RHEOLOGICAL CHARACTERIZATION AND FOULING MITIGATION OF COCONUT CREAM EMULSION

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RHEOLOGICAL CHARACTERIZATION AND FOULING MITIGATION OF COCONUT CREAM EMULSION

by

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LIST OF ABBREVIATIONS

A	Weltmann parameters that represent the initial shear stress (Pa)
AOAC	Association of Official Analytical Chemists
B	Weltmann parameters that represent the time coefficient of thixotropic breakdown (Pa)
CCE	Coconut Cream Emulsion
CCE NS	CCE Non-Soluble
CCE S	CCE Serum Layer
CIP	Clean in Place
CSRs	Controlled Shear Rates
FTIR	Fourier Transform Infrared
GFD	Generated Fouling Deposition
GFDs	Generated foulant deposits
K	Consistency coefficient ($Pa.s^n$)
LS CCE	Low Serum CCE
LVR	Linear viscoelastic region
m	Reaction order decay
n	Flow-behavior index (dimensionless)
pH	Potential of hydrogen ion
SEM	Scanning Electron Microscope
SKM	Second-order structural kinetics model
t	Shear Time (s)
t_m	The Time At Which The Maximum Shear Stress (t_m = 5s)
$\dot{\gamma}$	Shear rate (s^{-1})
η_∞	Equilibrium (steady-state) viscosity (Pa.s)
η_o	Initial viscosity (Pa·s)

κ	Decay (breakdown) rate constant (s^{-1})
τ	Shear Stress (Pa)
τ_o	Yield shear stress (Pa)

PERINCIAN REOLOGI DAN PENGURANGAN FOULING EMULSI KRIM KELAPA

ABSTRAK

Emulsi santan (CCE) merupakan emulsi minyak-dalam-air yang digunakan sebagai ramuan penting dalam masakan di kebanyakan kawasan Asia dan Pasifik dan terkenal sebagai susu daripada produk bukan tenusu berasaskan tumbuhan. Namun begitu, beberapa masalah teknikal perkilangan CCE terutamanya proses pengendapan kotoran (fouling deposition), iaitu proses pembentukan lapisan yang terjadi apabila struktur reologi beberapa komponen dalam CCE musnah disebabkan oleh proses pemanasan dan pengumpulan haba pada permukaan panas. Kajian ini dijalankan bertujuan memahami dan mengurangkan masalah pengendapan kotoran di dalam CCE melalui perubahan struktur pada gumpalan CCE dan permukaan panas. Kajian ini terbahagi kepada empat fasa utama. Pada fasa pertama, perincian reologi bagi gumpalan CCE menggunakan ricih keadaan mantap (steady-state shear flow measurement) dan pemodelan bersandar masa (time-dependent modelling) dalam julat suhu 10-50°C telah dikaji. CCE telah menunjukkan sifat tiksotropik bersandar masa yang signifikan pada semua suhu secara menurun dalam kelikatan apabila suhu meningkat daripada 10 hingga 50°C. Berdasarkan keputusan daripada tiksotropik dan uji kaji bersandar masa, CCE merupakan emulsi lembut yang mudah dimusnahkan disebabkan oleh ricihan dan suhu. Tambahan pula, ciri-ciri reologi CCE dan sifat pengendapan kotoran terjana (GFDs) pada suhu tinggi 60-90 °C telah dijalankan dalam fasa kedua. Perubahan struktur disebabkan oleh haba-teraruh (heat-induced) dalam gumpalan CCE mungkin dapat menghasilkan gel zarah apabila dipanaskan. Secara reologi, perubahan struktur telah berlaku pada suhu ≥85°C berkaitan dengan pembentukan gel-gel penzarahan. Pada suhu ~70 °C, lapisan GFDs dapat dilihat dengan mata kasar. Komposisi kimia, transformasian inframerah Fourier (FTIR), pengimejan imbasan mikroskop elektron (SEM), imej visual dan penghitungan jisim telah digunakan untuk memeriksa secara teliti GFDs tersebut. Berdasarkan keputusan daripada fasa ini, perubahan struktur disebabkan oleh haba-teraruh dalam protin dan lemak telah membentuk beberapa gel penzarahan yang dipenuhi lemak (fat-filled particulate gel) yang boleh dilihat pada lapisan permukaan panas seperti GFDs. Dalam fasa ketiga, peranan pH dalam perubahan struktur dan pengendapan kotoran telah dikaji. Kadar kelikatan, modulus G′ dan jisim GFDs yang meningkat secara signifikan apabila pH CCE beralkali telah menunjukkan bahawa gel zarah yang terbentuk dalam gumpulan CCE dan GFDs adalah sandar pH. Fasa terakhir telah dilakukan untuk mengkaji peranan kritikal protin semasa perubahan struktur CCE dan pembentukan kotoran. Pembuangan kebanyakan protin daripada pembuangan serum CCE telah menghasilkan serum rendah (LS) CCE. Perubahan kecil dari segi struktur dalam LS CCE telah mengurangkan pembentukan GFD. Kesimpulannya, CCE merupakan emulsi lembut yang berinteraksi dengan pemanasan dan menghasilkan gel-gel penzarahan yang dipenuhi lemak dalam gumpalan CCE dan kotoran. Tambahan pula, protin merupakan komponen penting yang menyebabkan pembentukan kotoran semasa pemanasan berterusan. Oleh sebab itu, pembentukan GFDs dapat dikurangkan dengan mengawal penghasilan gel penzarahan melalui penyingkiran kepekatan protin dalam serum CCE.

RHEOLOGICAL CHARACTERIZATION AND FOULING MITIGATION OF COCONUT CREAM EMULSION

ABSTRACT

Coconut cream emulsion (CCE) is a popular oil-in-water emulsion used in many Asian and Pacific food products and is gaining popularity as a non-dairy plant-based milk worldwide. However, its factory production is faced with technical challenges, particularly fouling deposition, which is the formation of layers due to structural changes in the emulsion during heat processing and the accumulation of these layers on heated surfaces. This study aimed to understand and mitigate fouling deposition in CCE by investigating structural changes in heating surfaces and CCE bulk. Four main phases made up this research activity. In the first phase, the rheological characteristics of the CCE bulk were investigated through steady-state shear flow measurement and time-dependent modelling in a temperature range of 10–50 °C. The CCE exhibited thixotropic time-dependent behavior at all temperatures, showing a significant decrease in viscosity when temperature increased from 10 °C to 50 °C. Results indicated that CCE is a delicate emulsion that readily degrades structurally by shearing and temperature effects. While the rheological characteristics of CCE and generated foulant deposits (GFDs) behavior at heat processing temperatures of 60–90 °C were studied in the second phase. Particle gel was thought to form during heating as a result of heat-induced structural changes in the CCE bulk, which may have led to the formation of certain foulants and subsequent build-up on the heated surface. Rheologically, heat-induced structural changes were observed at ≥85 °C, which were associated with particulate gel formation. At ~70 °C, the GFDs first appeared as a visible layer to the naked eye. Chemical composition, Fourier transform infrared (FTIR), scanning electron microscopy (SEM), visual imaging, and mass calculations were performed to explore the GFDs. The results suggested that heat-induced structural changes in the proteins and fats had led to the development of some fat-filled particulate gels in the CCE bulk, which appeared on the heating surface layer as GFDs. Meanwhile the roles of pH in structural changes and fouling deposition were studied in the third phase. Viscosity, G′ modulus, and GFDs mass increased significantly when the CCE's pH moved toward the alkaline range, suggesting that the particle gel formed in the CCE bulk and the GFDs are pH dependent. In the final phase, the critical roles of proteins during structural changes in the CCE and fouling formation were investigated. Most of the proteins were removed by discarding most of the CCE's serum, and yielding low serum CCE (LS CCE). Minor structural alterations were found in LS CCE, minimizing the GFDs formation capabilities. In conclusion, the CCE is a delicate emulsion, which interacts with heat treatment and yields fat-filled particulate gels in the CCE bulk, causing fouling. Proteins are the most likely components that contribute to fouling formation during extended heating. Therefore, the GFDs were successfully mitigated by controlling particulate gel formation through the reduction of protein concentration in the CCE.

CHAPTER 1

INTRODUCTION

1.1 Background and rationale of the study

Coconut cream emulsion (CCE) is the liquid obtained from the kernels of coconut (*Cocos nucifera* L.) by mechanical force and without water addition. Coconut products are essential ingredients in many Asian and Pacific dishes. The demand for coconut cream has sharply increased recently (Aydar et al, 2020) because of the rise in the popularity of non-dairy milk products among consumers. According to Mintel's study, consumption of plant-based milk substitutes climbed by 19% in three months beginning in February 2019 when compared to consumption statistics from 2018. Each category of plant-based milk substitutes also exhibited year-over-year growth. For instance, sales of coconut milk increased between 2017 and 2018 by 16% (Wood, 2019). To preserve and extend the shelf life, thermal is required to kill dangerous germs commonly found in unprocessed coconut milk and its cream, for instance, pasteurization, which involves heating a coconut emulsion to 72 °C for 20 min. An ultrahigh temperature (UHT) is achieved by heating to 121 °C for 20 min (Pichitvittayakarn et al., 2010). As a complex biological fluid made primarily of fat, proteins, carbohydrates, and minerals, coconut cream in the form of a white oil-in-water emulsion can lose some of its rheological qualities and are denatured, forming deposits on heated surfaces. The formation of deposits on heat exchanger surfaces is referred to as “coconut milk fouling” (Pichitvittayakarn et al., 2006). In general, fouling is a ubiquitous problem in the food industry, yet details are scarce on how such deposits grow over time to unsustainable levels. These deposits cause the temporary suspension of processes for equipment cleaning, increasing maintenance cost.

Studying the underlying fouling mechanism is critical to understanding fouling in food equipment. Understanding fouling rates through mechanistic models is necessary to developing strategies for minimizing fouling (Yang et al., 2018). The flow rate is an essential factor affecting fouling deposition. When the coconut cream flow rate decreases, the values of the fouling factor increase at the end of experiments. This means that fouling deposits accumulate more quickly on equipment surfaces when the flow rate of coconut cream is lower. (Pichitvittayakarn et al., 2010). Fouling on a hot surface can be classified as a bulk-controlled process reaction, or a surface process reaction. When fouling is a bulk-controlled process, surface modifications may not be sufficient to prevent deposition. While when fouling is a surface-controlled process, deposited species must be predetermined for the surface to develop a deposition-resistant surface (Changani et al., 1997). Regarding the CCE, whether coconut cream fouling is a bulk reaction or a surface process is unclear. Many attempts to commercially increase the shelf life of coconut cream have been made for many years, involving canning, aseptic packaging, and spray drying. Heat treatment for sterilization and pasteurization has been used in the canning and aseptic packing of coconut cream and is performed continuously in pipelines. Before being transferred to a container, coconut milk is pumped and sheared. The deformation and flow of materials are deeply involved in the mechanical handling of coconut cream. These mechanical features are referred to as rheological properties. The rheological characteristics of food products are critical to flow operation design, quality control, storage, measurement stability, and texture prediction (Davis, 1973). Rheological data are critical to optimizing equipment design, assuring proper heat treatment, and preventing product overheating in food exposed to thermal processing conditions (Anderson et al., 2002). The viscoelastic characteristics of food are evaluated via dynamic rheological testing, which involves subjecting samples to cyclic loading, during which stress and strain harmonically oscillate. Dynamic assessments are the primary rheological procedures for investigating fluid structures (Bui, et al., 2012). Food products, particularly dairy milk, have been studied for many years, and the body of knowledge on dairy milk and fouling deposition is growing. Coconut cream fouling behavior is not well explored despite its widespread use. Understanding the phenomena governing the build-up of deposits is crucial due to its high cost. However, the structure of CCE as a complex fluid requires specialized knowledge, and no comprehensive literature review exists on this topic. Further research is urgently needed.

1.2 Problem Statement

The statement suggests that CCEs fouling deposits accumulate more quickly than other types of fouling deposits, such as those from dairy products. Unfortunately, despite the severity of these problems, effective solutions to CCEs fouling deposits have yet to be found. The only way to reduce this issue is temporarily halting the process and removing deposits. Unfortunately, this method results in product loss, increases the cost of downtime for cleaning, incurs high maintenance costs, and needs additional workforce costs, energy costs, and environmentally unfriendly chemicals for cleaning. However, most cleaning protocols are designed for dairy-based fouling, and dairy-based cleaning protocols may not be effective for CCE fouling due to differences in chemical and physical properties. Dairy milk is a complex mixture of water, fats, proteins, lactose, vitamins, and minerals. On average, cow's milk is approximately 87% water, 3.7% fat, 3.3% protein, and 5% lactose, with trace amounts of vitamins and minerals. The proteins in dairy milk are primarily casein and whey proteins. While coconut milk, on the other hand contains about 24% fat, 2.3% protein, 6.4% carbohydrates, and 0.5% ash.

1.3 Objective

The general objective of this study is to investigate and mitigate the mechanism of fouling deposition in CCE. The specific objectives of the study are as follows:

1) To characterize the rheological properties of CCE bulk under the combined effect of shear rate and temperature.
2) To rheologically investigate the heat-induced structural changes of CCE bulk, which subsequently lead to the formation of foulant.
3) To explore the fouling deposition characteristics and the chemical composition of fouling at different temperatures using a laboratory scale design.
4) To examine pH effect on the rheological changes and fouling deposition in the CCE.
5) To investigate the impact of low protein CCE on the rheological changes and fouling deposition in the CCE.

1.4 Hypothesis

The CCE is an oil-in-water emulsion stabilized by naturally emulsified proteins and contains a significant quantity of fat. The structural integrity of such system may be affected by temperature and shearing. Hence, investigating changes in the CCE bulk and heating surfaces at various temperatures may increase understanding of the mechanism underlying fouling deposition. Owing to the characteristics of fat and globular proteins in the CCE, they play a vital role in changes in the CCE bulk and heating surfaces. Hence, two temperature ranges (mild and heat processing) might explain structural changes in the CCE bulk. Additionally, pH and protein concentration manipulation may contribute to understanding and mitigating such changes. Raising the pH toward an alkaline level would alter aggregation and promote particulate gel formation and fouling deposition. By contrast, eliminating the majority of serum proteins may prevent aggregation and gel formation. After most of the serum is discarded, the fouling deposition may appear and behave differently from the fouling deposition from whole CCE, which may help in considerably reducing the fouling deposition mass.

1.5 Thesis organization

This thesis is divided into seven chapters; the present chapter includes a general introduction of CCE composition and its industrial issues, focusing on fouling deposition. The problem statement, objectives, and hypothesis for this study are briefly discussed. A thorough literature review on coconut cream and milk chemical composition, structural instability, and fouling deposition is presented in Chapter 2.

Given that CCE is an oil-in-water emulsion highly affected by temperature, a wide temperature range was used in this study. Specifically, a mild temperature range and a heat-processing temperature range were used. Chapter 3 discusses the rheological characterization of CCE bulk under the combined effect of shear rate and temperature, in the mild temperature range (10–50 °C). The heat-processing temperature range was explored in Chapter 4, which is divided into two parts. The first part illustrates rheologically investigation of the heat-induced structural changes of CCE bulk at heat processing temperature, which subsequently lead to the formation of foulant particles in the bulk solution. The second part explored the fouling deposition characteristics and the chemical composition of fouling at different temperatures. After understanding the temperature effect on structural changes in the CCE bulk and GFDs processes, the effect of increasing pH values toward the alkaline region on both processes was achieved, as elucidated in Chapter 5. An attempt to mitigate fouling deposition was presented in Chapter 6, which discusses the effect of serum removal from CCE on bulk structure changes and GFDs. Finally, Chapter 7 summarizes the results and provides suggestions and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Coconut

Coconut (*Cocos nucifera* L.) is a monocotyledon palm (commonly known as coconut palm) from the Palmaceae family (Pham, 2016). Spanish explorers have named coconut cocos, which means grinning face because of the three small eyes found on its base; it grows abundantly in Malaysia and South Asia. The coconut is a one-seeded drupe classified as a fruit but frequently mistaken as a nut (Onsaard, et al., 2006). The coconut is one of the most valuable trees in the world. It greatly contributes to a country's economy because it produces a wide range of culinary items, such as kernels, water, oil, milk, and sap sugar, earning it the moniker "tree of life" (Ohler, 1999). The coconut palm is economically valuable and widely used in many Asian and Pacific traditional dishes (DebMandal & Mandal, 2011).

In general, the entire development of the fruit takes about one year. First, the husk and shell grow, and the embryo sac cavity considerably enlarges. This cavity is filled with liquid; after about four months, the husk and shell increase in thickness (Figure 2.1). The solid endosperm forms against the cavity's inner wall after six months. This first layer is thin and gelatinous; the soft white endocarp becomes hard and dark brown at about eight months, and the fruit matures within 12 months (Ohler, 1999).

2.1.1 Coconut milk and cream

Coconut milk and coconut cream are essential ingredients in many Asian and Pacific food dishes. Coconut milk and its cream tend to be used interchangeably in the literature, in the food business, and by consumers. Coconut milk refers to the liquid obtained by exerting mechanical force on coconut meat, and water is typically added. Based on CODEX STAN240-2003, coconut milk is made by pressing or squeezing ripe coconut flesh (Kernel) with water, it is a diluted emulsion that contains at least 12.7% total solids, with 2.7% non-fat solids, and 10% fat. While coconut cream is an un diluted emulsion, it has a minimum of 25.4% solids, with 5.4% non-fat solids, and 20% fat, as shown in Figure 2.2. The presence of proteins in the aqueous phase is what stabilizes the oil-in-water emulsion of coconut milk.

Coconut milk is a complex biological multicomponent fluid composed of fat, proteins, glucose, and minerals. It is an oil-in-water emulsion stabilized by natural emulsifiers, such as globulins and albumins, and phospholipids, such as lecithin and cephalin (Onsaard, et al., 2005). Some proteins interact with fatty globules in aqueous coconut milk phases and serve as emulsifiers surrounding surfaces (Peamprasart & Chiewchan, 2006). The age of the nut and cultural practices, variation, and geographical location influence the composition of mature kernel. Moreover, different maturity stages tend to significantly impact the chemical makeup of coconut meat and milk (Patil, et al., 2017). Fat percentage is adjusted according to the local requirement, between 15% and 40% (Narataruksa, et al., 2010). Coconut milk is a white oil-in-water emulsion consisting of globulins, albumins, and phospholipids, which act as stabilizers (Raghavendra & Raghavarao, 2010). Coconut emulsion is not physically stable and is inclined to phase separation, separating into a cream and serum layer within 5–10 hours of manufacturing (Tangsuphoom & Coupland, 2009).

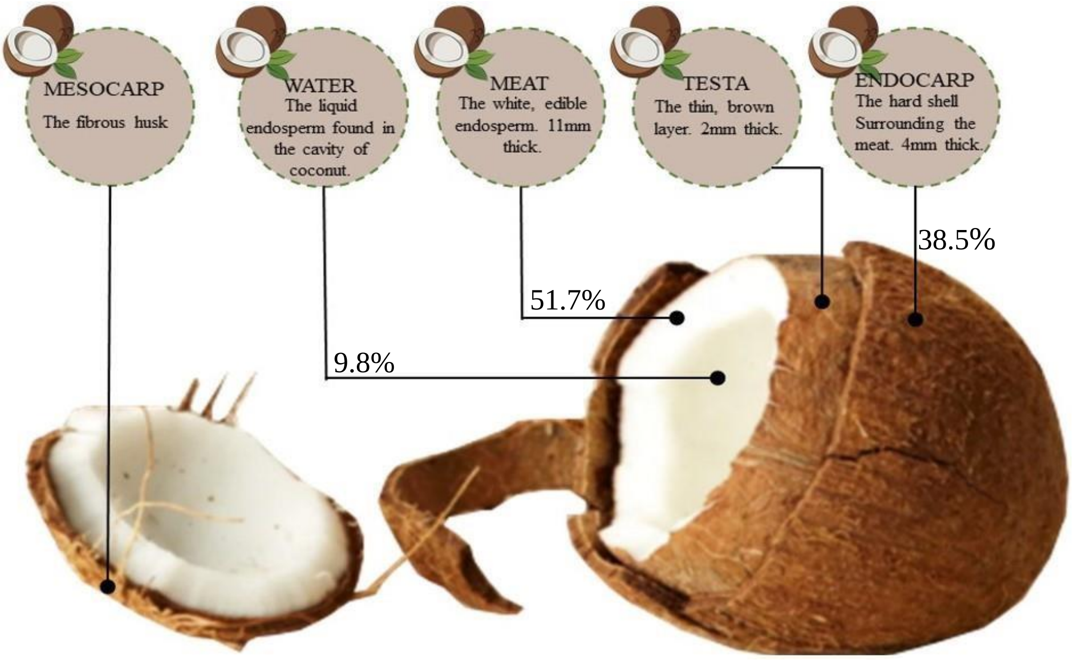

Figure 2.1 Coconut fruit cross-section. (The chemical percentage sited from (Patil & Benjakul, 2018).

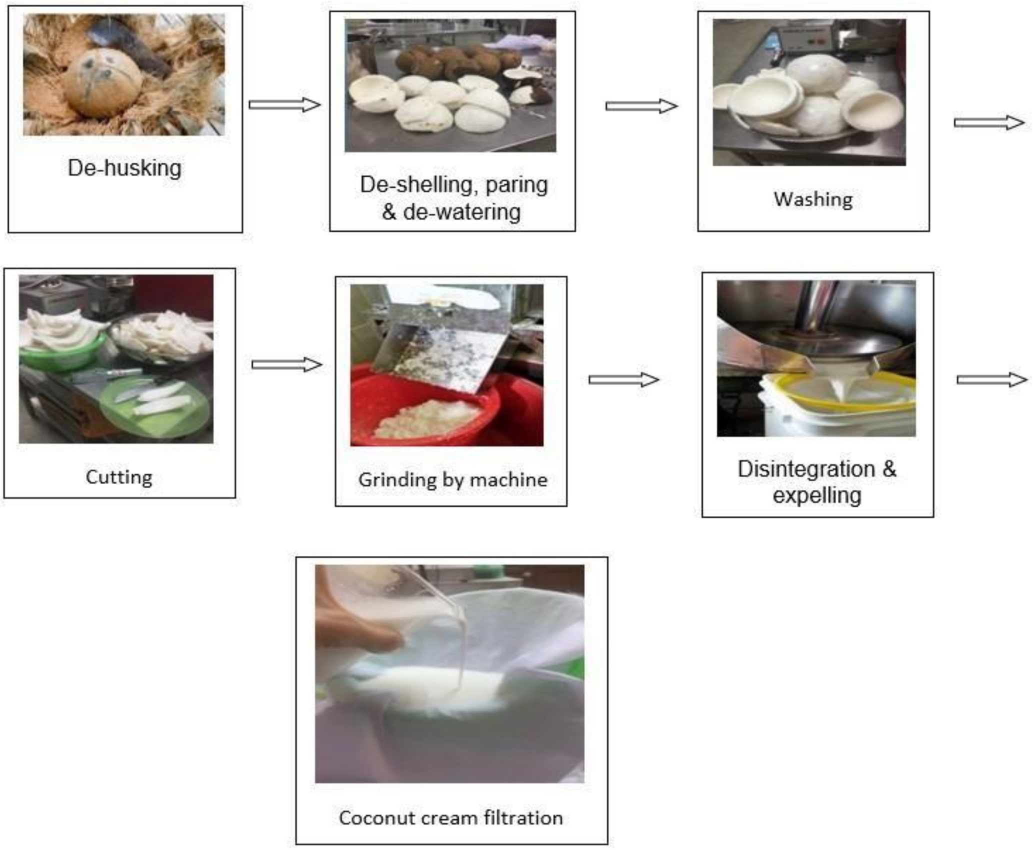

Figure 2.2 Coconut cream extraction.

2.1.2 Chemical composition of coconut milk

Grated coconut meat is widely used in making coconut milk (kernel) (Patil & Benjakul, 2018). Coconut meat (analog) is a high-nutrient and vitamin- and mineral dense food and has been referred to as a “functional food” because it has numerous health benefits and high nutritional value (Edem & Elijah, 2016c). Moreover, the antioxidant capabilities of coconut and its derivatives are due to biologically active elements, such as antioxidant vitamins, phenolic compounds, and amino acids (Thakurmet al., 2020). Table 2.1 tabulated the proximate composition of coconut milk, which was extracted from coconut kernel without any addition of water. Moreover, fat is a crucial component in coconut because it influences the visual and sensory qualities of coconut milk products and the foods that use them as an ingredient.

Table 2.1 Chemical composition of fresh coconut milk.

Nutrient (%w/w)	P. Waraporn et al.,2006	USDA, 2014*	Food agency of Sweden, 2015*	U. Patil et al., 2017
Moisture	70.57	54	-	61.55
Protein	2.99	3.6	3.4	2.90
Fat	17.00	35	33.5	30.34
Ash	-	1.2	-	1
carbohydrate	-	6.7	6.1	4.21

**Corresponding to the information (Chambale et al., 2014).*

2.1.2(a) Proteins

Coconut is one of the possible sources of high-nutritive-value proteins and has a well-balanced profile (Patil & Benjakul, 2018). Proteins are charged and surface-active molecules that can facilitate oil-in water emulsion and maintain its stability. They adsorb on the droplet’s surface and provide repellent interactions (such as electrostatic and steric) that aid in preventing droplet aggregation (McClements, 2016). The major proteins in coconut meat are globulin and albumin, which are soluble in NaCl and water (Kwon & Rhee, 1996). Coconut milk proteins are sensitive to temperature, and heating treatment degrades coconut proteins and increases the average droplet size of coconut milk, mainly resulting in the instability of milk (Jiang & Xiang, 2015).

Different solvents are often used to fractionate coconut proteins into five fractions: water, sodium chloride, isopropanol, acetic acid, and sodium hydroxide soluble fractions, namely, albumin, globulin, prolamin, glutelin-1, and glutelin-2 fractions. Globulin (salt soluble) and albumin (water soluble) account for 40% and 21% of the total protein, respectively, and are the dominant proteins in coconut endosperm or kernel (Kwon et al., 1996).

A study on albumin and globulin fractionation from defatted coconut meat showed that a protein with a molecular weight of 55 kDa is prevalent in both fractions (Patil et al., 2017). The globulin fraction has a higher average hydrophobicity than albumin. The molecular weight of the prolamin fraction is 17–56 kDa, whereas the molecular weight of the glutelin-1 fraction was 14–100 kDa. In addition, 11S (cocosin) and 7S globulin are the two primary forms of coconut globulin. Moreover, cocosin represents 86% of total globulin (Balasundaresan et al., 2002).

Garcia et al. (2005) purified and characterized the 11S and 7S globulins of coconut. The composition of total globulins is approximately 86% for 11S and 14% for 7S. Cocosin possesses disulfide bonds, and 7S has neither disulfide bonds nor carbohydrate groups. Patil et al. (2017) showed that globulin fraction had a higher average hydrophobicity than albumin. The globulin fraction in coconut is typically the most abundant (36%), followed by albumin (19%), glutelin-1 (10%), glutelin-2 (4%), and prolamin (2%). The sum of the five protein fractions accounted for 71% of the total proteins in the defatted meat. The results revealed that sequential extraction with five solvents cannot fully extract all proteins from defatted coconut meat (Patil, et al., 2017). According to Kwon et al. (1996), the most abundant protein component in defatted coconut meat was globulin (40.1%), followed by albumin (21%), glutelin-1 (14.4%), glutelin-2 (4.8%), and prolamin (3.3%).

Balachandran and Arumughan (2002) reported that 80% of protein can be classified as albumin and globulin in the coconut endosperm. Hagenmaier et al. (1972) demonstrated that the aqueous phase dissolves roughly 30% of the proteins in coconut milk and the remaining proteins act as emulsifiers for fat globules. Protein structure can be affected by environmental conditions like pH, temperature, and ionic strength, and this can impact the ability of proteins to stabilize emulsions. A change in pH can alter the electrical charge of a protein, affecting how it interacts with other molecules. Changes in temperature and ionic strength can cause proteins to denature or alter their electrostatic interactions with other molecules. Understanding how environmental conditions affect protein structure is crucial for developing and optimizing emulsions for different applications like food and cosmetics. By controlling these conditions, it is possible to tailor the emulsifying properties of proteins to meet specific needs, resulting in emulsions with desired texture, stability, and appearance (Das & Kinsella, 1990). Only Huang et al. (2016) performed the proteomic profiling of coconut, aiming to identify variants of storage protein subunits in the mature coconut endosperm; approximately ten major bands were found with approximate molecular weights ranging from 12 kDa to 55 kDa. Coconut protein has high glutamic acid, arginine, and aspartic acid content but lacks sulfur-containing amino acids, such as methionine. The albumin fraction has low levels of most amino acids. However, lysine, arginine, and glutamic acid are significantly abundant. Globulin and glutelin-2 have similar amino acid composition. Notably, globulin has higher concentrations of all amino acids than glutelin-1 does. Globulin contains many essential amino acids, including phenylalanine and valine. An amino acid analysis demonstrated that coconut proteins have high levels of glutamic acid, arginine, and aspartic acid (Kwon et al., 1996).

Glutamine or glutamic acid is the primary amino acid found in albumin and globulin. However, differences in protein pattern and amino acid composition have been observed between these fractions (Lin et al., 2020). Charged amino acids are abundant in the globulin portion of coconut, including aspartic acid, glutamic acid, arginine, and lysine, which are the primary charged amino acids (Patil et al., 2017).

Amino acid profiles of coconut protein from different references are presented in Tables 2.2 and 2.3.

Table 2.2 Amino acid profile of the coconut protein.

Essential amino acids (%, w/w)	**Fresh Endosperm (USDA, 2014) ***	**Coconut protein conc. (Somruedee thaiphanit, 2015)**
Histidine	2.19	2.2925
Isoleucine	3.69	2.0545
Leucine	6.99	4.7699
Lysine	4.16	3.3476
Methionine	1.77	1.5512
Phenylalanine	4.79	4.3078
Threonine	3.43	2.7611
Tryptophan	-	1.3807
Valine	5.72	3.3253
Non-essential amino acids		

Table 2.2 (Continued)

Essential amino acids (%, w/w)	**Fresh Endosperm (USDA, 2014) ***	**Coconut protein conc. (Somruedee thaiphanit, 2015)**
Alanine	4.81	3.6468
Arginine	15.48	12.2219
Aspartic acid	9.21	8.6481
Cysteine	1.87	1.6299
Glutamic acid	21.57	21.6721
Glycine	4.47	3.9061
Proline	3.90	3.3710
Serine	4.86	4.111
Tyrosine	1.09	2.1073

*Corresponding to the information (Chambale et al., 2014).

Table 2.3 Amino acid profile of the coconut protein.

Amino acids	**(Kwon et al., 1996)**			**(Patil et al., 2017) g/100g**	
Polar	**Albumin**	**Globulin**	**Gluteline-1**	**Albumin**	**Globulin**
Arginine	17.9	15.0	14.2	16.53	14.88
Aspartic acid	5.6	8.9	8.3	8.02	9.20
Glutamine	24.9	17.5	17.0	24.07	19.66
Histidine	1.8	1.9	1.9	2.40	2.82
Lysine	5.1	3.5	3.5	6.26	5.00
Serine	3.1	5.0	3.9	4.76	5.00
Threonine	3.3	3.3	3.2	3.17	3.40
Tyrosine Nonpolar	3.0	3.7	3.1	2.55	3.30
Alanine	2.9	4.1	3.9	5.99	4.46
Cysteine	-	-	-	0.00	0.01
Glycine	4.0	4.9	4.5	4.42	4.96
Isoleucine	2.8	4.1	3.7	2.44	3.54
Leucine	3.9	6.5	6.5	5.13	7.23
Methionine	1.2	2.9	2.1	1.40	1.94
Phenylalanine	2.7	5.9	4.6	3.45	5.19
Proline	2.7	3.4	3.2	5.45	3.86
Valine	3.5	7.5	6.7	3.89	5.47

2.1.2(b) Fat

Coconut fat differs from other vegetable oils because it has high amounts of medium-chain fatty acids, particularly lauric acid (Dayrit, 2014). As a result of its high level of saturation and good stability, coconut fat has emerged as one of the most sought-after oils worldwide. Saturated fatty acids, which make up 90% of coconut fat’s composition, are its main component (Boemeke et al., 2015). Triacylglycerols are esterified with component fatty acids to form coconut fat, which also includes minor components such phospholipids, sterols, tocopherols, and volatile substances. These compounds have a significant impact on how coconut fat behaves chemically and physically (Deen, 2020).

Coconut milk oil has high amounts of saturated fatty acids, such as lauric acid, myristic acid, and palmitic acid (Kahwaji & White, 2019). It was mentioned by Boateng et al., (2016) that Coconut oil is composed of the fatty acids, caprylic acid C -8:0 (8%), capric acid, C-10:0, (7%), lauric acid C-12:0, (49%), myristic acid C-14:0(8%), palmitic acid C-16:0 (8%), stearic acid C-18:0 (2%), oleic acid C-18:1 (6%) and 2% of C-18:2 linoleic acid.

The melting point of coconut oil is about 24–27 °C, and its thermal stability can reach up to 200 °C (Kahwaji & White, 2019).

2.1.2(c) Carbohydrates and minerals

Most carbohydrates contain sugars (mainly sucrose) and some types of starch. The ethanol-precipitated polysaccharides of the liquid endosperm of coconut are mainly composed of galactose and arabinose and minor amounts of mannose and glucose. Gel filtration chromatography has revealed that coconut milk comprises galactose and arabinose and small amounts of glucose and rhamnose (White, et al., 1989). Phosphorus, calcium, and potassium are the most common minerals in raw coconut milk (Seow & Gwee, 1997). Water-soluble B vitamins and ascorbic acid likely have low concentrations in freshly extracted milk.

2.1.2(d) Volatile compounds

Wang et al. (2018) identified 31 volatile chemicals in coconut milk, including lactones (34.4%), esters (31.5%), aldehydes (20.0%), acids (3.8%), ketones (2.3%), alcohols (1.4%), and others (0.6 %) through solid-phase microextraction and gas chromatography-mass spectrometry. The microbial breakdown of the oil's fatty acids before pressing or extraction is usually the cause of the ketones found in crude oil. Additionally, it is thought that the flavour and scent of coconut is caused by the considerable amount of lactones contained in crude CNO (Deen, 2020).

2.1.3 Coconut milk and cream usage

Liquid and powdered coconut milk (or cream) and oil are the most popular food commodities made from fresh coconut meat (kernel), which contains highly nutritious fats, fibers, proteins, carbohydrates, microminerals, such as potassium and phosphorus, niacin, and riboflavin vitamins (Bawalan & Chapman, 2006). The demand for coconut milk or cream is overgrowing (Abdulsamad, 2016) because of increased consumer appreciation of its health benefits, and alternative milk food products and beverages are needed to respond to a growing awareness of lactose intolerance (McGregor & Sheehy, 2017). The market research company Frost & Sullivan showed that USD 193 million were estimated for the retail value of coconut based alternative milk and beverage products in the USA in 2014. Coconut milk dominated at USD 104 million (Frost-Sullivan, 2015). The alternative milk market (almond, soy, and coconut) was projected to grow by 18% annually from 2014 by 2021 USD 6.27 trillion. Edem and Elijah (2016b) showed that coconut milk has recently gained popularity because of its widespread use in the confectionery, bakery, biscuit, and ice cream industries around the world. Moreover, owing to the high nutritional content and distinct flavor of coconut milk, it has become a popular food emulsifier and cooking ingredient (Iguttia et al., 2011). It is crucial to prepare a variety of foods, such as curry, desserts, coconut jam spread, coconut syrup, coconut cheese, bread, and beverages (Gwee, 1988; Banzon et al., 1990). Coconut milk can be used in place of milk in some confections, such as Chocolate. Also, it has been used to produce VCO and serves as a food ingredient (Patil et al., 2017). Furthermore, coconut milk is a good source of proteins, including prolamin, globulin, albumin, and glutenin and can be used as an animal milk alternative, potentially contributing to the mitigation of protein deficiency in underdeveloped countries.

Furthermore, it is used as a raw material to produce dairy-like products, such as yogurt (Edem & Elijah, 2016a). According to Yaakob et al. (2012), coconut milk has a higher nutritional value than cow milk. Moreover, it is rich in minerals and vitamins, containing roughly 35% fat, 54% moisture, and 11% nonfat solids (Simuang et al., 2004; Tansakul & Chaisawang, 2006; Sanful, 2009).

2.2 Coconut milk Stability

Coconut milk is an oil-in-water emulsion made from coconut solid endosperm aqueous extract. The emulsion is highly unstable because of the large droplet size and the poor emulsifying qualities of coconut proteins in the oil–water interface (Tangsuphoom & Coupland, 2008). The instability of coconut emulsions is due to the insufficient amounts and quality of coconut proteins (Monera & Del Rosario, 1982; Onsaard et al., 2006). Rapid phase separation and high viscosity are undesirable in coconut milk emulsions because they degrade products' sensory qualities (Cancel, 1979).

The aqueous phase of a coconut milk emulsion contains some proteins, which act as emulsifiers to stabilize oil droplets (Peamprasart & Chiewchan, 2006). The hydrophilic and hydrophobic groups of these compounds can reduce interfacial tension between two phases, improve oil droplet dispersion in the aqueous phase, and improve emulsion stability (Monera & Del Rosario, 1982). Moreover, proteins act as emulsifiers, stabilizing oil droplets in coconut milk (Senphan et al., 2015). Emulsifiers perform two roles in the stability of emulsions. These roles are related to (1) lowering interfacial tension between a water phase and oil and (2) forming a mechanically cohesive interfacial film surrounding oil droplets and preventing coalescence (Patil & Benjakul, 2018).

Similar to most emulsions, natural coconut milk is usually unstable and stratified. It frequently exhibits a floating fat layer, protein flocculation, sediment, and other issues during storage because of its high-fat content. When the product is let to stand, numerous layers (i.e., whey, cream, and oil) emerge, even after repeated homogenization. Water and emulsion stratification has been a physically undesirable fault in the production and processing of coconut milk (Ng et al., 2014). Emulsion instability can be caused by three primary mechanisms: (1) creaming, (2) flocculation, and (3) coalescence (McClements, 2016), as demonstrated in Figure 2.3.

Creaming occurs when the densities of two phases differ and a phase separation occurs (Beydoun et al., 1998). Within 5–10 hours of production, cream separates from the aqueous phase in coconut milk (Seow & Gwee, 1997). Shaking separated milk can quickly re-homogenize it (Escueta, 1980). The aggregation of oil droplets caused by weak repulsive forces and strong attractive forces between oil droplets is known as flocculation. Oil droplets in the dispersed phase remain linked to each other during flocculation, and their structural integrity is preserved; this feature causes the cream to separate from the aqueous phase (McClements & Demetriades, 1998).

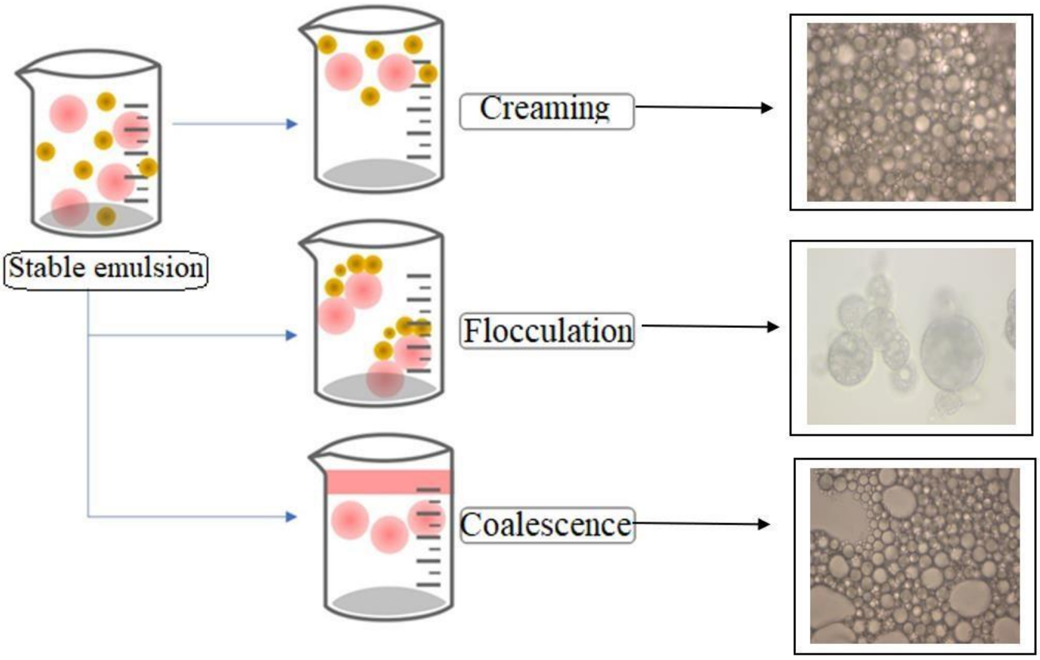

Figure 2.3 Coconut milk instability.

The separation of oil from emulsions, including coconut milk emulsion, is caused by coalescence. During coalescence, the breaking of protein coatings surrounding oil droplets lead to the coalescence of two small droplets into a large droplet. The coconut protein’s low surface activity and poor emulsifying properties are the primary causes of coconut milk emulsion instability (Monera & Del Rosario, 1982). Environmental factors, such as pH, temperature, processing conditions, and emulsion composition, influence the rate of emulsion collapse.

2.2.1 Effect of heat temperatures on coconut milk stability

Heat treatment increases the shelf life of coconut milk but can induce emulsion instability. Furthermore, when coconut milk is heated to a high temperature (80 °C or higher), coconut proteins coagulate and are denatured (Raghavendra & Raghavarao, 2010). When proteins in coconut milk are exposed to high temperatures for an extended amount of time, denaturation and precipitation occur. Acidic and basic pH environment promote the denaturation of coconut proteins during heating (Onsaard et al., 2006).

By investigating the effects of heating and homogenization on the stability of coconut milk emulsions, Tangsuphoom and Coupland found that heating enhanced the degree of coalescence, flocculation, and creaming in non-homogenized and homogenized samples. The degree of flocculation increases viscosity (Tangsuphoom & Coupland, 2005). They mentioned that owing to denaturation and subsequent aggregation of coconut proteins, coconut milk coalesced and flocculated after being heated at 90 °C or 120 °C for 1 hour (Tangsuphoom & Coupland, 2008).

Coconut proteins have been shown to undergo denaturation and coagulation at 80 °C or above (Natataruksa et al., 2010). The instability of the emulsion upon heating is a result of the denaturation of coconut milk proteins, and proteins are not water soluble and act as an emulsifying agent for the oil-water emulsion of coconut milk (Seow & Gwee, 1997). Jiang and Xiang (2015) mentioned that heating results in protein denaturation and increases the average droplet size of coconut milk. Moreover, many properties of an emulsion (i.e., stability, appearance, and texture) depend on the size of the droplet.

2.2.2 Effect of pH on coconut milk stability

Oil droplet size and pH are the most critical factors determining emulsion stability in coconut milk (Marina et al., 2009). Coconut milk is unstable over a pH range of 3.5–5, and its maximum stability was observed at pH 6.5 and pH 1.5–2 (Monera & Del Rosario, 1982). Meanwhile, Raghavendra, and Raghavarao (2010) concluded that coconut milk emulsions are extremely unstable at pH 7–8 and pH 3–6. Owing to the polar groups in proteins, changes in the emulsion's pH directly impact their intramolecular and intermolecular interactions. The emulsion's instability can be enhanced by the low pH of coconut milk, which inhibits the repulsion of protein film surrounding oil droplets (Patil et al., 2017). Acetic acid (25% w/v) disrupts coconut milk emulsion as coconut milk proteins coagulate and precipitate at pH 4 (Zakaria et al., 2011).

The stability of a coconut milk emulsion was determined by internal variables, primarily pH and protein concentration. The net charge of proteins surrounding oil droplets can be affected by pH, and when a protein's net charge is zero (isoelectric point), the repulsion of the protein film that surrounds oil droplets is reduced. As a result, the emulsion stability of coconut milk decreases (Patil et al., 2017).

Additionally, it was mentioned by Carrijo (2002) that coconut protein solubility is typically low, ranging from pH 4 to 5, but increases if the pH is above or below this range. The isoelectric point, often known as the pH range between 4 and 5, is where the majority of coconut's protein constituents, such as endosperm extracts, coconut skim milk, and coconut protein isolate, are least soluble.

Coconut proteins are susceptible to heat and undergo denaturation and coagulation upon heating to 80 °C (Kwon & Rhee, 1996). Heating coconut milk at a high temperature promotes protein denaturation. Thus, the large aggregates of emulsion droplets appear (Peamprasart & Chiewchan, 2006). When repulsive forces are sufficient, oil droplets tend to appear as collectively separate entities, forming a stable emulsion. Protein denaturation occurs when coconut milk is heated. DSC studies of raw and undiluted coconut milk revealed several endothermic transitions at high temperatures (80–120 °C). This result reflects coconut proteins' varying thermal denaturation behavior and complex protein composition. Two major transitions with denaturation peaks at 92 °C and 110 °C were observed. The transition at a high temperature transition is due to the denaturation of globulins, whereas the other may be attributed to overlapping transitions and some globulins (Seow & Goh, 1994). Moreover, DSC experiments have been conducted on diluted coconut milk (10% fat) obtained from frozen coconut meat and mixed with distilled water (2:1 w/w); The thermograms of this coconut milk emulsion revealed two distinct peaks at 85 °C and 100 °C, which are comparable to the denaturation temperatures of coconut 7S and 11S globulins (Tangsuphoom & Coupland, 2008).

2.3 Rheological properties

The knowledge of the rheological properties of food plays a fundamental role in the development of new products, dimensioning and operation of equipment involved in its processing, and the quality control of products and processes. The influence of formulation components has been studied, and the structures of products are related to their rheological characteristics (Zheng et al., 2017).

The rheological properties of coconut milk have been examined in some studies. Coconut milk with fat content (15%–30%) exhibits pseudoplastic behavior at a flow behavior index (*n*) between 0.756 and 0.923 and temperature range of 70–90 °C (Simuang et al., 2004). The Power Law model has been used to fit the flow curves of coconut milk (Simuang et al., 2004; Muda 2002).

According to the steady and dynamic rheological property tests, the loss modulus (G″) of coconut milk is more significant than the storage modulus (G′), which is compatible with the pseudoplastic fluid model and depicts a shear-thinning effect (Lu et al., 2019).

Coconut milk's flow behavior index (*n*) ranges from 0.713 to 0.930, indicating a pseudoplastic behavior. Preheating significantly impacts the perceived viscosity of coconut milk. At high preheating temperatures, increase in viscosity was detected at similar fat concentrates, and this tendency becomes prominent as the fat content of samples increases. The composition of coconut milk, such as stabilizing agent and fat content, significantly affect the flow behavior of coconut milk (Tangsuphoom & Coupland, 2005).

Many authors have observed similar behavior for the rheological study of nut-based beverage made of Brazil nut and Macadamia, were classified as non-Newtonian fluids with pseudoplastic character (n <1) (Silva et al, 2020).

2.4 Fouling deposit formation

2.4.1 Fouling issue

Fouling is commonly characterized as the accumulation and deposition of unwanted materials from a product stream on processing equipment surfaces (Thonon, 2008). The thermal instability of some food components leads to the production of fouling deposits on heat transfer surfaces in the form of food. The food industry incurs costs amounting to billions of pounds because of fouling. In the dairy industry, the entire cost due to fouling accounts for 80% during production (Bansal & Chen, 2006). A common challenge in the food sector is the lack of information on how the accumulation of deposits to unmanageable levels can be prevented through inexpensive and time-saving equipment cleaning operations. The underlying fouling mechanism should be examined for analyzing the fouling process in food equipment.

Studying fouling may help researchers understand the underlying processes (Fryer et al., 1996). Insights from this endeavour might facilitate the formulation of novel heat exchange methods that can mitigate or prevent fouling. As a result, there may be a reduction in the expenditures associated with fouling. Fouling rates may be better understood by using mechanistic models, which can then be used in designing methods for reducing fouling. Fouling is undesired during processing, and its undesirable effects are as follows (Jeurnink et al., 1996):

1) Drop in heat transmission coefficient
2) Decrease in pumping efficiency as a result of increase in pressure drop
3) loss of product left on the hot wall.
4) Loosened deposits contaminating processed products.