang, W., Ge, Z., Zhang, L., Li, C., Zhang, B., & Zong, W. (2019). Comparison of the effects of dynamic high-pressure microfluidization and conventional homogenization on the quality of peach juice. *Journal of the Science of Food and Agriculture*, 99(13), 5994-6000. http://dx.doi.org/10.1002/jsfa.9874. PMid:31215047.

Wang, W., Chen, H., Ke, D., Chen, W., Zhong, Q., Chen, W., & Yun, Y.-H. (2020). Effect of sterilization and storage on volatile compounds, sensory properties and physicochemical properties of coconut milk. *Microchemical Journal*, 153, 104532. http://dx.doi.org/10.1016/j.microc.2019.104532.

Wei, S., Li, X., Gruber, M. Y., Li, R., Zhou, R., Zebarjadi, A., & Hannoufa, A. (2009). Characterization and high-pressure microfluidization-induced activation of polyphenoloxidase from Chinese pear (*Pyrus pyrifolia* Nakai). *Journal of Agricultural and Food Chemistry*, 57(12) PMid:19459679.

Zhou, D.-N., Zhang, B., Chen, B., & Chen, H.-Q. (2017). Effects of oligosaccharides on pasting, thermal and rheological properties of sweet potato starch. *Food Chemistry*, 230, 516-523. http://dx.doi.org/10.1016/j.foodchem.2017.03.088. PMid:28407943.

Supplementary Material

Supplementary material accompanies this paper.

Table S1. Effect of DHPM pressure on the texture of coconut milk.

Table S2. Modeling of the flow curve between 1 and 100 s^{-1} of the shear rate of the coconut milk using the power law model.

Table S3. Effect of microfluidization on the taste of coconut milk.

Figure S1. Effect of DHPM pressure on the particle size distribution of coconut milk. To the right of the picture are photographs of the coconut milk after DHPM treatment and static placement for 24 h.

Figure S2. The centrifugal sedimentation rate of the coconut milk at different pressures and its linear relationship with particle size.

This material is available as part of the online article from https://www.scielo.br/j/CTA