Research Article

Fouling Formation and Application of Reduced-Protein Coconut Cream in Ice Cream Production

Avan Maghazechi[1,2*], Shin-Yong Yeoh[1*], Yu-Ying Tan[1], Azhar Mat Easa[1]

[1]Food Technology Division, School of Industrial Technology, Universiti Sains Malaysia, 11800, USM, Penang, Malaysia.
[2]Food Science and Quality Control Department, College of Agricultural Engineering Science, University of Sulaimani, Sulaimani, Iraq

*syyeoh@usm.my, avanfq@gmail.com

ABSTRACT

This study investigated the effects of reduced-protein coconut cream (RPCC) on fouling during heat treatment and its potential application in ice cream production, aiming to address the costly fouling issue. RPCC was produced by removing insoluble proteins from fresh coconut cream (FCC). This study categorised FCC and RPCC foulants (FCC-F and RPCC-F, respectively) based on two heat treatment durations at 72°C: 2 h (FCC-2-F and RPCC-2-F) and 4 h (FCC-4-F and RPCC-4-F). RPCC-F exhibited significantly ($p<0.05$) reduced mass and protein content ($p<0.05$) than F-FCC, making it easier to clean due to its enhanced water solubility. RPCC ice cream demonstrated higher fat content($p<0.05$), greater overrun ($p<0.05$), and a faster melting rate ($p<0.05$). Although its appearance and aroma were comparable to regular ice cream, it received significantly ($p<0.05$) lower scores in texture, flavour, and overall acceptance during sensory evaluation. The study indicates that RPCC, despite its lower sensory acceptability score, can be a viable substitute in ice cream recipes. Nevertheless, RPCC remains considered safe as a dairy substitute in other food items. RPCC could be tested as a dairy-free substitute in products like yoghurt and assessed for its long-term shelf life and stability in frozen and non-frozen applications.

Received: 23 December 2024
Accepted: 26 March 2025
Published: 30 September 2025
DOI: https://10.51200/ijf.v2i2.5824

Keywords: fouling; meltdown; proximate; reduced-protein coconut cream; sensory

1. Introduction

Coconut milk and coconut cream are essential ingredients in many Asian and Pacific dishes. Coconut milk and its cream tend to be used interchangeably in the literature, in the food business, and by consumers (Maghazechi et al., 2021). As per CODEX STAN 240-2003, coconut milk is produced by pressing or squeezing grated mature coconut meat (kernel) with added water, resulting in a diluted emulsion containing no less than 12.7% total solids, 2.7% non-fat solids and 10% fat. In contrast, coconut cream is an undiluted emulsion from the same mature coconut kernel, containing at least 25.4% total solids, 5.4% non-fat solids, and 20% fat.

Heat treatment of milk at 72 °C for 20 min provides short-term storage benefits by eliminating pathogenic microorganisms, degrading enzymes, and ultimately improving the shelf life and quality of the product (Azizi-Lalabadi et al., 2023). They also explained that the accumulation of undesirable deposits on heating surfaces may occur during high-temperature processing of coconut cream, a phenomenon known as fouling, which diminishes heat transfer efficiency. This fouling decreases the thermal efficiency of the heat transfer surface and creates a protective layer that can harbour microorganisms, posing a potential risk to consumers (Awais & Bhuiyan, 2019). The formation of fouling deposits on heat exchanger surfaces remains a significant challenge in the thermal processing of coconut. It was reported that in coconut milk processing, fouling mechanisms initiate with the deposition of denatured proteins and other components from the water phase onto heat transfer surfaces (Saikhwan et al., 2022). This deposition, coupled with protein denaturation, causes instability in the coconut emulsion. Consequently, fat and carbohydrates linked with fat can accumulate within the fouling layers. The formation of coconut cream fouling was primarily attributed to protein denaturation, aggregation, and gelation, with carbohydrates and ash contributing to a lesser extent (Maghazechi et al., 2022).

It was highlighted by Maghazechi et al. (2022) that existing research has predominantly focused on coconut milk, with comparatively less attention on coconut cream. They noted that fouling presents a more significant challenge in coconut cream than coconut milk due to its higher total solid content, reducing heat transfer efficiency. Cleaning equipment fouled by coconut milk deposits typically involves chemical and mechanical techniques. Initially, the deposit is softened by a cleaning solution and removed through mechanical actions such as scouring and pigging (Saikhwan et al., 2015). However, it was pointed out by (Maghazechi et al., 2022) that the use of numerous cleaning chemicals that are not environmentally friendly leads to additional costs for materials and labour. Understanding the composition of fouling deposits on heat surfaces is critical for advancing knowledge related to fouling hypotheses and mechanisms, improving fouling mitigation strategies, and optimizing process design.

This study addresses this gap by investigating the impact of producing RPCC, which involves removing most of the protein from FCC, on fouling development. Additional stabilizers have been incorporated to maintain the stability of coconut milk (Patil & Benjakul, 2018). To improve stability and prolong shelf life, processed coconut milk often contains food additives such as guar gum as a stabilizer and polysorbate 60 (tween 60) as an emulsifier (Promlok et al., 2021). Tween 20 and guar gum were employed in our study.

Consumer ice cream is a highly favoured dessert, with global per capita consumption increasing and total sales anticipated to exceed $75 billion by 2024 (Alves da Paz et al., 2025). Ice cream is primarily made from cow's milk containing various beneficial substances. However, it is not advised for specific consumer groups, such as those with lactose intolerance (Góral et al., 2018). Studies on coconut milk ice cream have been conducted over the years (Beegum et al., 2022) Coconut cream is commonly used to make various food products, including biscuits, desserts, dishes, and ice cream (Devi & Ghatani, 2022). To our knowledge, RPCC has not been used in ice cream. Our study aims to investigate the physicochemical properties of FCC, RPCC, and the fouling substances produced during the heat treatment of both types and to determine customers' acceptance of RPCC in ice cream.

2. Materials and Methods

2.1 Materials

FCC was purchased from a street vendor at Pasar Taman Tun Sardon, Penang, Malaysia. Other ingredients such as dairy milk powder (Fonterra Brands (Malaysia) Sdn Bhd), whipping cream (Arla Food Inc., Denmark), coarse grain sugar (Malayan Sugar Manufacturing Co. Bhd), and corn syrup (Pinnacle Foods Group LLC, USA) were purchased from Tesco Extra Sungai Dua, Penang, Malaysia. Food-grade chemicals, including coconut and vanilla flavouring, Tween 20, glycerol monostearate (GMS), guar gum, and carboxymethylcellulose (CMC), were purchased from Sim Company Sdn Bhd, George Town, Penang, Malaysia.

2.2 Preparation of RPCC

The preparation of RPCC was conducted according to Onsaard et al. (2006) and Maghazechi A. (2023) using freeze-thaw treatment with modifications. The FCC was frozen at -20 °C for at least 12 h before being thawed and heated to 40°C in a water bath (Memmert WNE 14, Germany). Then, the FCC was centrifuged at 5500 g for 30 min at 35 °C using a benchtop refrigerated centrifuge machine (Kubota Model

5500, Japan). This process separated the FCC into three layers: the top layer consisting of melted coconut oil, the middle layer comprising the aqueous component, and the bottom layer containing the undissolved component. The melted coconut oil and aqueous components were collected by using a syringe. After that, Tween 20 (0.1% w/w) and guar gum (0.25% w/w) were added as an emulsifier and stabilizer to these separated phases. The mixture was homogenized at a pressure of 10 MPa using a pressure homogenizer (Armfield Ltd. Model FT9, Ringwood, England). The homogenization was repeated four times.

2.3 Preparation of coconut cream foulants

The heat treatment of FCC and RPCC was conducted using a modified method by Khaldi et al. (2015) and Saikhwan et al. (2016). 1L of each sample was preheated to 60 °C by placing it into two rectangular stainless-steel containers (29 cm × 15 cm × 7 cm) in a water bath (Wisd WiseBath WB-11, Germany). Then, the samples were transferred to a second water bath with a temperature of 90 °C. Two stainless steel plates (12 cm × 6 cm) were positioned at the side of each container. The timer was started once the temperature reached 72 °C. FCC-F and RPCC-F were obtained by removing the first and second stainless steel plates after 2 (FCC-2-F and RPCC-F-2) and 4 h (FCC-4-F and RPCC-F-4) heating, respectively.

2.4 Preparation of ice-cream

The ice cream composition is illustrated in Table 1 and was prepared following a formulation and method adapted from Choo et al. (2010). The ice cream mix was prepared by weighing all the ingredients and thoroughly blending them in 1 kg batches. Subsequently, the mix was heated at 74 °C for 10 min and homogenized at 10 MPa four times using the pressure homogenizer (Armfield Ltd. Model FT9, Ringwood, England). The ice cream mix was cooled to room temperature rapidly and then aged at 4 °C overnight. The flavouring was added to the mix before being frozen in an ice cream maker (Ice Cream Machine Malaysia Model AI 7215, Malaysia) at a constant speed for 30 min. Vanilla flavour was included in both formulations to achieve consistency in flavour and aroma. Finally, the final product was stored at -20 °C.

Table 2. Ice cream formulation

Ingredients (%)	**Composition (%)**	
	Regular ice cream	**RPCC ice cream**
Water	61.3	61.3
Milk fat	12	-
Coconut oil as (RPCC)	-	12
MSNF	11	11
Sugar	10	10
Corn syrup solids	5	5
Coconut flavour	0.4	-
Vanilla flavour	-	0.4
Glycerol monostearate	0.15	0.15
Carboxymethylcellulose	0.15	0.15

"–" denotes the absence of the ingredient in the formulation. RPCC, reduced-protein coconut cream; MSNF, milk solids-not-fat

2.5 Preparation of samples for analysis

Proximate analysis, pH measurement, and temperature profiles were conducted on FCC and RPCC samples.

The study of FCC-F and RPCC-F samples included foulant mass, water solubility, and proximate composition. Regular and RPCC ice cream were evaluated for pH, fat content, and sensory characteristics.

2.6 Proximate analysis

2.6.1 Determination of moisture content

The pre-dried moisture dish with its lid was weighed, and the measurement was recorded (AOAC, 2000). Approximately 3g of the sample was placed in the moisture dish with its lid. The dish containing the sample was dried overnight in a Memmert UM 600 convection oven (Schwabach, Germany) at 105°C. After drying, the dish with the sample was covered with its lid and allowed to cool in a desiccator for 30 min before weighing. The analysis was performed in triplicate, and the moisture content of the sample was calculated using equation 1:

Moisture content (%) $=(a+b-c)/b\times100\%$ ------------------- Eq. (1)

where a is the weight of the moisture dish with lid (g), b is the weight of the sample (g), and c is the weight of the dried sample with the moisture dish and lid (g).

2.6.2 Determination of protein content

The protein content was determined using the Kjeldahl method with modification (AOAC, 2000). During the digestion step, approximately 0.3g of the sample (d) was placed into a micro-Kjeldahl digestion flask. Two Kjeldahl tablets and 10 mL of H_2SO_4 were added to the flask and then positioned on a VELP Scientifica Model DK 42/26 digestion block (Milan, Italy). The sample was digested at 350°C for 4 h or until the solution became clear, light blue-green. After cooling, 10 mL of distilled water was added to the flask. The protein content was calculated using equation 2:

Total nitrogen (%) $= (1.4007\times (V_s - V_b) \times M)/W$ ------------------Eq. (2)

where Vs represents the volume of HCl used for the sample (mL), Vb is the volume of HCl used for the blank, M denotes the molarity of the HCl solution, and W indicates the weight of the sample (g).

Protein content (%) =% Nitrogen ×6.25

2.6.3 Determination of fat content

The fat content was analyzed using the Mojonnier ether extraction method with slight modifications (AOAC, 2000). Approximately 2g of the coconut cream or foulant sample was weighed into a Mojonnier flask. A clean, pre-dried weighing dish was weighed, and the weight was recorded. 1.5 mL of NH_4OH was added and mixed thoroughly to the flask, followed by 3 drops of phenolphthalein indicator. For the first extraction, 10 mL of 95% ethanol was added to the flask, which was then stopped and shaken vigorously for 15 s. Next, 25 mL of ethyl ether and 25 mL of petroleum ether were added, with each solvent followed by vigorous shaking for 1 min. The flask was then allowed to stand until the aqueous phase separated from the ether phase. The ether solution was decanted into the weighing dish, avoiding suspended solids or aqueous phases. This extraction process was repeated two more times: for the second extraction, 5 mL of 95% ethanol, 15 mL of ethyl ether, and 15 mL of petroleum ether were used; for the third, only 15 mL of ethyl ether and 15 mL of petroleum ether were used. After all the ether evaporated in a fume hood, the dish was dried in a Memmert UM 600 convection oven (Schwabach, Germany) at 100°C for 30 min. Once cooled to room temperature in a desiccator, the weight of the weighing dish with the extracted fat was measured and recorded. A blank test was also performed using 10 mL of water instead of cream. The fat content was calculated using equation 3:

Fat content (%) $=((d-e)-f)/g\times100\%$ -----------------Eq. (3)

where d represents the weight of the weighing dish containing the extracted fat (g), e is the initial weight of the weighing dish (g), f is the weight of the residue from the blank (g), and g is the weight of the sample (g).

2.6.4 Determination of ash content

The ash content was measured using the gravimetric method (AOAC, 2000). Approximately 5g of the sample was placed into a pre-weighed, dried crucible. The sample was ignited in a muffle furnace

(Thermolyne Type 6000 Furnace, USA) at 550°C until all the carbon was burned off, leaving only the ash. Next, the crucible was allowed to cool in a desiccator before being weighed. The ash content was then calculated as equation 4:

Ash content (%) =(h-i)/j×100% -------------------Eq. (4)

where h represents the weight of the crucible with the ash (g), i is the weight of the empty crucible (g), and j is the weight of the sample (g).

2.7 Determination of pH

The pH of FCC and RPCC were determined according to (Thirukumaran et al., 2023). All analyses were repeated three times.

2.8 Temperature profile

The temperature of the FCC and RPCC during heating treatment was recorded according to the modifications of the methods by Saikhwan et al. (2022). The cream temperature was measured using a Hanna Model HI 935007 thermocouple thermometer (Woonsocket, USA), recorded every minute for 4 h, and plotted on a graph, with analysis repeated three times.

2.9 Measurement of foulant mass

The mass of the foulant was determined using the method described by Felfoul et al. (2015). The masses of cleaned and dried stainless-steel plates were measured both before and after each run using a precision weighing balance. All analyses were repeated three times. The total mass of the foulant was obtained according to the equation 5:

Weight of foulants = weight of plate with foulants — Weight of plate ------------Eq. (5)

2.10 Measurement of foulant water solubility

The water solubility of the foulant was determined using the method modified by Kusumayanti et al. (2015). All analyses were repeated three times. Approximately 0.5 g sample was weighed and added into a centrifuge tube with 10 mL of distilled water. The sample was heated in a water bath at 60°C for 30 min without stirring. Then, it was centrifuged at 1600 rpm for 10 min using a centrifuge machine (Kubota Model 4000, Japan). Approximately 5 mL of the supernatant was transferred to a pre-dried moisture dish and dried in a convection oven (Memmert UM 600, Germany) at 105°C overnight. After cooling in a desiccator, the dish was weighed. The water solubility was calculated using equation 6:

Water solubility (%) = (Weight of soluble substance (g))/ (Weight of sample in dry basic(g)) ×100% -------- Eq. (6)

2.11 Measurement of ice cream overrun

The overrun was calculated by comparing the weights of a fixed volume of ice cream mix and the resulting ice cream (Wu et al., 2019).

2.12 Ice cream meltdown profile

The meltdown of ice cream samples was evaluated at 25 ± 2 °C using a 50 g ice cream sample block (height 1.5 cm, diameter: 6.5 cm). The sample block was placed on a sieve with 2 mm openings that were positioned above a pre-weighed beaker. The mass of the melted ice cream collected in the beaker was recorded at 5 min intervals for 60 min duration. The mass of melted ice cream (g) was plotted against the time (min) (Choo et al., 2010; Santana et al., 2011). All analyses were repeated three times.

2.13 Sensory evaluation

The sensory evaluation was approved by the University human ethics committee (code number: USM/JEPeM/17110608, Jawatankuasa Penyelidikan Manusia USM (JEPeM)). All participants were provided written informed consent.

The sensory evaluation was conducted in the sensory lab of the School of Industrial Technology, Univerisiti Sains Malaysia, which features a preparation area. 50 panellists, comprising students from the university, participated in the evaluation. Before the sensory evaluation, each panellist was required to read an information sheet and sign a consent form to participate. The evaluation aimed to determine the panellist's acceptability of RPCC ice cream compared to regular ice cream. Ice cream was kept in the freezer for -20 °C before serving in cups. Panellists evaluated the samples using a 7-point hedonic scale to rate five attributes: appearance, aroma, texture, flavour, and overall acceptability (Granato et al., 2012).

2.14 Statistical analysis

All analyses were repeated three times in this study. Results were reported as mean ± standard deviation. A dependent t-test was used to analyze and compare the results between FCC and RPCC, as well as the foulant formed from FCC and RPCC. An independent t-test was used to analyze and compare the results between regular ice cream and RPCC ice cream. All analyses were conducted at a 95% confidence level ($P < 0.05$). IBM SPSS Statistics version 22 (IBM Corporation, New York, USA) was used to perform the statistical analysis.

3. Results and Discussion

3.1 Composition and temperature profile of FCC and RPCC

According to Malaysia Food Regulations 1985, Regulation 254, and Codex standards, the pH of coconut cream should not be less than 5.9 (Codex Alimentarius, 2022). The pH value of RPCC was 5.92 ± 0.03, which was significantly ($P<0.05$) lower than that of FCC, which was measured at 5.97 ± 0.05. Both samples met the regulatory standards. The pH range of coconut cream was reported by Thirukumaran et al. (2023), who also emphasized the importance of pH as a microbiological deterioration diagnostic. The reduction in pH may be attributed to the increase in free fatty acids resulting from the hydrolysis of triglycerides into glycerol and free fatty acids by microbial lipase. The thawing process during RPCC preparation brought the coconut cream to room temperature or higher, promoting lipase activities. Storage of the extracted coconut oil at room temperature increased the lipase activities (Waisundara et al., 2007). Furthermore, the free fatty acid content may rise during storage due to the reaction between the oil and any residual water (Patil & Benjakul, 2017).

The results in Table 2 indicate a significant decrease in the protein content from 3.08% in FCC to 0.86% in RPCC, indicating the successful removal of most proteins. The freeze-thaw treatment destabilized the oil-in-water emulsion of coconut cream. Freezing at -20°C could cause fat droplets to partially coalesce and crystallize, leading to severe destabilization when the oil and water phases in the emulsion crystallize. Upon thawing, the oil and water separated (Patil & Benjakul, 2018). The undissolved protein, serving as the natural emulsifier, coagulated and lost its emulsifying property, so it was removed after centrifugation. The protein content in the RPCC may be attributed to the soluble protein in the water phase. The protein content was reported by Saikhwan et al. (2022) as 2.63 ± 0.04 g per 100 mL of coconut milk, similar to the protein content in FCC (3.08%).

Table 2. Composition (wet basis) of FCC and RPCC.

Composition (%)	Samples	
	FCC	RPCC
Moisture	63.65 ± 0.90*	63.81 ± 0.26*
Protein	3.08 ± 0.15^{a}	0.86 ± 0.14^{b}
Fat	28.50 ± 0.96*	27.14 ± 0.81*
Ash	0.95 ± 0.04*	1.05 ± 0.09*
Carbohydrate	3.82 ± 1.33^{b}	7.14 ± 0.87^{a}

Results display mean ± standard deviation (n = 3) values. Letters $^{a-b}$ indicate significant difference (P < 0.05) between values within a particular column. *No significant difference was observed in the moisture, fat, and ash content among the samples. FCC, fresh coconut cream; RPCC, reduced-protein coconut cream.

There were no significant (P<0.05) differences in the moisture, fat, and ash contents between FCC and RPCC. According to Saikhwan et al. (2022), coconut milk's fat level is normally modified to satisfy regional standards, ranging from 15 to 40%, which is comparable to the fat contents of FCC (28.5%) and RPCC (27.14%). Their coconut milk extract contained approximately 31.6 ± 1.3 g of fat per 100 ml. The carbohydrate content in RPCC was double that of FCC, with 7.14% in the former and 3.82 % in the latter. This difference may be attributed to removing coconut protein, contributing to the overall carbohydrate content. Coconut milk typically contains approximately 2–5% carbohydrates, primarily soluble galactomannan and mannan. These components have not been found to increase fouling rates or alter fouling characteristics (Saikhwan et al., 2022).

Pasteurization is a mild heat treatment that preserves coconut cream (Maghazechi et al., 2022). Both FCC and RPCC initially experienced a rapid temperature increase (Figure 1). However, the temperature of FCC began to drop after approximately 50 min of heat treatment. This suggests a decline in heat transfer efficiency, which is likely due to the formation of foulant. The deposition of fouling on a heat transfer surface acts as an insulating barrier, hindering heat transfer from the liquid to the solid surface (Awais & Bhuiyan, 2019). The temperature decreased further below the desired temperature (72°C) after 110 min, implying that the heat treatment after this point may have been insufficient to kill the bacteria in the coconut cream. The continuous temperature decline may be attributed to the increased foulant formation on the heat transfer surface. On the other hand, RPCC maintained a relatively constant temperature with a slight increase after 40 min of heat treatment. The temperature started to decline only after 140 min of heat treatment and did not drop below 72°C within 4 h of heat treatment. This result suggests that the heat transfer efficiency was enhanced after removing most of the protein from the coconut cream.

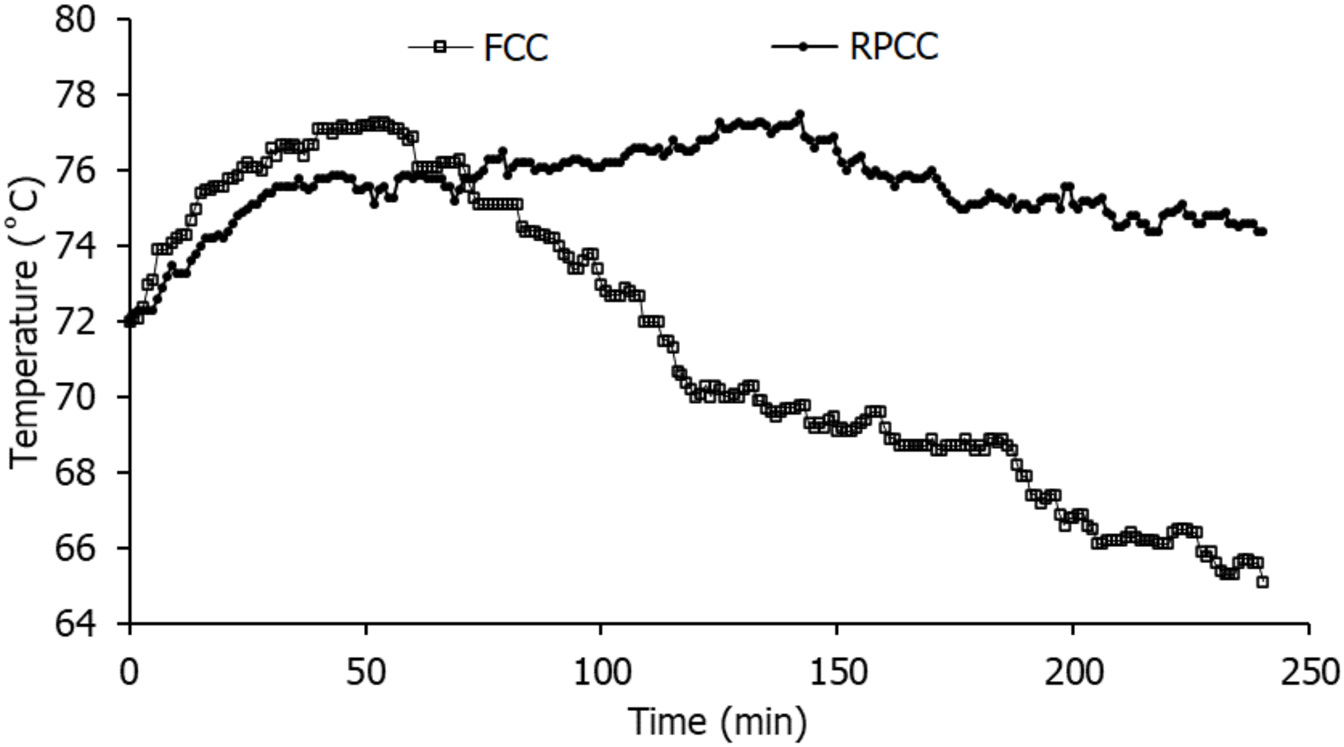
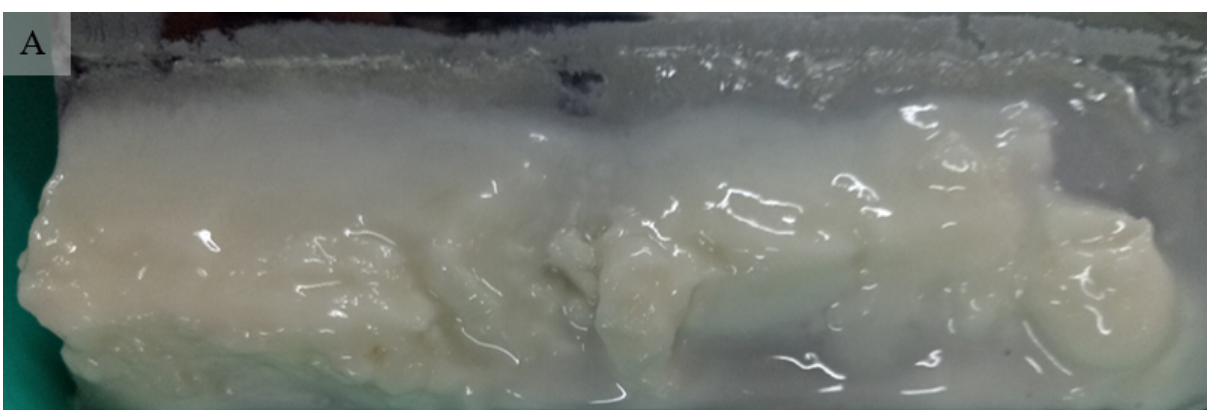


Figure 1. Temperature profiles of the FCC and RPCC during pasteurization for 4 h. FCC, fresh coconut cream; RPCC, reduced-protein coconut cream.

3.2 Mass and water solubility of coconut cream foulants

Images of foulants obtained from FCC-F and RPCC-F at 2 and 4 h of heating are illustrated in Figure 2. FCC-F and RPCC-F displayed similar colors to coconut milk. FCC-F deposition was centralized in Figures 2a and c, whereas RPCC-F was distributed around the center (Figures 2b and d). FCC-F produced thicker and more significant amounts of foulants than RPCC-F when heated for the same duration at 2 and 4 h of heating.



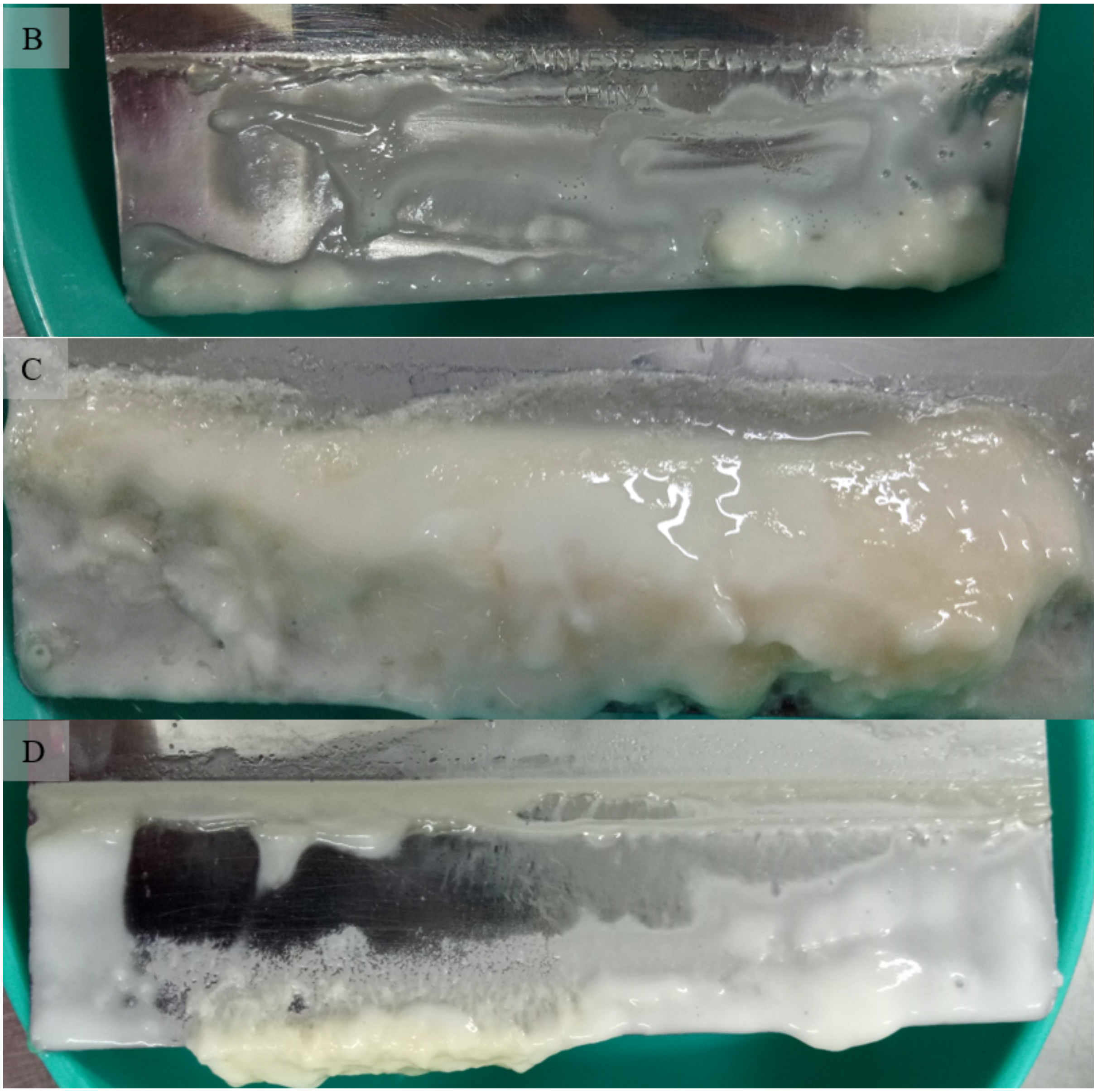


Figure 2. Coconut cream foulants obtained after 2 and 4 h of heating. (a) FCC-2-F, (b) RPCC-2-F, (c) FCC-4-F, and (d) RPCC-4-F. FCC-2-F, fresh coconut cream foulant after 2 h heating; RPCC-2-F, reduced-protein coconut cream foulant after 2 h heating; FCC-4-F, fresh coconut cream foulant after 4 h heating; RPCC-4-F, reduced-protein coconut cream foulant after 4 h heating.

Table 3 illustrates that RPCC-2-F exhibited a significantly lower foulant mass ($P<0.05$) than FCC-2-F. As shown in Table 2, RPCC had a markedly lower protein content, suggesting that removing most proteins from coconut cream significantly reduced the foulant mass formed after 2 h of heating. This finding aligns well with the study conducted by Saikhwan et al. (2022), which reported that changes in protein mass had a more substantial impact on foulant mass than changes in fat mass. Due to the higher mass of the foulant formed on the heat transfer surface, the temperature of the FCC dropped drastically during heat treatment (Figure 1). On the other hand, the temperature of RPCC remained relatively constant and did not decrease for the first 2 h of heat treatment, as the amount of foulant was minimal.

There was a significant ($P<0.05$) mass difference between FCC-4-F and RPCC-4-F (Table 3). Removing the insoluble protein from FCC reduced the foulant formation on the stainless-steel plate after 4 h of heat treatment (Figure 2d). There was an apparent increase in the mass of the foulants from 2 to 4 h of heating. It was reported by Saikhwan et al. (2022) that the mass of fouling increased over time when the pasteurization progressed. They also observed an increased mass of proteins and fats in the foulants. The significant buildup of foulant in FCC-4-F and RPCC-4-F might cause a drop in the temperature experienced by these samples. The temperature in FCC decreased to about 65 °C due to the thicker fouling layer.

RPCC-2-F had significantly higher water solubility than FCC-2-F (Table 3), suggesting that RPCC-2-F is more easily removed, and its high solubility may facilitate the cleaning of the foulant from the heat transfer surface. Similarly, RPCC-4-F demonstrated significantly higher water solubility than FCC-4-F (Table 3). The higher water solubility of foulants could strengthen interactions with water molecules, allowing them to dissolve more readily and enhancing cleaning efficiency by reducing adhesion to surfaces. Studies have shown that increased water solubility could weaken fouling gel adhesion, reducing its weight and strength (Wang et al., 2022). This loss of structural integrity suggests that highly soluble foulants could be easier to remove, requiring less mechanical or chemical intervention during cleaning.

Table 3. Mass and water solubility of FCC-2-F, RPCC-2-F, FCC-4-F, and RPCC-4-F.

Sample	Mass (g)	Water solubility (%)
FCC-2-F	13.69 ± 0.01[a]	2.67 ± 0.44[a]
RPCC-2-F	2.59 ± 0.01[b]	12.67 ± 0.51[b]
FCC-4-F	17.12 ± 0.02[a]	4.76 ± 0.47[a]
RPCC-4-F	3.74 ± 0.01[b]	16.70 ± 0.41[b]

3.3 Composition of coconut cream foulants

The FCC-2-F protein and fat composition was measured at approximately (5.64%) and (85.5%), respectively, whereas the RPCC-2-F showed scores of approximately (3.3%) for protein and (69.54%) for fat. This indicates that the contents of RPCC-2-F have been significantly reduced. It was elucidated by Saikhwan et al. (2022) that the fouling mechanisms of coconut milk started with protein denaturation, followed by fat deposition during pasteurization. Fat was initially absorbed evenly into the fouling layers. Subsequently, fat droplets led to further deposition on top of the initial fouling layers because of the emulsion instability induced by the protein denaturation. Moreover, they also observed that mineral depositions also occurred due to reduced solubility near a heated surface. The denaturation and coagulation of coconut proteins have been reported to occur at temperatures above 80 °C ((Patil & Benjakul, 2018). While it was concluded by Konkamdee & & Saikhwan (2015), that protein denaturation also resulted in the agglomeration of fat globules. In RPCC, the fat globules were stabilized by a non-protein emulsifier, Tween 20, which likely prevented the emulsion from being disrupted in the original coconut cream. The coconut milk emulsified with Tween 20 was stable regarding droplet size and phase separation when heated at 70°C (Thirukumaran et al. (2023). The fat content of coconut cream fouling was 85.57%, as reported by Maghazechi et al. (2022), which was similar to the fat content of FCC-2-F (85.5%).

The ash content of FCC-2-F was lower ($P < 0.05$) than that of RPCC-2-F. Additionally, PRCC-2-F had a higher carbohydrate content than FCC-2-F, consistent with the significantly higher carbohydrate content in RPCC compared to FCC (Table 2). This finding is supported by a study by Chutrakul et al. (2019), which highlighted the substantial presence of carbohydrates in coconut milk foulants. The coconut cream fouling at 70°C contained a minimum of 3.10% carbohydrates and 1.90% ash (Maghazechi et al., 2022), aligning closely with the carbohydrate content of FCC (7.43%) and its ash content (1.43%).

Additionally, more protein and fat were deposited as the heat treatment holding time increased, indicating that the protein and fat content of FCC-4-F was considerably ($P<0.05$) higher than that of RPCC-4-F. The reduction in protein and fat content in RPCC-4-F compared to FCC-4-F may be due to changes in heat transfer dynamics caused by the removal of stainless steel plates. Since protein denaturation is crucial for fouling formation, a lower protein concentration in RPCC-4-F likely resulted in less fat entrapment.

Maghazechi et al. (2022) highlighted that prolonged heat treatment increases protein aggregation, promoting fat binding. Additionally, FCC-4-F had significantly ($P < 0.05$) higher protein and fat content than RPCC-4-F, indicating that extended heating led to greater deposition. Conversely, the RPCC-4-F maintained a significantly ($P<0.05$) higher ash and carbohydrate content than the FCC-4-F, where the latter has 16.63% carbohydrate and 2.64% ash, whereas the former has 1.41% ash and 4.41% carbohydrate. According to Maghazechi et al. (2022), more protein begins to denaturant, agglomerate, and deposit when the heat treatment temperature or holding time is increased. This is followed by fat binding in the protein matrix.

It was discovered by Saikhwan et al. (2022) that the different layers of fouling deposits may contain varying proportions of proteins, fats, carbohydrates, and minerals. They concluded that this information is crucial for selecting the appropriate cleaning agent and optimizing the cleaning procedure for coconut milk foulants. Additional details regarding the proximate analysis of foulants are included in the electronic supplementary figures (Fig. S1 and S2).

Overall, it can be concluded that proteins play a major role in coconut cream fouling formation. With a reduction in the protein concentration in coconut cream, there is no more protein to denaturize and deposit, and consequently, fat binding is no longer possible.

3.4 pH, fat content, overrun, and meltdown profile of regular and RPCC ice cream

An increase in the amount of MSNF (milk solids non-fat) leads to higher acidity and a corresponding decrease in the pH of the ice cream mix, which typically ranges between 6.3 and 6.5 (Mostafavi et al., 2017). Table 3 reveals that the regular and RPCC ice cream had a slightly higher pH than this normal range. This deviation might be attributed to the reduced levels of MSNF, particularly the milk proteins, minerals, and dissolved gases (Lima et al., 2016). Furthermore, the pH of the regular and RPCC ice cream did not show a significant difference ($p<0.05$). The fat contents of the regular and RPCC ice cream fulfilled the requirement of a minimum of 10% fat as stated in Malaysia Food Regulations 1985, Regulation 116. Ice cream usually has a fat content ranging from 10-16%, derived from dairy or non-dairy sources. The fat content in ice cream affects its melting resistance, shape retention after freezing, dryness, and hardening (Akbari et al., 2019). The RPCC ice cream exhibited a significantly higher fat content than the regular ice cream, likely due to a higher fat content in RPCC compared to dairy cream. In the study conducted by Perera & Perera (2021), the fat percentage of coconut milk ice cream varied between 11.06 and 11.66%. In the preliminary studies, the overrun of regular ice cream was 10.5%, while it was 13.36% for RPCC ice cream. Air incorporation in ice cream should be between 10 and 50% (Beegum et al., 2022). Therefore, the overrun values obtained in the ice cream formulations are consistent with the previous study. Overrun is related to the amount of air incorporated into the ice cream during production, which influences its texture and physical properties. Several factors, including proteins, fats, emulsifiers, and stabilizers, play crucial roles in ice cream incorporating air and stabilizing air cells(Beegum et al., 2022). The overrun of the coconut milk ice cream ranged from 8.76 to 15.31%, as reported by Góral et al. (2018), which closely aligns with our result. They also explained that the protein content primarily influenced ice cream overrun in the mixture. Therefore, the low aeration observed in their study was likely due to the absence of animal protein and the low protein content in coconut milk. Furthermore, the overrun of ice cream is influenced by both the source and content of fat (Perera & Perera, 2021). The RPCC ice cream had a higher overrun than the regular ice cream, possibly due to the different fat sources used, with RPCC and dairy cream contributing differently to the volumes of ice cream produced (Choo et al., 2010).

The melting rate of regular and RPCC ice cream over 60-min intervals was achieved by using a meltdown profile. Meltdown serves as a research tool to study and forecast certain physical properties, such as the melting rate and shape retention (Wu et al., 2019). The RPCC ice cream had a higher melting rate (0.67 g/min) than the regular ice cream (0.61 g/min). At the end of the observation period, the RPCC ice cream had a higher mass of melted ice cream. The increasing melting rate can be attributed to the lower melting resistance of coconut oil, a vegetable fat (Mahisanunt et al., 2019). The electronic supplementary figure (Figure S3) contains the meltdown profile result.

3.5 Sensory evaluation of ice cream

In the acceptability test, a regular ice cream with the same fat content and coconut flavor as the RPCC ice cream was prepared for comparison. There was no significant difference in the appearance and aroma attributes between the regular and RPCC ice cream (Table 4), indicating that RPCC ice cream had a similar appearance and aroma to regular ice cream. However, the texture, flavor, and overall acceptability of the regular ice cream were significantly higher than those of the RPCC ice cream. Panelists detected a significant difference in the texture and flavor of RPCC ice cream. The lower sensory scores for texture and flavor in RPCC ice cream can be attributed to its compositional differences from regular ice cream, particularly the significant reduction in protein content. As shown in Table 2, the protein content in RPCC is considerably lower than in FCC. Additionally, the fat content in RPCC ice cream comes from coconut oil instead of milk fat. Milk fat contains a complex mix of fatty acids contributing to a rich mouthfeel, whereas coconut oil primarily consists of medium-chain triglycerides. This change in fat composition, combined with the lower protein content, likely contributed to the altered texture perception. The RPCC ice cream contains natural coconut oil, which has a distinct taste that differs from the balanced dairy fat and coconut flavor combination in regular ice cream. The panelists may have found this difference less familiar or appealing, leading to lower scores for flavor. Despite these differences, all the ice creams received sensory scores of more than 4.5, suggesting a generally neutral to slightly positive rating from the panelists. However, further formulation adjustments may be necessary to improve the texture and flavor acceptability of RPCC ice cream.

Table 4. pH, fat content (%), and sensory attributes of regular and RPCC ice cream.

Parameters	Regular ice cream	RPCC ice cream
pH	6.67 ± 0.02*	6.65 ± 0.01*
Fat content (%)	12.23 ± 0.57^{b}	14.84 ± 0.51^{a}
<u>Sensory attributes</u>		
Appearance	5.40 ± 1.11*	5.12 ± 1.41*
Texture	5.26 ± 1.43^{a}	4.50 ± 1.37^{b}
Flavour	5.50 ± 1.43^{a}	4.82 ± 1.59^{b}
Aroma	5.18 ± 1.06*	4.98 ± 1.44*
Overall acceptability	5.52 ± 1.09^{a}	4.98 ± 1.35^{b}

Results display mean ± standard deviation (n = 3) values for pH and fat content (%). Results display mean ± standard deviation (n = 50) values for sensory attributes. Letters$^{a\text{-}b}$ indicate a significant difference (P<0.05) between values within a particular column. RPCC, reduced-protein coconut cream. *No significant difference was observed in the pH, sensory appearance, and aroma among the samples.

4. Conclusion

Since most insoluble proteins were eliminated, RPCC was generated with a lower protein content, indicating that the treatment of FCC was successful. The 2-h and 4-h pasteurization process successfully produced RPCC-F with a reduced mass and protein, with increasing water solubility, suggesting a simplified foulant cleaning process. The lowered fat content in RPCC-2-F was due to the more effective stabilization of fat globules by the non-protein emulsifier, Tween 20. Removing stainless steel plates in RPCC-4-F likely altered heat transfer, reducing protein denaturation and, consequently, fat entrapment in the fouling layers. The higher fat content may have masked the higher ash and carbohydrate contents in RPCC-F compared to

FCC-F. RPCC ice cream demonstrated higher fat content, overrun, and melting rate than regular ice cream. While its appearance and aroma were like regular ice cream, it received significantly lower scores for texture, flavor, and overall acceptance in sensory evaluations. Despite this, all the ice cream samples received sensory scores above 4.5, indicating a generally positive response from the panelists. The sensory properties of RPCC ice cream can be improved by enhancing texture with protein fortification, optimizing stabilizers, and modifying fat composition. Flavor can be refined by balancing coconut and vanilla flavors, adjusting sweetness, and incorporating fruit juice or nectars for better acceptance. RPCC remains a viable and safe dairy substitute for other food products. Additionally, removing insoluble proteins from coconut cream can reduce fouling and streamline processing, decreasing labor, chemical cleaning, and maintenance costs. RPCC could be evaluated as a substitute in other dairy products, such as yogurt, to determine its potential as a versatile dairy-free alternative. Additionally, long-term shelf life and stability studies are recommended to understand better how RPCC performs in frozen and non-frozen applications, providing valuable insights for its broader use.

Acknowledgments

The authors acknowledge the Ministry of Higher Education Malaysia for Fundamental Research Grant Scheme (FRGS) with Project Code FRGS/1/2024/TK05/USM/01/4 for funding. The authors acknowledge the School of Industrial Technology, Universiti Sains Malaysia, for testing facilities and support.

References

Akbari, M., Eskandari, M. H., & Davoudi, Z. (2019). Application and functions of fat replacers in low-fat ice cream: A review. Trends in Food Science & Technology, *86*, 34–40.

AOAC. (2000). AOAC International Official methods of analysis of AOAC International. In *Gaithersburg, MD, USA*. The Association of Official Analytical Chemists: Gaithersburg, MD, USA.

Awais, M., & Bhuiyan, A. A. (2019). Recent advancements in impedance of fouling resistance and particulate depositions in heat exchangers. International Journal of Heat and Mass Transfer, *141*, 580–603.

Azizi-Lalabadi, M., Moghaddam, N. R., & Jafari, S. M. (2023). 9 - Pasteurization in the food industry. In S. M. Jafari (Ed.), Thermal Processing of Food Products by Steam and Hot Water (pp. 247–273). Woodhead Publishing.

Beegum, P. P. S., Nair, J. P., Manikantan, M. R., Pandiselvam, R., Shill, S., Neenu, S., & Hebbar, K. B. (2022). Effect of coconut milk, tender coconut and coconut sugar on the physico-chemical and sensory attributes in ice cream. Journal of Food Science and Technology, 1–12.

Choo, S. Y., Leong, S. K., & Henna Lu, F. S. (2010). Physicochemical and Sensory Properties of Ice-cream Formulated with Virgin Coconut Oil. Food Science and Technology International, *16*(6), 531–541.

Chutrakul, T., Rangton, N., Daochot, R., Sattayathitikul, N., & Saikhwan, P. (2019). Enzyme-based integrated solution to cleaning of coconut milk foulants. Food and Bioproducts Processing, 113, 93–100.

Devi, M., & Ghatani, K. (2022). The use of coconut in rituals and food preparations in India: a review. Journal of Ethnic Foods, 9(1), 37.

Felfoul, I., Lopez, C., Gaucheron, F., Attia, H., & Ayadi, M. (2015). Fouling Behavior of Camel and Cow Milks Under Different Heat Treatments. Food and Bioprocess Technology.

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. Lwt, 92, 516–522.

Granato, D. , Masson, M. L. , & & Ribeiro, J. C. B. (2012). Sensory acceptability and physical stability evaluation of a prebiotic soy-based dessert developed with passion fruit juice. Food Science and Technology, 32(1).

Khaldi, M., Ronse, G., Andre, C., Blanpain-Avet, P., Bouvier, L., Six, T., Croguennec, T., Jeantet, R., & Delaplace, G. (2015). Relationship between β-lactoglobulin denaturation and fouling mass distribution in a plate heat exchanger.

Konkamdee, W., & & Saikhwan, P. (2015). Effect of pasteurization on protein and fat contents remaining in coconut milk. Journal of Food Science and Agricultural Technology (JFAT), 1, 182–187.

Kusumayanti, H., Handayani, N. A., & Santosa, H. (2015). Swelling Power and Water Solubility of Cassava and Sweet Potatoes Flour. Procedia Environmental Sciences, 23, 164–167.

Lima, J. G. de, Brito-Oliveira, T. C., & Pinho, S. C. de. (2016). Characterization and evaluation of sensory acceptability of ice creams incorporated with beta-carotene encapsulated in solid lipid microparticles. Food Science and Technology (Campinas), 36(4), 664–671.

Maghazechi A. (2023). Rheological Characterization And Fouling Mitigation Of Coconut Cream Emulsion [PhD thesis]. USM.

Maghazechi, A., Mohammadi Nafchi, A., Tan, T.-C., & Easa, A. M. (2022). Rheological characterization and fouling deposition behavior of coconut cream emulsion at heat processing temperature range. Food Science & Nutrition, 10(11), 3801–3813.

Maghazechi, A., Nafchi, A. M., Tan, T.-C., Seow, E.-K., & Easa, A. M. (2021). Rheological characterization of coconut cream emulsion using steady-state shear and time-dependent modeling. Journal of Food Engineering, 306, 110642.

Mahisanunt, B., Hondoh, H., & Ueno, S. (2019). Effects of tripalmitin and tristearin on crystallization and melting behavior of coconut oil. Journal of the American Oil Chemists' Society, 96(4), 391–404.

Mostafavi, F. S., Tehrani, M. M., & & Mohebbi, M. (2017). Rheological and sensory properties of fat reduced vanilla ice creams containing milk protein concentrate (MPC). Journal of Food Measurement and Characterization, 11(2), 567–575.

Onsaard, E., Vittayanont, M., Srigam, S., & McClements, D. J. (2006). Comparison of properties of oil-in-water emulsions stabilized by coconut cream proteins with those stabilized by whey protein isolate. Food Research International, 39(1), 78–86.

Patil, U., & Benjakul, S. (2017). Characteristics of albumin and globulin from coconut meat and their role in emulsion stability without and with proteolysis. Food Hydrocolloids, 69, 220–228.

Patil, U., & Benjakul, S. (2018). Coconut Milk and Coconut Oil: Their Manufacture Associated with Protein Functionality. Journal of Food Science, 83(8), 2019–2027.

Perera, K., & Perera, O. (2021). Development of Coconut Milk-Based Spicy Ice Cream as a Nondairy Alternative with Desired Physicochemical and Sensory Attributes. International Journal of Food Science, 2021(1), 6661193.

Promlok, D., Kanjanaprayut, N., Kiatisereekul, N., Chanthateyanonth, R., & Jariyaboon, M. (2021). Influence of food additives on blister formation in tinplate can of coconut milk. Journal of Food Engineering, 300, 110513.

Saikhwan, P., Nuchnet, C., Wanakayont, W., & Suksa-nga, A. (2016). Extraction of Coconut Oil from Coconut Milk Foulants Using Enzyme. MATEC Web of Conferences, 62, 02008.

Saikhwan, P., Somana, J., & & Konkamdee, W. (2022). Fouling mechanisms of coconut milk foulants formed during pasteurization. Food and Bioproducts Processing, 136, 184–195.

Saikhwan, P., Thongchan, S., Jumwan, N., Thungsiabyuan, P., Sakdanuphap, J., Boonsom, S., Kraitong, P., & Danwanichakul, P. (2015). Cleaning studies of coconut milk foulants formed during heat treatment process. Food and Bioproducts Processing, 93, 166–175.

Santana, I. A., Ribeiro, E. P., & Iguti, A. M. (2011). Evaluation of green coconut (Cocos nucifera L.) pulp for use as milk, fat and emulsifier replacer in ice cream. Procedia Food Science, 1, 1447–1453.

Thirukumaran, R., Nimbkar, S., Mahalakshmi, L., Leena, M. M., Moses, J. A., & Anandharamakrishnan, C. (2023). Impact of different emulsification techniques on the stability of coconut milk. Journal of Agriculture and Food Research, 12, 100608.

Waisundara, V. Y., Perera, C. O., & Barlow, P. J. (2007). Effect of different pre-treatments of fresh coconut kernels on some of the quality attributes of the coconut milk extracted. Food Chemistry, 101(2), 771–777.

Wu, B., Freire, D. O., & Hartel, R. W. (2019). The effect of overrun, fat destabilization, and ice cream mix viscosity on entire meltdown behavior. Journal of Food Science, 84(9), 2562–2571.