Dairy whipping cream: Effects of cream volume, temperature and fat content on foam formation and foam properties

A thesis presented in partial fulfilment of the requirements for the degree of

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DECLARATION

I hereby declare that the thesis entitled "**Dairy whipping cream: Effects of cream volume, temperature and fat content on foam formation and foam properties**" submitted by me, for the award of the degree of Master of Food Technology to Massey University, is a record of Bonafide research work carried out by me under the supervision of Dr. Lara Matia-Merino.

I further declare that I have used AI for grammar corrections and creating images for my literature review section. I also declare that the work reported in this thesis has not been submitted and will not be submitted, either in part or full, for the award of any other degree or diploma in this institute or any other institute or university.

ABSTRACT

Whipping cream is a unique multiphase dairy system in which fat crystallisation, air incorporation, partial fat coalescence, protein adsorption, and continuous phase restructuring occur simultaneously under mechanical shear, directly influencing product stability, texture, and sensory quality. Despite its widespread industrial and culinary use, the dynamic physicochemical changes occurring during the whipping process remain incompletely understood, particularly with respect to the combined effects of processing parameters, temperature, fat content, and formulation.

Most existing studies focus on final product characteristics such as overrun, firmness, and foam stability, while providing minimal understanding of the dynamic, real-time physicochemical changes occurring during the whipping process. In particular, the continuous evolution of mechanical resistance, fat destabilisation, and structural transitions under shear has not been sufficiently quantified using in-situ or process-based measurements. Additionally, the combined effects of processing parameters—such as cream volume, temperature, and fat content—are often investigated in isolation, leaving a lack of integrated understanding of how these variables interact to define the whipping window and the transition from optimal foam formation to overwhipping and butter formation. This thesis aims to systematically investigate the physicochemical transformations occurring during the whipping of cream, with a specific focus on torque development, microstructural evolution, aeration behaviour, and textural characteristics.

In the first phase of the study, the influence of whipping volume (200 ml, 400 ml, and 600 ml) on the whipping dynamics of cream at 7°C was evaluated using a Kenwood electronics mixer. Torque vs time profiles were generated to characterise resistance development during whipping. Key parameters, including exponential time constants, whipping rates, peak torque values, time to peak torque, optimum whipping time, and the peak window, were determined. The results suggests that whipping volume significantly affected mechanical energy input and structural development, with a 400 ml volume providing the most reproducible torque behaviour and allowed for the formation of an evenly distributed air bubble matrix stabilised by a robust yet sufficiently aerated fat network. Consequently, this volume was selected as the optimal condition for subsequent experiments.

In the second phase, the effect of whipping temperature (7°C, 10°C, and 13°C) on whipped cream characteristics was investigated. Temperature was found to play a critical role

in fat crystallisation behaviour and partial coalescence kinetics. Lower whipping temperatures promoted greater fat solidity, enhanced partial coalescence, and improved foam stability, resulting in higher firmness and more uniform microstructures. In contrast, elevated temperatures reduced fat crystal content, leading to weaker structural networks and reduced whipping stability. The CLSM micrographs at 7°C showed fine, evenly distributed air bubbles surrounded by a cohesive fat network.

The third phase examined the influence of fat content (32%, 36%, and 40%) on whipping performance. Fat standardisation was achieved through centrifugation and recombination with skim milk. Increasing fat content significantly enhanced partial coalescence, overrun, and textural strength; however, excessively high fat levels narrowed the whipping window and increased susceptibility to overwhipping. CSLM imaging confirmed denser fat networks at higher fat contents, providing direct microstructural evidence of the observed macroscopic properties.

After each experiment, the whipped cream samples were characterised using a combination of visual rosette analysis, texture profile analysis, overrun measurements, and confocal scanning laser microscopy (CSLM). The results from all the experiments suggests that the optimum conditions for whipping dairy cream rely on a specific synergy of formulation and processing parameters. To achieve the ideal product profile the volume (400ml), temperature (7°C), and fat content (36%) should be maintained.

The findings indicate that the consistent production of high-quality whipped cream requires strict control over processing variables to balance aeration with structural rigidity. Specifically, maintaining solid fat content through temperature regulation, utilizing an optimal fat concentration of 36%, and standardizing batch volumes are critical for stability. Furthermore, torque profiling emerged as a reliable real-time metric for predicting phase inversion, offering industrial utility in preventing over-whipping. Conversely, deviations such as excessive shear, elevated temperatures, or surplus fat were shown to accelerate structural collapse and promote premature churning. These results substantiate existing theories of foam formation while providing novel microstructural insights into the sensitivity of the whipping process to operational parameters.

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Chapter 1: THESIS INTRODUCTION

The aim of this research is to understand the physicochemical changes that occur in whipping cream during the whipping process by monitoring torque changes using a Kenwood mixer. By studying how different factors such as cream volume, whipping temperature, and fat content influence the physical and functional properties of the foam, future predictions can be made.

Whipped cream is one of the most widely used products in the food industry, it is mainly used in desserts and baked goods as a surface decoration, ornamental topping and a filling. Whipping cream's unique sensory attributes such as light, airy texture, smooth mouthfeel and its characteristic creamy aroma are the main reason for its popularity among consumers. However, these sensory qualities are what enable whipped cream to be such a strong commercial product and, therefore, a highly marketable item in both the retail and food service markets. Factors such as the volume of cream, temperature while whipping the cream, and fat content of the cream, influence molecular and structural changes in the production of whipping cream. The stability of whipping cream is one of the important factors in determining its functionality in food products. To improve the stability of whipping cream, ingredients such as stabilizers are added to its formulation. These stabilizers work by increasing viscosity of the soluble phase, which helps to strengthen the overall structure of the foam by preventing syneresis and collapse of the foam (Dabo et al., 2024). So, stabilisers play an important role in whipping cream by maintaining the desired consistency and appearance during its storage and application.

The importance of whipped cream in the food industry is not just as a widely used product but also because it serves as a useful model system for studying interfacial phenomena and complex emulsions when it comes to fundamental research of aerated emulsions. The emulsion stability, mainly during the whipping process, is determined by the interactions that happen at the milk fat-water interface, also dependent on the degree of droplet crystallinity. Studying these interactions at the interfaces provides insights into the mechanisms of emulsion formation and emulsion stability (Zhou et al., 2020).

Partial coalescence is the very important mechanism in whipped cream production. The controlled destabilisation of the fat phase is required to achieve the desired texture in products (Petrut et al., 2016). The process of partial coalescence during whipping ensures that fat crystals attach to air bubbles; this contributes to the stability and aeration in the final product (Mohamad

Fauzi, 2024). To form a light and aerated texture which is characteristic of whipping cream, it is important to have an interaction between fat crystals and air bubbles. During the whipping process, partially coalesced fat globules help in stabilising the air bubbles by creating a stable foam network. Temperature is also important in this process because it has a direct influence on fat crystallisation and the emulsion stability. The quality of the final product is significantly affected by the temperature at which cream is processed. To ensure the optimal fat crystallisation and stability of the emulsion, it is important to maintain proper temperature control. This is necessary to attain satisfactory whipping properties (Templeton & Sommer, 1933).

The other important factor that influences the behaviour of dairy fat during the whipping process is the variation in fat content. For example, a low-fat formulation does not have enough solid fat to provide the same structural integrity. Due to this, these formulations may require functional ingredients or the addition of stabilisers to maintain the structural integrity and texture of whipped cream by compensating for the reduced solid fat content (Abd El Aziz et al., 2016).

Innovative approaches are currently being explored by the food industry to enhance the production of whipped cream by adding novel additives derived from food grade materials. These developments are intended to address significant technical challenges mainly related to stabilisation, while also aligning with consumer preferences for healthier alternative products (Dabo et al., 2024).

The present thesis aims to understand in depth, the process of whipping, by monitoring the changes in torque using a modified Kenwood mixer, using fresh dairy cream. This is to be able to establish the basis for further research, based on recombined whipping cream.

1.1 RESEARCH QUESTIONS

- How do different volumes of cream affect the whipping process and the key characteristics of the final whipped cream?
- What is the impact of temperature on fat crystallization and partial coalescence during whipping and in the final whipped cream?
- How does fat percentage influence the whipping process and the quality of the final whipped cream?
- Can monitoring the torque using a modified Kenwood mixer provide insightful information on the whipping process of emulsions?

1.2 RESEARCH OBJECTIVES

- To analyze the torque-time relationship during whipping and identify key parameters such as peak torque, whipping time, and whipping window.
- To identify the effect of whipping various volumes of cream on the whipping process and the quality of the final whipped cream (stability, texture, overrun and microstructure).
- To study the effect of temperature on fat crystallization and partial coalescence by analysing torque changes and key quality parameters of the whipped cream formed (stability, texture, overrun, and microstructure).
- To investigate the role of fat percentage during whipping, by analysing torque changes and key quality parameters of the whipped cream formed (stability, texture, overrun and microstructure).

Chapter 2: LITERATURE REVIEW

2.1 DAIRY FAT

2.1.1 FATTY ACID COMPOSITION

Whipping cream gets its important physical and chemical characteristics from the types of fatty acids it contains. The fat in cow's milk is made up of various types of fatty acids that have different lengths and amounts of saturated fats (Li et al., 2022). Because of this diversity, melting, crystallisation, and the tendency of fat globules to coalesce during whipping are all affected. Because of these properties, cream is able to incorporate and retain air effectively during whipping. It is important to know about these fatty acids' properties to ensure industrial food products are of good quality and consistent each time (Dabo et al., 2024). To determine the functional properties of the whipping cream, it is important to understand the molecular structure of fatty acids in milk fat, especially the chain length of fatty acids and degree of saturation. These structural characteristics play an important role in key physical behaviours like the melting profile and crystallisation pattern of the fat, these physical behaviours are directly linked to the cream's ability to whip and form a stable foam (Liu et al., 2021). Usually, saturated fatty acids are the main part of commercial whipping cream, making up about 91.6%, with unsaturated fatty acids accounting for only 7.6%. The high amount of saturation in the liquid helps the crystals form more easily and steadily, which is necessary for the whipped product's structure and texture (Dabo et al., 2024).

Several medium chain and long chain saturated fatty acid species found in milk fat contribute to overall functionality of the whipping cream. Fatty acids in milk include chain lengths ranging from short to long, specifically butyric acid (C4:0), caproic acid (C6:0), caprylic acid (C8:0), capric acid (C10:0), lauric acid (C12:0), myristic acid (C14:0), palmitic acid (C16:0), and stearic acid (C18:0), each found in varying proportions (Gużewska et al., 2024; Månsson, 2008). The structure of medium- and long- chain fatty acids is shown in **Figure 1**.

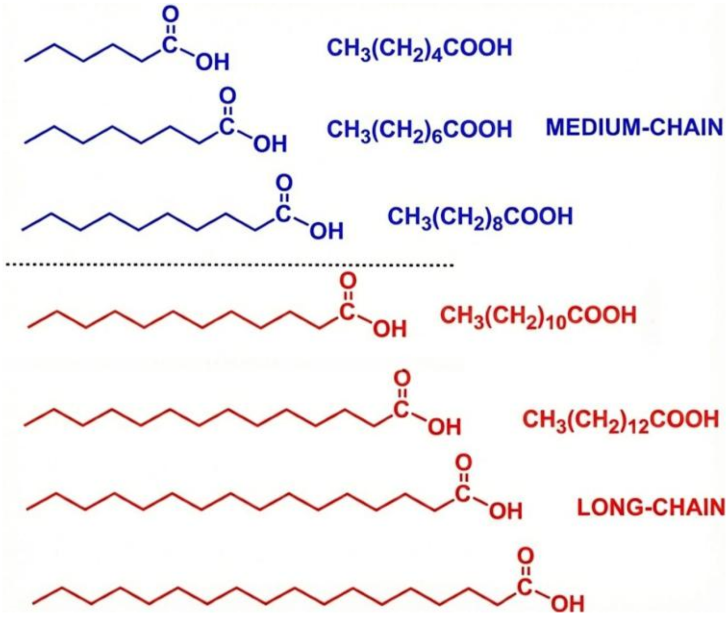


Figure 1: Illustration of fatty acids of various lengths. Fatty acids of 6, 8, or 10 carbon atoms are generally referred as medium chain, adapted from (Marriott, 1994).

The fatty acid arrangement in triacylglycerol (TAG) molecules is highly organised and not randomly arranged. A typical TAG is shown in **Figure 2.** The structural organisation of fat has a considerable impact on the physical and functional characteristics. Short chain fatty acids like butyric acid (C4:0) and caproic acid (C6:0) are typically esterified at sn-3 position of the glycerol backbone. In contrast, saturated fatty acids with longer chains, such as palmitic acid (C16:0) and stearic acid (C18:0), are typically found at the sn-1 and sn-2 positions (Staniewski et al., 2021). The non-random distribution of milk fat influences its melting behaviour and crystallization, which in turn impacts the behaviour of fat during the whipping process. The arrangement of fatty acids within triglycerides (TAGs) is crucial for determining functional properties of cream, including texture, stability, and ability to incorporate air during whipping (Månsson, 2008).

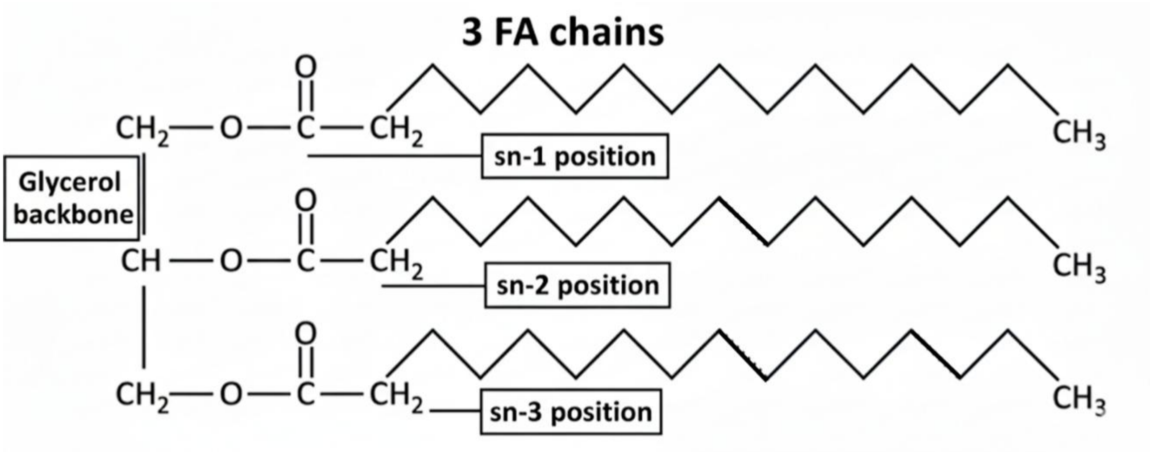


Figure 2: Illustration of triacylglycerol molecule structure, adapted from (Alfieri et al., 2017).

The positional specificity influences the melting properties of fats, with sn2 position exhibiting greater resistance to hydrolysis and consequently affecting the release of fatty acids during digestion and processing. The fatty acids composition in milk is not fixed, it is affected by multiple factors, such as cow's diet, lactation stage and seasonal variations (Baer, 1991). For instance, the proportions of unsaturated C18 fatty acids can be increased by feeding regimes that are high in fresh grass or oilseed supplements, higher levels of short and medium chain saturated fatty acids can be promoted by hay or grazing (Sanjayaranj et al., 2022).

Changes in dietary sources of fatty acids can modify the composition of solid fat content (SFC) in cream, which can impact its crystallization properties and whipping abilities (Liu et al., 2021). Seasonal variations, like between summer and winter, also regulate the fatty acid profile, with winter milk typically showing higher solid fat content levels as a result of higher concentration of saturated fatty acid content (Yener et al., 2021). The melting range of milk fat is decided by the balance between saturated and unsaturated fatty acids, which is important for the partial coalescence of fat globules during whipping process. The greater proportion of solid fat at the whipping temperature facilitates the creation of stable fat network which can capture and stabilize air bubbles, resulting in a preferred foam structure. The melting points of saturated and unsaturated fatty acids are given in **Table 1**.

Table 1: Fatty acids in milk fat and their melting point, adapted from (Bylund, 2003).

Fatty acid	% of total fatty acid content	Melting point °C	Status at room temperature (~25 ºC)
Saturated			
Butyric acid	3.0 – 4.5	–7.9	Liquid
Caproic acid	1.3 – 2.2	–1.5	
Caprylic acid	0.8 – 2.5	+16.5	
Capric acid	1.8 – 3.8	+31.4	Solid
Lauric acid	2.0 – 5.0	+43.6	
Myristic acid	7.0 – 11.0	+53.8	
Palmitic acid	25.0 – 29.0	+62.6	
Stearic acid	3. 0 – 7.0	+69.3	
Unsaturated			
Oleic acid	30.0 – 40.0	+14.0	Liquid
Linoleic acid	2.0 – 3.0	–5.0	
Linolenic acid	Under 1.0	–5.0	
Arachidonic acid	Under 1.0	–49.5	

An excess of liquid fat, which typically arises from high levels of unsaturated fatty acids, can impede partial coalescence and decrease foam stability. The crystallization behaviour of milk fat is closely related to its fatty acid composition, which in turn influences the formation and stability of whipped cream foams (Henderson, 2022). The complexity of milk fat is highlighted by the presence of minor fatty acids and a broad spectrum of chain lengths, extending from short-chain (C4:0) to long-chain (C18:3) species (Briard et al., 2003).

The diversity impacts not only the physical characteristics of the fat but also its sensory attributes and nutritional profile. Previous studies have suggested that the complex fatty acid compositions of milk lipids is a significant factor in determining distinct characteristics of dairy fat (Huppertz et al., 2020). The complexity of this phenomenon extends beyond academic interest, having significant implications for the dairy industry, as it forms the basis for the technological capabilities of cream in whipping process (Dabo et al., 2024).

2.1.2 FAT GLOBULAR MEMBRANE

The milk fat globule membrane (MFGM), also known as the fat globular membrane (FGM) is a complex, multilayered structure which encloses fat droplets found in milk and cream. The membrane originates from apical plasma membrane of secretory cells within the mammary gland, and it is made up of a broad variety of biomolecules, such as phospholipids, glycolipids, proteins, glycoproteins, enzymes, triacylglycerols, and minor constituents like sterols and other amphiphilic molecules. This is shown in **Figure 3**. The structural integrity and composition of the MFGM are important for maintaining the stability of fat droplets within the milk serum phase, as its components act as natural emulsifiers that inhibit the coalescence of fat droplets during storage and processing (Sun et al., 2022).

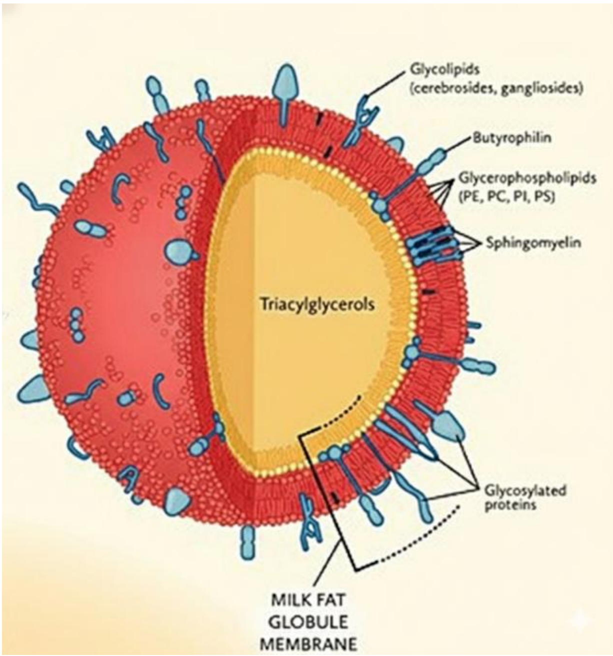


Figure 3: Illustrates the composition of milk fat (Nutrition, 2017).

The diameter of fat globules, which usually falls between 0.2 and 15.0 μm, is mainly influenced by the characteristics of the milk fat globule membrane. The majority of fat in milk and cream is contained within globules ranging between 1.0 and 8.0 μm in diameter, and the structural composition of the membrane, characterized by a rich content of proteins and lipids, is important in preventing the aggregation of these droplets. The amphiphilic nature of the membrane components, especially phospholipids and proteins, allows them to be adsorbed at the oil water interface, thereby decreasing interfacial tension and offering steric and electrostatic stabilization (Sun et al., 2022; Wang et al., 2022).

The stabilization of the emulsion is necessary for maintaining the integrity of the fat globules in the cream, particularly when subjected to mechanical stresses during processing. However, during whipping process, the target is the destabilization of this fat. The milk fat globule membrane's (MFGM) integrity is compromised during whipping due to the incorporation of air and mechanical forces (Wang et al., 2022). For foam formation and stabilization, a partial disruption of the membrane is essential for permitting the partial coalescence of fat globules. Excessive damage or removal of the membrane, that can result from production of AMF (anhydrous milk fat) or excessive shear, can result in a decrease in the stability of the whipped cream foam (McKenna, 2000).

The balance between membrane stability and controlled disruption is critical for optimal whipping performance. The functional properties of the MFGM depend on specific membrane components. Sphingomyelin, for example, plays a role in modulating the membrane's physical properties, adding to its rigidity and resistance to coalescence (Andrade & Rousseau, 2021; Zheng, 2014). Glycoproteins and enzymes in the membrane add complexity, altering how it interacts with other milk proteins and affecting emulsion stability. In previous studies, it is suggested that the unique composition of the MFGM, especially its sphingolipid content, is essential for stabilizing fat globules (McSweeney et al., 2020). Processing conditions like temperature and mechanical treatment can significantly change the structure and composition of the MFGM. For instance, homogenization breaks apart the membrane, which leads to milk proteins, mainly caseins and whey proteins, adsorbing onto the newly formed fat globule surfaces (Yao et al., 2024). By changing the interfacial properties, it is very likely that the whipping characteristics of the cream will be affected.

In recombined creams that use AMF (anhydrous milk fat) as the fat source, the lack of native membrane components leads to changes in emulsion stability and foam properties. The natural phospholipid-protein interface is replaced by a simpler interfacial layer composed of milk proteins and emulsifiers (Andrade & Rousseau, 2021). The stability of the fat globule membrane is crucial for both the shelf life and physical properties of cream, as well as its whipping performance. A stable milk fat globule membrane (MFGM) is important for lasting emulsion stability, while a less stable membrane can encourage the partial coalescence needed for whipped cream and butter making (Goff et al., 2005). The interaction between membrane composition and processing induces modifications, and the functional needs of the final product highlights the key role of the milk fat globule membrane (MFGM) in determining the quality and performance of whipping cream. In summary, the fat globule membrane is a highly complex structure that controls how fat droplets behave in cream. Its composition, integrity, and interactions with other milk components are essential for emulsion stability and creating the desired foam structure during whipping (Andrade & Rousseau, 2021; McSweeney et al., 2020).

2.1.3 FAT CRYSTAL POLYMORPHISIM

A definitive characteristic of dairy fat is the polymorphism of fat crystals, which could directly impact the physical properties and performance of whipping cream. The term polymorphism describes the capability of fat molecules, specifically triacyclglycerols (TAGs), of crystallizing into a variety of distinct solid structures. Each structure has its own specific melting point, stability, and shape. The most significant polymorphic forms in the context of whipping cream are the α, β′, and β forms, as shown in **Figure 4**. The β′-crystal form is particularly desirable because its impact on smoothness of the texture and allows better fat spreadability. The stability and formation of these polymorphs are determined on how TAGs are arranged. This arrangement is influenced by the fatty acid composition and the conditions used during processing. The crystallization and melting behaviour of milk fat is complex. It contains many TAG species that vary in chain lengths and levels of unsaturation (Lawler & Dimick, 2002). This variability results in a wide variety of melting points, as well as the presence of various polymorphic forms within the same fat matrix. The SFC profile, which outlines the ratio of solid to liquid fat at various temperatures, in turn reflects the variety of polymorphs which is essential for the aeration and stability of whipped cream (Zhou et al., 2022).

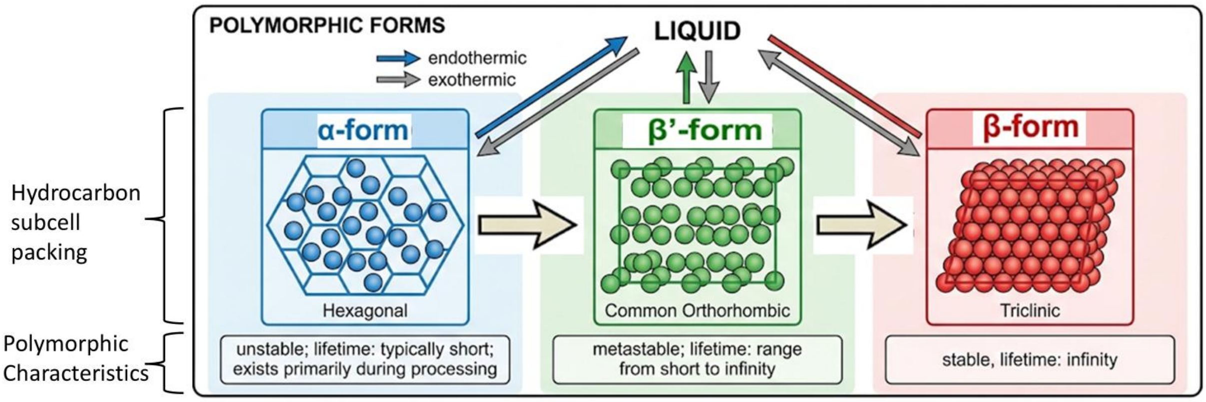


Figure 4: Illustrates polymorphic forms of fat crystals, adapted from (Rogers et al., 2008).

The SFC profile is influenced by both the intrinsic TAG composition and also the crystallization pathway, which can be regulated by cooling rates, degree of supercooling, and the presence of emulsifiers or other minor additives. The process of fat crystallisation in whipping cream begins during cooling, where TAG molecules nucleate and grow into crystals. The nucleation process can be either heterogeneous, taking place at interfaces like the fat-water boundary or between fat droplets, or it can be homogeneous, occurring within the bulk fat phase. The resulting crystal morphology and polymorphic form are very sensitive to the cooling method and the presence of surface-active compounds. Rapid cooling typically results in the formation of the less stable α-form, which can then transform into the more stable β′-form during storage or when warmed gently (Henderson, 2022). The β′-form is particularly significant in dairy applications due its production of small, needle-like crystals. A fine stable network of these crystal forms, which can capture air and water, which enhances foam stability and texture. Seasonal and compositional changes in milk fat also influence polymorphic behaviour (Zhou et al., 2022). The previous studies, it is suggested that incorporating unsaturated fatty acids (UFA), such as linseed, into milk fat results in thicker layers in the crystalline structure. Small-angle X-ray diffraction (SAXD) was used to reveal this. Changes in composition can alter the balance between various polymorphic forms, which impacts the rheological characteristics and whipping performance of cream (Tzompa-Sosa et al., 2016).

In the previous studies, it suggests that we can track seasonal changes in TAG and fatty acid composition using rheological and X-ray techniques. These methods reveal changes in the crystal network and polymorphic distribution (Buldo et al., 2013). The relationship between fat globule size and polymorphism is also important. The authors noted that the size of milk fat globules influences both the crystallisation temperature and the size and type of crystals formed (Panchal, 2020). It also influences the overall solid fat content and rheological properties. Globules, often created by homogenisation, which are typically smaller, can change the nucleation dynamics and results into different polymorphic outcomes that differ from those when compared to larger, native globules (Lopez et al., 2002). The partial coalescence of fat globules during whipping has direct impact on the stability and texture of whipped cream, and is also influenced by the presence and type of fat crystals. Emulsifiers and proteins can further affect polymorphism of fat crystals. The research studies indicate that adding low molecular weight emulsifiers can enhance the stability of fat droplets and alter the interfacial properties, thereby influencing the nucleation and growth of particular polymorphic forms. Emulsifiers might also push proteins away from the fat-water interface, changing the crystallisation environment and potentially encouraging the formation of the β′-form crystals, which helps foam stability. However, adding proteins alone seems to have a limited effect on polymorphic transitions, indicating that their main role is likely in stabilising the initial emulsion and contributing to the foam structure (Henderson, 2022).

The formation and melting points of fat crystals determine the optimal window for whipping, since solid fat is required for partial coalescence and air incorporation, but excessive solidification can impede foam creation. Crystallization conditions can be manipulated by controlled cooling and the use of particular emulsifiers to tailor the polymorphic forms of whipping cream to acquire desired functional properties in whipping cream (Chalermnon, 2013; Liu et al., 2021). In summary, the complex phenomenon of dairy fat crystal polymorphism is influenced by TAG composition, processing conditions and the presence of minor components including emulsifiers. The prevalence of the β′-form is especially beneficial for whipping cream as it provides the necessary structural framework for the formation of stable foam and a desirable texture (Kontkanen et al., 2011).

2.2 DAIRY CREAM TYPES

2.2.1 NATURAL CREAM

Natural cream is a dairy product with its original composition, taken directly from milk and only concentrated by centrifugation. It usually has a high fat content, often around 36%, as seen in products available at supermarkets (Moens et al., 2016). The structure and properties of natural cream depend on the unique qualities of milk fat, which is one of the most complex natural fats due to its varied lipid makeup. Milk fat contains different-length triglycerides unlike other fats such as vegetable oils. This complexity gives it unique functional properties, such as taste and mouthfeel, which are highly valued in making whipped cream (Mohamad Fauzi, 2024).

Natural cream stability and behaviour during processing are strongly connected to the properties of fat globules. These globules are enclosed in membranes, which are very essential for stability against clumping. To give an example, the structural integrity of these membranes is critical to the storage stability of cream but is destroyed when making butter by churning. Moreover, the fat globule size of dairy creams (micron- to nano-scale size) has been proven to have a significant impact on the churnability and general functionality of dairy creams.

The temperature is also a very important factor to define the physical characteristics of natural cream. Research has shown that natural cream can be tempered at certain temperatures to affect its texture and consistency. For example, tempering at 20°C or 30°C changes the crystallisation behaviour of milk fat in the cream matrix and thus affects its rheology and suitability in different applications (Moens et al., 2016).

Seasonal changes in raw cream composition lead to differences in whipping performance. However, regions like California reduce these effects by maintaining consistent herd lactation and cattle feed throughout the year (Bruhn & Bruhn, 1988). The composition of natural cream is closely linked to its performance in food systems. The presence of caseins is key, as they act as natural emulsifiers in homogenized dairy products. Additionally, adding whey protein concentrate (WPC) can change properties such as viscosity and foam formation in low-fat creams. These changes demonstrate how dairy components can be adjusted to meet specific industrial needs (Mulakhudair et al., 2023).

The molecular structure of milk fat in natural cream also affects crystallization during processing. This has been influenced by a variable lipid composition in different length scales, thus the significance of learning the chemical composition of milk fat in the optimization of the quality of the product (Tzompa-Sosa & Arita-Merino, 2022). Dietary or chemical alteration of these factors has opened up possibilities to customize dairy ingredients to suit specific applications, e.g., fractionation to increase the spreadability of butter (Panchal, 2020). Natural cream is still a foundation product in dairy food production, as it is rich in composition and is versatile in functionality. It is a unique blend of triglycerides and proteins that makes it compatible with various applications, besides exhibiting desirable sensory qualities such as taste and texture (Mohamad Fauzi, 2024; Mulakhudair et al., 2023).

2.2.2 RECOMBINED CREAM

Recombined cream is produced by homogenizing anhydrous milk fat, usually skim milk powder, and water, followed by heat treatment to produce a uniform cream similar to natural dairy cream. It may contain additional emulsifiers and stabilizers, to obtain the desired functional characteristics of the product. The process gives more control of what the cream consists of and what its properties are, and this makes it suitable for several industrial applications. The addition of proteins like caseins, is important in emulsion stabilization and in aeration during whipping. These proteins help form a strong interface that supports air blending and improves foam stability (Dabo et al., 2024). Moreover, sodium caseinate can create smooth surfaces in whipped cream systems, which further helps stabilize air-water interfaces (Hanazawa et al., 2018).

The changes of temperature also have a great influence on the physical characteristics of recombined cream in the process as it affects the distribution of particle size in the cream, thereby affecting its whipping capacity. As an example, research has proved that various forms of anhydrous milk fat applied in recombined creams perform dissimilarly at temperatures between 4°C and 15°C. These temperature-sensitive changes affect the texture and volume development during whipping (Wang et al., 2019).

Moreover, the melting curve of recombined creams can be altered by tempering procedures, hence altering their structure and whipping characteristics (Moens et al., 2016). Composition of fatty acids and triacylglycerol (TAG) structure in the recombined cream are also important factors that determine the functionality of the cream. The desirable β′-crystal structures are generated by the presence of asymmetrical TAGs and certain fatty acids and are required to obtain good whipping properties. This crystalline formation enhances whipping aeration and stability of foam (Shin et al., 2021).

Recombined hybrid creams often include vegetable fats like solidified lauric acids, such as palm kernel oil or coconut oil. These fats imitate the short- and medium-chain glycerides found in butterfat. They improve mouthfeel and melting properties while remaining suitable for industrial needs. In many recombined cream formulations emulsifiers are essential in the uniform distribution of fat globules in the water phase. The low molecular weight (LMW) emulsifiers are especially efficient stabilizers of whipped cream systems, lowering the interfacial tension and facilitating partial coalescence during shear as the interface is weakened after protein displacement (Fredrick et al., 2013; Mohamad Fauzi, 2024).

This regulated coalescence is critical in terms of attaining consistent viscosity and texture during the whipping process. The economic importance of recombined creams is linked to their flexibility in food applications. The fact that they can be customized to suit certain purposes, such as aerosol creams and shelf-stable products, adds to their significance in the modern food production systems (Zhou et al., 2020). In general, recombined cream is a complex combination of science and technology aimed at maximising the functionality of dairy products for industrial applications. Its custom-designed composition allows precise control over molecular interactions and structural changes throughout processing stages (e.g., whipping, tempering, and storage) (Dabo et al., 2024; Moens et al., 2016; Mohamad Fauzi, 2024).

2.2.3 UHT CREAM

Ultra-High Temperature (UHT) cream undergoes high-temperature processing to increase its shelf life while keeping its useful properties. The temperature usually gets over 135°C for a few seconds. This process effectively kills bacteria and ensures the cream stays stable for a long time without refrigeration. It also affects the cream structure and composition, especially the fat globules and protein interactions (Bruhn & Bruhn, 1988; Dhungana et al., 2019).

The lactulose content in UHT-treated milk indicates how severe the heat treatment was. Lactulose forms when lactose breaks down due to high temperatures, which can affect the cream's taste and nutritional value. Lactulose is a good indicator of UHT cream's thermal history, as the level of its formation is proportional to how much heat the cream is exposed to. Also, the size of the droplet affects thermal stability in oil-in-water emulsion, including that of dairy creams. Small fat globules are more resistant to destabilisation by heat stress, which is vital in the preservation of the structural integrity of UHT cream during storage and usage (Dhungana et al., 2019).

Temperature change in processing and further use also influences the whipping properties and stability of UHT cream. When UHT treatment is excessive, proteins in the food may denature and fat crystallisation may be altered, and thus the whipping functionality may be impaired (Dabo et al., 2024; Nguyen et al., 2015).

The properties of the UHT cream may also be altered by the addition of emulsifiers or surfactants, which further alter the behaviour of the cream during whipping. It has been established that low-molecular-weight surfactants, apart from protein displacement, may promote formation and penetration of fat crystals at an air-liquid interface during whipping, leading to partial coalescence and foam stabilisation. These emulsifiers combine with milk proteins and natural surface-active components such as milk fat globule membranes (MFGM), maintain a proper distribution of air, water, and oil in the whipped cream systems (Dabo et al., 2024; Nguyen et al., 2015).

In native creams MFGM comprises mostly of phospholipids that do not form strong networks like homogenised or recombined creams. This difference highlights how processing methods can influence the functional properties of UHT cream (Dhungana et al., 2019). Raw cream composition variations that occur seasonally do not make much difference to UHT-treated products if standardisation procedures are followed. For example, California dairies have consistent feed formulations and herd lactation status all year round, and thus variations in raw materials are minimal.

2.3 SEASONAL VARIATIONS IN MILK COMPOSITIONS

2.3.1 EFFECT OF SEASONAL CHANGES ON FAT PERCENTAGE

Seasonal changes significantly influence the fat percentage in milk, which subsequently impacts the properties and behaviour of dairy cream. Variations in fat content are closely tied to environmental factors such as temperature, feed composition, and lactation cycles of dairy cows. Understanding the fluctuations in milk composition, is key for determining the structural and functional properties of whipping cream. Seasonal fluctuations in the milk fat content have been found with higher fat percentage occurring in late seasons than during early and mid-seasons. For example, studies indicate that the fat percentage gradually increases from early to late seasons, with values rising from about 4.74% in early seasons to 5.59% in late seasons. Detailed information is shown in **Table 2**. This rise is due to shifts in cow diets and metabolic changes throughout the year (Li et al., 2022; Linn, 1988).

Table 2: Properties and composition of milk and cream influenced by seasonal variation (adapted from (Li et al., 2022).

Parameter	Season	Mean ± SE	Seasonal variation
Fat-milk (%)	Early	4.74 ± 0.07	Late > Early, Mid
	Mid	4.97 ± 0.11	
	Late	5.59 ± 0.08	
Protein-milk (%)	Early	3.60 ± 0.10	Late > Early, Mid
	Mid	3.83 ± 0.08	
	Late	4.65 ± 0.12	
Protein-cream (%)	Early	2.38 ± 0.05	Late > Early
	Mid	2.51 ± 0.07	
	Late	2.69 ± 0.06	
Fat globule size (D_{43}, μm)*	Early	5.39 ± 0.13	Early > Mid > Late
	Mid	4.52 ± 0.07	
	Late	4.30 ± 0.04	

* D_{43} (volume-weighted mean diameter)

The recent studies, indicate that the changes to the composition of cream have significant impact on its thermal properties and whipping characteristics of cream, highlighting the relationship between the fat content and its functional effects. Milk fat's molecular structure varies with the seasons, impacting its crystallization behaviour and rheological properties (Li et al., 2022). The seasonal variations in the composition also affects the TAG (triglyceride) and fatty acid profile in milk fat, thereby altering its crystallization process. The effects of these changes is significant for understanding how cream behaves during the whipping process, as they impact microstructure and foam stability (Tzompa-Sosa & Arita-Merino, 2022). The crystal network formed by milk fat has been characterized using oscillatory rheology under varying seasonal conditions. The cream from the early part of the season provides the most desirable whipping properties such as faster whipping, higher firmness, and large fat globule size (Li et al., 2022).

The seasonal variation in milk composition is not only for changes in fat content, but also involve alterations in MFG size. Milk produced in early seasons tend to have larger milk fat globule size than milk from later seasons (Li et al., 2022). A decrease in globule size is associated with higher fat concentrations and leads to better emulsification properties during the cream production (Mulakhudair et al., 2023). Such structural changes are significant for optimizing whipping cream formulations that are suited to particular seasonal conditions. Year-round temperature variations make these effects by impacting the melting behaviour of milk fat. Recent research studies show the need to adjusting processing conditions, including temperature profile, to take into account the seasonal variations in milk composition. Protein interaction with fat droplets also plays an important role in maintaining the stability of emulsions in different seasonal conditions. Casein proteins shows strong emulsification properties and whey proteins provide stability as emulsifying agents (Mulakhudair et al., 2023). Increases in protein concentration during seasonal periods, combined with higher fat percentages contribute to improved cream stability by decreasing the surface tension between protein surfaces and fat globule. This synergistic effect is mostly important for recombined dairy cream produced using anhydrous milk fat (AMF) and skim milk under strictly controlled homogenization conditions (Mohamad Fauzi, 2024). The implications of these seasonal variations extend beyond basic compositional analysis; they provide valuable insights into optimising industrial processes for whipped cream production. By understanding how factors such as TAG composition, MFG size, protein-fat interactions, and thermal properties evolve throughout the year, manufacturers can refine their methods to achieve consistent product quality despite environmental variability (Li et al., 2022; Mohamad Fauzi, 2024; Tzompa-Sosa & Arita-Merino, 2022).

2.3.2 IMPACT ON WHIPPING CHARACTERISTICS

The recent studies, indicate that understanding the impact of milk composition on product quality depends on the seasonal patterns (Li et al., 2022). One of the key factors influencing the characteristics of the whipped cream is the temperature. At fridge temperatures (~5°C), cream shows its optimal foaming properties, but its foaming ability decreases greatly at higher temperatures, such as 25°C. The disruption of globule membrane can be linked to the coexistence of liquid and crystalline fat phases.

The adsorption of liquid oil onto the surfaces of bubbles causes instability in these surfaces, which leads to decreasing the stability of foam (Ihara et al., 2010). The size of milk fat globule significantly influences both whipping time and stability of foam. With larger globules whipping time is decreased and a more uniform foam structure is achieved. As evident from the seasonal effects on milk fat globule size, the environmental factors have a significant impact on the characteristics of dairy products throughout the year (Li et al., 2022).

Lactose degradation can be caused by high temperature treatment, resulting in a decrease in pH and the formation of formic acid, which may impact whipping performance indirectly by modifying protein interactions within the cream matrix (Dhungana et al., 2019). Studies have shown that incorporating emulsifiers such as Lactic Acid Esters of Mono- and Diglycerides of Fatty Acids (LACTEM) can alter textural characteristics in aerated systems by enhancing rigidity and brittleness (Allen et al., 2008). At low concentrations, these emulsifiers resemble the texture of whipped dairy cream, indicating their potential use in improving whipping properties across different seasonal conditions (Smiddy et al., 2009).

Milk fat melting fractions are also influenced by variations in fatty acid composition. Higher levels of C16:0 are associated with increased melting points, whereas C18:1 cis-9 exhibits an inverse relationship. Seasonal differences in the composition of organic and conventional milk affect the lowest melting fraction, which in turn has a direct impact on foam formation during the whipping process (Truong et al., 2020).

Improving whipped cream production processes is facilitated by understanding molecular and structural changes. Manufactures can improve product quality at various times of the year by taking into account seasonal variations in milk composition, temperature control and processing techniques.

2.4 EMULSION SCIENCE IN WHIPPING CREAM

2.4.1 OIL IN WATER EMULSION

The structural integrity and functionality of whipped cream relies heavily on the properties of the oil-in-water emulsion formed by stabilizing the fat globules within aqueous phase at the initial dispersion stage. These emulsions are highly dependent on the interaction of proteins and lipids at the oil-water interface, as the protein layer stabilizes the droplets. Milk fat is found in nature as an oil-in-water emulsion, shown in **Figure 5**, stabilised by a distinctive lipoprotein structure *i.e.* milk fat globule membrane (MFGM) (McSweeney et al., 2020). The membrane is very important to ensure the dispersion of fat globules, avoid coalescence, making the emulsion uniform and stable. In recombined cream, the proteins that are adsorbed at the interface play a substantial role in emulsion stability by creating a viscoelastic layer, which decreases interfacial tension. Dairy emulsions can be stabilised using casein proteins and being amphiphilic, they can interact with both hydrophilic water molecules and hydrophobic lipid molecules.

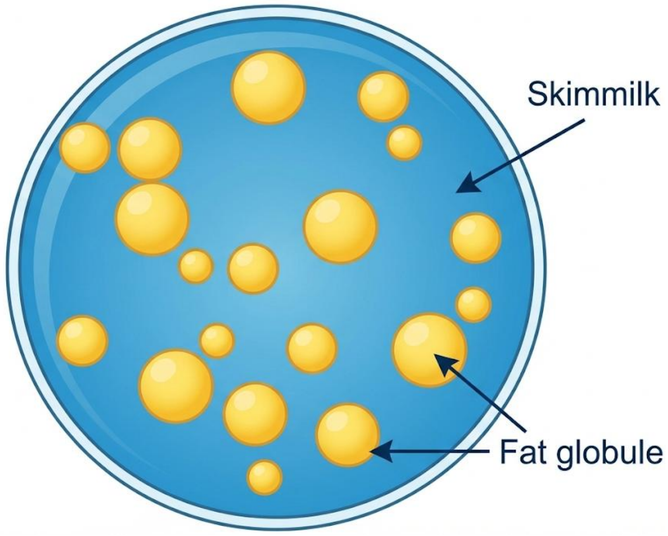


Figure 5: Illustration of oil in water emulsion in milk and cream, adapted from (Bylund, 2003)

These emulsions are stabilized by repulsive forces between the emulsion droplets; attractive forces such as van der Waals, hydrophobic or depletion forces must be overcome by repulsive forces such as hydration, steric and electrostatic forces, all involved in resisting droplet aggregation and subsequent phase separation via creaming (Cheng, 2022). Stabilisation and oil in water emulsions in dairy systems is very much reliant on fat globule properties, and interfacial composition. The native MFGM layer is heavily composed of phospholipids, which can be easily disrupted by shear. Proteins, especially caseins and whey proteins, adsorb onto the oil-water interface, giving electrostatic and steric stabilisation and these protein layers can't be easily disrupted by shear. An example is sodium caseinate which is effective in stabilising oil in water emulsions during homogenisation, with stability being provided by producing electrostatic repulsion and steric hindrance (Hemar et al., 2001). A steric barrier can be further provided by the hydrated polyoxyethylene chains of some emulsifiers, which decreases the probability of droplet coalescence (Liang et al., 2018). Size distribution of fat droplets in the emulsion is a decisive parameter that affects both physical stability and the textural characteristics of the final product. The result of droplet aggregation is the increase in the average droplet diameter, as well as the decrease in the specific surface area of the emulsion. Such a decrease in surface area is a sign of larger aggregates being formed, which may disrupt emulsion stability and change the mouthfeel of the cream (Hemar et al., 2001).

The interaction between the droplet size distribution, droplet surface area and the dynamics of droplet aggregation is therefore key in the understanding of oil in water emulsions behaviour in dairy systems. Emulsifiers are known to be important in the regulation of interfacial properties of the oil in water emulsions. Although some emulsifiers, e.g. sorbitan esters, are not water-soluble, they have a strong affinity with water at the interface. These emulsifiers are able to offer a steric barrier which eliminates the proximity of the oil droplets and the subsequent coalescence of the oil droplets hence making the emulsion stable against aggregation (An & Zheng, 2025). Solid particle stabilization of oil in water emulsions is also observed in Pickering emulsions. Solid particles in such systems are adsorbed at the interface between oil and water, which forms a physical barrier that inhibits coalescence of the droplets and increases emulsion stability (Fuller, 2015). Additional complexity is brought by fat crystallisation in the dispersed phase of oil in water emulsions. Nucleation and growth of the fat crystals in the fat globules may change the rheological properties of the emulsion and affect the behaviour of partial coalescence during whipping (Fuller, 2015).

Studies done by (Henderson, 2022) indicate that effective methods of regulating flocculation in protein-stabilised emulsions require effective strategies to maintain stability during processing and storage. An oil-in-water emulsion is loaded with air during the whipping process, which converts this system into a foam structure. During whipping, there is partial coalescence between fat globules, resulting in the formation of aggregates that increases foam stability. Too much aggregation may however, create hinderance in air incorporation and decrease overrun.

2.4.2 INTERFACIAL CHARACTERISTICS

The nature of the interface is important in defining the stability and properties of emulsions throughout whipping. An interface between air and serum in whipped cream is especially important, as it determines the foam formation and stability. At this interface, proteins and fat globules interact, and this interaction affects the elasticity and structural integrity of this interface. Variations in heat treatment including high-temperature short-time (HTST) pasteurisation have been demonstrated to influence protein composition on the air-serum interface, which may increase foam elasticity and stability (Smith et al., 1999). Another important aspect that influences interface behaviour is adsorption of proteins as well as emulsifiers on the bubble surfaces. Emulsifiers have the potential to compete with proteins to occupy the bubble surface, which changes electrostatic interactions and film stabilization and weakens the interface, making more susceptible to partial coalescence. This competition may result in alteration of firmness during whipping reflected in changes in bubble diameter distribution (Han et al., 2018). These alterations show the importance of molecular interactions at the interface in the regulation of foam properties. The destabilization of fat also plays an active role in the dynamics at the interface. During storage, fat crystal redistribution of secondary fat crystals can take place, which impacts emulsion stability and whipping characteristics (Wang et al., 2025).

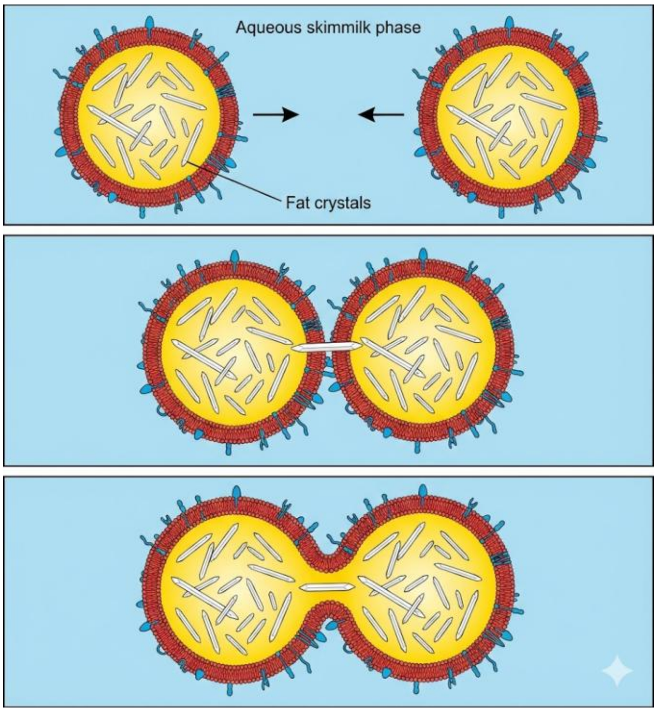
Also, the smaller droplet sizes have been linked to delayed or no crystal formation in droplets, which inhibited partial coalescence and have influence on whipping times. As an example of this, smaller droplet emulsions (0.41 μm) have a whipping time that cannot be detected whereas larger diameter droplets (4.52 μm) whip more effectively (Mohamad Fauzi, 2024). Interface behaviour is also determined by milk fat crystallisation characteristics. The crystallisation of fat molecules and their rearrangement into a different structure influences the surface tension of droplets and the protein adsorption dynamics (Henderson, 2022). Moreover, compositional aspects like percentage of total fat affect formation of films at the air-serum interface. Higher-fat creams have lower leakage rates because they are stiffer and have better overrun during whipping (Scurlock, 1987). Such observation highlights the nature of how the changes in fat content alter the interfacial characteristics and enhance the foam stability. Surface tension measurements also give further details of interfacial dynamics during storage. Alterations in emulsion microstructure are demonstrated by alterations in the physicochemical properties such as zeta potential and chemical interactions at the interface over time (Xu et al., 2022). These results highlight the fact that storage and compositional considerations are complex factors that influence interfacial behaviour. Lastly, proteins and emulsifiers play an important role in ensuring interfacial properties remain constant during processing. Their existence affects the distribution of droplet size, interactions of proteins at the bubble surfaces and the structure of the entire foam after whipping (Tamime, 2009). These additives make the production of the whipped cream homogeneous by maximising the molecular interaction at the interface. Overall, the interaction between proteins, fats, and emulsifiers, on interfaces offers helpful information in managing microstructural alterations at the whipping stage. Such interactions at the molecular level are vital in creating stable foams with desirable textural properties of multiple formulations (McSweeney et al., 2020).

2.5 PARTIAL COALESCENCE

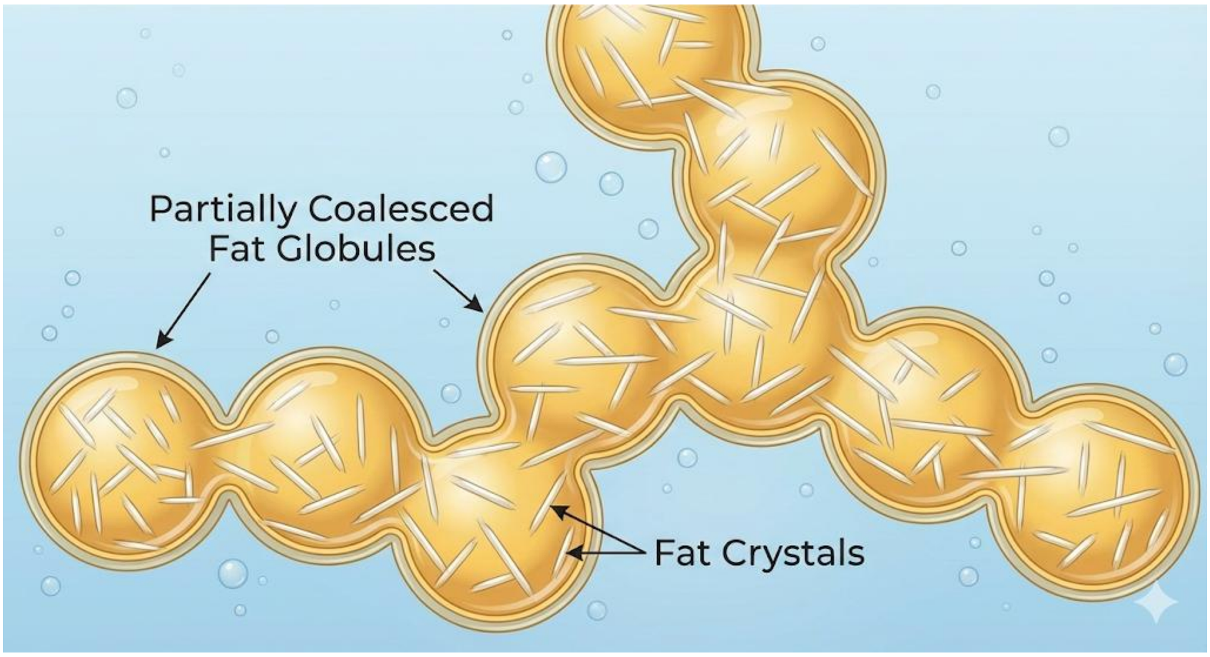
2.5.1 DEFINITON AND PROCESS

In oil in water emulsion, the coalescence of two globules can occur due to the film between them breaking apart, resulting in their merging. This phenomenon is referred to as coalescence. Incomplete coalescence may occur when crystals are present in the oil phase, as the crystal structure can hinder the globules from merging completely. Lumps of different sizes and shapes are formed (Boode & Walstra, 1993). The partial coalescence mechanism is shown in **Figure 6.**

Partial coalescence is an important phenomenon during whipping of cream, where fat globules interact and destabilise to produce a network that traps air bubbles and the aqueous phase. This is an essential mechanism, key to obtain the texture and structure needed in whipped cream. Initially, the emulsion is whipped in, introducing air into the milk system, which destabilises the milk fat droplets under the influence of shear and the presence of fat crystals. These destabilised droplets partially merge to form a structural matrix in which air bubbles get trapped, which stabilises the foam (Mohamad Fauzi, 2024). The partial coalescence process starts with the interaction of the fat globules in the presence of mechanical agitation. Fat crystals found in these globules are important to triggering the process of coalescence by offering rigidity and the ability of droplets to interact, as shown in the systematic representation of partial coalescence below.



(a)



(b)

Figure 6: Illustration of the (a) partial coalescence mechanism and (b) network of partially coalesced fat globules, (straight lines within the globules are fat crystals), Adapted from (Fuller, 2015; Goff, 1997).

The process of maturation before whipping, i.e., the storage of cream at temperatures between 4°C and 10°C for at least 24 hours, favours the crystallisation inside fat droplets and thereby enables them to undergo partial coalescence during whipping (Dabo et al., 2024). Shear forces that occur during whipping, also contribute to this effect, as they cause the disruption of emulsified fat droplets allowing them to aggregate. The other factor that has a significant effect on partial coalescence is temperature. An increase in whipping temperature, which is normally between 5°C and 15°C, decreases the solid fat content in the emulsion. Such reduction of solid fat may decrease functionality due to the reduced level of partial coalescence necessary to be achieved in order to produce foam stability. Fat content is also important in the entrapment of air bubbles, and therefore whipping in the correct range of temperature is important in producing maximum overrun and firmness of the foam (Henderson, 2022).

Faster cooling rates have been shown to support partial coalescence more effectively by increasing interactions between fat globules at the air-water interface (Nguyen et al., 2015). The changes in structure during whipping are also affected by compositional factors like fat percentage, emulsifiers, and particle size distribution. Low-trans vegetable fat formulations behave differently depending on whether partial coalescence needs to be promoted or avoided. For example, these formulations tend to experience partial coalescence during processes like whipping, but they resist destabilization from thermal fluctuations because of their lower solid fat content (Henderson, 2022).

Tempering techniques can also be used to improve shear-induced partial coalescence in systems where the product formulation makes this difficult. Microscopic studies show that partial coalescence is a key destabilization mechanism during whipped cream production. However, it is important to differentiate it from other processes like flocculation or true coalescence that can occur at the same time under certain conditions. Factors such as protein release during centrifugation or infrequent encounters between fat globules can affect these processes and influence overall foam stability (Fredrick et al., 2013; Henderson, 2022).

The development of partial coalescence at various stages of whipping is well documented. In the beginning, proteins temporarily stabilize air bubbles before getting replaced by partially coalesced fat droplets as whipping continues. This shift marks the formation of a stable foam structure with maximum overrun values. Additionally, changes in parameters like the air-to-cream ratio during production fine-tune foam characteristics such as firmness and bubble volume fraction (Drelon et al., 2006). Overall functionality heavily depends on maintaining a good balance between compositional elements and processing conditions. For example, stabilized whipped creams show bigger bubble sizes and greater lamella length at the top of foams because of added stabilizers. These changes lead to a decrease in air volume in foams but improve structural integrity (Smith et al., 1999).

2.5.2 FACTORS INFLUENCING PARTIAL COALESCENCE

Partial coalescence is an important process in whipping cream. Here, fat globules interact under mechanical and thermal conditions to create interconnected networks. Several related factors influence this process, including droplet size, temperature, shear forces, air incorporation, and the presence of emulsifiers. the rate and degree of partial coalescence are influenced by the size of fat droplets. Compared to larger droplets, smaller droplets exhibit distinct nucleation processes and crystallization rates. The variations in structure and type of fat crystals within the emulsion are influenced by these differences, which in turn influence the whipping properties of cream (Han et al., 2018; Mohamad Fauzi, 2024). The recent studies, suggests that smaller droplet sizes enhance stability during whipping. These differences influence the structure and types of fat crystals within the emulsion, which, in turn, affects the whipping properties of cream (Mohamad Fauzi, 2024).

Temperature cycling also significantly affects partial coalescence. Changes in temperature can alter crystal growth and structure within fat globules, making them more or less likely to coalesce. In high-protein emulsions experiencing temperature changes, protein can move away from the oil-water interface, which increases the sensitivity to partial coalescence (Han et al., 2018; Petrut et al., 2016).

Tempering conditions further modify whipping behaviour by affecting shear-induced coalescence. The shear forces applied while whipping are crucial for destabilizing fat globules and encouraging their aggregation into networks. Studies on rheology have shown strong connections between shear-induced deformation and partial coalescence. While rheology gives a general understanding of this destabilization mechanism, it does not provide direct confirmation or measurement of partial coalescence (Petrut et al., 2016).

The dynamics of partial coalescence are also contributed by air incorporation during the process of whipping. The way air bubbles interact with fat globules affects how well these bubbles are captured in the emulsion matrix. Poor coverage can occur when too much aggregation is formed limiting effective development of the network as experienced in recombined creams where the air bubbles do not promote partial coalescence (Smith et al., 1999). Emulsifiers like lactic acid esters of mono- and diglycerides (LACTEM) improve fat destabilization during whipping by encouraging irreversible aggregation of crystalline droplets. This change contrasts with the protein-protein bonding seen in emulsifier-free systems. It shows that emulsifiers actively shape foam stability through molecular interactions (Allen et al., 2008; Mohamad Fauzi, 2024). Moreover, the composition of milk and changes in fatty acids directly affect solid fat content and the morphology of crystals in cream emulsions. The variations of high-melting-point fats (SMFG) and low-melting-point fats (LMFG) have an impact on the whipping time because of their influence on the kinetics of partial coalescence. Fat content also interacts with protein content to regulate the viscoelastic property as measured by the storage modulus (G') in whipped cream (Dhungana et al., 2019). Together, these factors control the complex interactions between molecular arrangements, structural changes, and mechanical forces during partial coalescence, which is a key process in making whipped cream.

2.6 WHIPPING PROCESS: MECHANISIMS AND MOLECULAR EVENTS

2.6.1 INITIAL STATE STRUCTURE AND COMPOSITION OF WHIPPING CREAM

The whipping cream in its initial state can be described as a complex colloidal system in which fat globules are suspended in water, stabilized by a mixture of proteins and, in some instances, added emulsifiers. Several factors, such as fat content, fat crystallization, fat globule membrane composition and structure, and others such as proteins and emulsifiers, determine this system's physical and molecular properties (Dabo et al., 2024; Henderson, 2022). The proportion of these ingredients is vital to the incorporation and stabilization of air during the whipping of the cream. The fat globules of fresh cream are normally covered by a native milk fat globule membrane (MFGM) made up of phospholipids, proteins, and glycoproteins. It provides stabilizing effects that prevent early coalescence and clumping of the fat globules and keep the emulsion in a nearly stable state. The integrity of the MFGM is especially important, as it affects the cream's flow properties and its ability to whip well.

In previous studies, it suggests that creams with an intact natural MFGM have greater ability to change its structure and function than homogenized creams. This difference is due to the preservation of the membrane structure (Dhungana et al., 2019).

The fat phase in the initial state is not entirely liquid; it contains a mix of solid and liquid triglycerides. The ratio between these is determined by temperature and the specific fatty acid makeup of the cream. Solid fat content, or solid fat index, is a key factor because it influences how fat globules can partially merge during whipping, a necessary step for foam creation and stability.

In the research done by (Rousseau et al., 2005), the authors noted that the melting points and polymorphs of the fat phase are important for defining the cream's ability to whip. Temperature plays a key role at the start since it influences the fat crystallization level and the thickness of the continuous phase. Creams stored at reduced temperatures usually have a greater solid fat percentage that can enhance the partial coalescence of the fat globules during whipping but can also raise thickening and reduce flow (Riaublanc et al., 2005).

On the other hand, increasing the storage temperatures can lead to an increased level of liquid fat, which can decrease the capacity of the cream to entrap and stabilise the air bubbles. The cream consists of an aqueous phase, in which proteins, mainly caseins and whey proteins, are dissolved, playing a role in emulsion stabilisation and subsequent bubbles of air after whipping. Low molecular weight emulsifiers, whether added or naturally present in the food, may regulate the fat globule's stability by facilitating the desorption of proteins on the fat globule surface, thus allowing controlled aggregation during whipping. This principle is also utilised in many dairy applications in order to customise the behaviour of aggregation of fat globules.

Processing conditions (including homogenisation, heat treatment (e.g., UHT), and recombination) also affect the initial microstructure of the cream. The homogenization process destroys the native MFGM, leading to smaller fat globules with a protein-enriched surface that may change the whipping properties of cream and lower its plasticity (Dhungana et al., 2019). UHT treatment and recombination processes may further change how proteins and fat globules interact, affecting the stability and whipping performance of the cream. In the initial state, the stability of the emulsion relies on a precise balance of intermolecular forces. These forces include hydrogen bonding, hydrophobic interactions, ionic bonds, and disulfide bridges among proteins and between proteins and fat globules (Dabo et al., 2024).

Milk fat compositions vary with the seasons so do processing and formulations, which can make the starting point of whipping cream very different. These differences are expressed in differences in fat crystallization behaviour, emulsion stability, and finally, the ability of the cream to be whipped to a stable foam (Dabo et al., 2024; Riaublanc et al., 2005).

The melting thermograms of different cream types, as noted authors suggests that the melting profiles of anhydrous milk fat (AMF) and other lipid fractions vary depending on their physical state (bulk, emulsified, or whipped) and crystallization history (Flaviu et al., 2016). In conclusion, the starting conditions of the whipping cream determined by the interactions between fat globule structure, fat crystallization, protein composition, and processing history establish the environment for the follow-up molecular processes during whipping. The capability of the cream to change its stable emulsion state to the stable foam system, can be traced to the structural and composition properties set before the process of whipping (Dabo et al., 2024; Dhungana et al., 2019; Henderson, 2022).

2.6.2 SHEAR-INDUCED PARTIAL COALESCENCE

Shear-induced partial coalescence plays a key role in transforming dairy cream into a stable foam during whipping. This process involves the partial clustering of fat globules, creating a structure that gives the whipped cream stability (Mohamad Fauzi, 2024; Xu et al., 2022). It begins when mechanical shear, such as that from whipping, breaking the natural milk fat globule membrane (fresh cream) or the mixed protein/emulsifier layer membrane (UHT cream). The presence of solid fat crystals within the globules is vital. These crystals serve as anchors that help form connections between nearby globules, resulting in partial coalescence rather than complete merging (Xu et al., 2022).

Several factors influence the process of shear-induced partial coalescence, including the degree of fat crystallization, the size of fat globules, and the presence of emulsifiers and proteins. The solid fat content (SFC) is especially important (Moens et al., 2018). A sufficient amount of solid fat is necessary for forming stable aggregates, while too much liquid fat can prevent network development and weaken foam stability. The temperature of the cream can rise during whipping, which decreases the SFC and may limit the degree of partial coalescence. This change can ultimately affect both the texture and stability of the finished product(Henderson, 2022).

Mechanical shear not only breaks the fat globule membrane but also adds air into the mixture. The introduction of air bubbles is closely associated with the partial coalescence process. Partially coalesced fat globules can position themselves at the air-water interface, helping to stabilize the new bubbles (Henderson, 2022). Creating a network of fat globules around the air bubbles is crucial. This network prevents bubble merging and collapsing, which contributes to the volume and firmness of the whipped cream. The ability of fat globules to stick to and stabilize air bubbles improves with the presence of fat crystals, which provide necessary structure and interfacial activity (Dabo et al., 2024).

The interplay between shear-induced and air surface-mediated partial coalescence is complex. Both mechanisms help form the fat network, but shear-induced partial coalescence mainly relies on mechanical forces. In contrast, surface-mediated events depend on the interactions at the air-water interface (Fuller, 2015). According to (Moens et al., 2018), the relative roles of these mechanisms vary with processing conditions, and with the composition of the cream, e.g. the type of fat, the inclusion of emulsifiers, and the particle size distribution. The sensitivity of shear-induced partial coalescence to these factors highlights the need for careful control over formulation and processing parameters to achieve the best whipping performance.

Rheological methods that replicate the mechanical shear stresses during whipping tend to be adopted to investigate shear-induced partial coalescence. For example, a stress-controlled rotational rheometer with a concentric cylindrical cup allows for real-time monitoring of partial coalescence kinetics in the presence of air (Fredrick, 2011). This setup try to mimic the conditions of traditional whipping. This method offers insights into the changing fat network and how air incorporation affects the process. The structural effects of shear-induced partial coalescence are clear in the microstructure of whipped cream. Confocal microscopy shows that partially coalesced fat globules create a continuous network that traps air bubbles, with free fat droplets often seen attached to the bubble surfaces (Henderson, 2022; Mohamad Fauzi, 2024).

This network gives whipped cream its unique stiffness and volume, as well as its ability to resist drainage and collapse. The degree and type of partial coalescence can be adjusted by processing factors like cooling rate. Faster cooling encourages the formation of solid fat crystals, which increases the likelihood of partial coalescence during later whipping (Xiao, 2020). The effects of shear-induced partial coalescence impact the stability and sensory qualities of whipped cream. Too much or too little partial coalescence can result in issues like syneresis, graininess, or weak foam stability. The ratio of solid to liquid fat, the presence of proteins and emulsifiers, and the management of processing conditions are all vital for creating a stable foam. In addition to this, the complexity of milk fat composition—with a wide melting range as a result of the wide range of triacylglycerols, also makes difficult to predict and control the occurrence of partial coalescence (Fredrick, 2011; Mohamad Fauzi, 2024).

To conclude, shear-induced partial coalescence is a complex phenomenon that is controlled by the interaction of mechanical, compositional, and thermal factors. The primary importance of stability and formation of whipped cream foams underlines the necessity to have a comprehensive knowledge of the mechanism of molecular and structural changes and how the ingredient and process variables affect the ultimate quality of the product.

2.6.3 AIR INCORPORATION AND BUBBLE FORMATION

Air incorporation during the whipping of cream is a process that changes a liquid mixture into a stable foam by trapping air within a network of partially combined fat globules and proteins. The first stage of whipping involves mechanically introducing air into the cream, which leads to a coarse foam with relatively large air bubbles, usually around 150 μm in diameter. Shown in **Figure 7**. These air bubbles are very quickly coated with milk proteins, which adsorb at the air-water interface and have a very important role to play in preventing the immediate collapse of these air bubbles (Deosarkar et al., 2016). The proteins are surface-active agents, which lower the surface tension and give a protective film that slows down coalescence of the bubbles (Xiao, 2020).

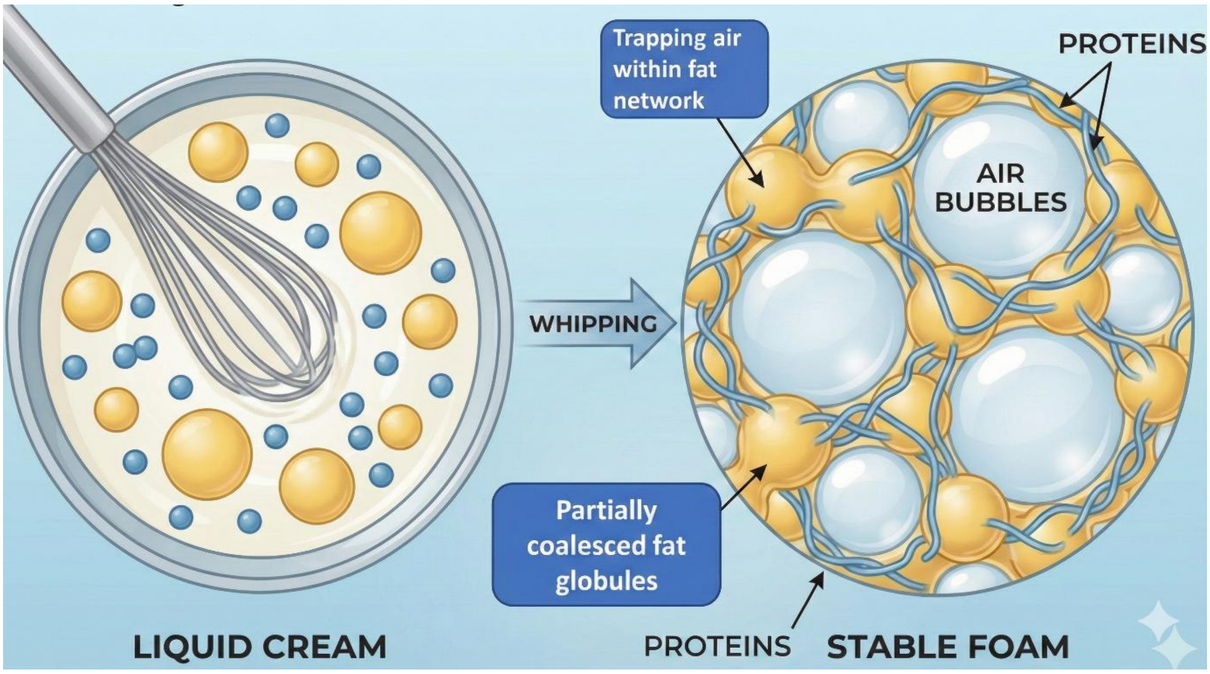


Figure 7 : Schematic representation of the mechanism of air incorporation and foam stabilization during cream whipping.

The emulsion must also be destabilized in order to incorporate air effectively. It happens due to partial coalescence of fat globules that is caused by the existence of both solid and liquid fat phases in the globules (Goff, 1997). During the process of whipping, mechanical shear and deformations of fat globules that contain crystalline fat, favour the formation of a network structure. This network fixates the air bubbles and the serum phase, giving it the trademark texture and consistency of whipped cream. The partially fused fat globules easily adsorbed around the air bubbles improving foam stability by acting as a barrier to gas diffusion and bubble merging. The size distribution of the air bubbles and their stability are affected by a number of factors, such as protein content, the casein-to-whey protein ratio, and the emulsifiers (Dabo et al., 2024).

As an example, increasing the concentration of protein may result in smaller and more uniformly distributed air bubbles, as proteins have a higher potential to stabilize newly formed interfaces. The stability of the foam may be controlled by manipulating the foam with a mixture of emulsifiers and stabilizers, which may either encourage the emulsion to destabilize in the process of whipping or increase foam stability during the storage and changes in temperature (Hunter et al., 2008). The interaction of these ingredients on the oil-water interface is significant in the prediction and regulation of the ultimate foam structure. Another factor that determines the efficiency of the incorporation of air is fat crystallization (Pilhofer et al., 1994). The crystalline form of the fat affects the capacity of fat globules to partially merge to create a network that can trap air. β'-crystals, e.g., are found to be related to numerous small bubbles and a larger overrun; β crystals lead to a smaller air inclusion and therefore smaller foam volume (Ogden & Rosenthal, 1998).

Fat crystallisation, which is adjusted with temperature and the addition of surfactants, may favour or impede the development of the protective fat layer covering air bubbles (Ghosh & Rousseau, 2011). Whipped cream prepared at reduced temperatures, e.g., 5°C, has better foaming ability because the liquid and crystalline fat coexist and enhance membrane disruption and effective air trapping. However, at higher temperatures, such as 25°C, foaming decreases significantly. This is likely due to the larger presence of liquid fat and the instability of the air-bubble interface (Gowida et al., 2023).

Bubble formation, breakup, and coalescence are very dynamic processes. They are influenced by how closely fat-globule-coated bubbles are packed within the foam. The interactions between the fat globules, proteins, and the air incorporated determine the maximum packing density and the consequent foam structure (Van Aken, 2001). The physical forces exerted during the whipping process not only add air but also allow fat globules to rearrange and partially coalesce, and this is critical to the formation of a stable foam network (Du et al., 2021).

One of the parameters, important in determining the efficiency of the whipping process, is the overrun— the rise in volume as a result of incorporating air. The overrun is affected by the viscosity of the serum phase, the rate of air incorporation and the resistance to shear during the whipping process (Xiao, 2020). The overrun may also be reduced by stabiliser blends, which increase the viscosity of the serum, thus making it more difficult to shear, and reducing the air that gets entrapped in the serum during the whipping process, resulting in longer whipping times and possibly influencing foam stability. Leakage of the serum, *i.e.*, the release of liquid out of the foam, is an indicator of foam instability, and it is especially important in industrial use (Xiao, 2020).

The size and elasticity of fat droplets also regulate the structural development of the foam. Addition of some ingredients, including Insoluble Soybean Fiber (ISF), can reduce the size of fat droplets and will increase the elastic modulus of the foam initially, thus strengthening the network structure and improving foam stability (Dabo et al., 2024). Yet too much partial coalescence or the wrong choice of ingredients may jeopardise long-term stability, which is why formulation and processing conditions should be tightly controlled. The acidity of cream before its pasteurisation may also affect the speed of the whipping process and the homogeneity of gas bubble distribution, which means that even slight compositional modifications can alter the dynamics of air incorporation. The interaction between the functionality of ingredients, product processing conditions, and the physical chemistry of the emulsion finally defines the success of air incorporation and the quality of the resulting whipped cream foam (Dabo et al., 2024).

2.6.4 NETWORK FORMATION AND FOAM STRUCTURE

The formation of the network of the whipping of cream occurs dynamically and is dependent on the interaction of fat globules, proteins, and emulsifiers that all together stabilize the air bubbles and determine the structure of the foam. The first phase of whipping involves the incorporation of air into the cream, resulting in air bubble dispersion into the continuous aqueous phase. These bubbles are also stabilized by an important adsorption of proteins and then, the partly coalesced fat globules on the air-water interface, and this combination creates a viscoelastic film that prevents the collapse of bubbles (Dabo et al., 2024). The result of this process is the three-dimensional network that entraps the air and water to provide rigidity to the foam (Liu et al., 2021).

The network is mainly formed through fat globules. Having different sizes and surface properties, they affect the kinetics of the developing foam and its stability. The smaller fat globules have a better surface area-to-volume ratio and offer better steric stabilization which decreases creaming, flocculation and coalescence rates in the emulsion, and they tend to result in a more stable foam structure (Cui et al., 2025). The fewer interfaces that systems with larger globules have enable a more efficient entrapment of air bubbles and a stronger network design. Another important factor is the crystallization of fat inside the globules. Partial coalescence of fat globules is encouraged by the presence of crystalline fat, and it is promoted as the whipping process continues due to the mechanical effect of whipping. The nature of fat crystals that form this network is also seen to affect its strength and integrity (Liu et al., 2021; Rogers et al., 2008).

Proteins, especially casein micelles, are adsorbed in the air-water interface and bind to fat globules to make the foam more stable. Protein adsorption and interfacial film cohesion are essential attributes of proteins to retain the integrity of the foam during and after whipping (Dabo et al., 2024). This compact packing minimizes foam destabilization processes, but too much clustering through coagulation should be prevented, since it may cause sedimentation and loss of foam stability. Another factor that determines the foam structure is the strength of the oil-water interface film. Greater interfacial films (e.g., formed by some protein-based microgels) cause fat semi-coalescence to occur more slowly and in a more controlled manner, increasing bubble stability over time.

Conversely, poorer interfacial films would cause coalescence and formation of large aggregates, quickly reducing foam stability. Processing conditions also have an effect on the formation of networks, including temperature and the presence of stabilizers. When manufacturing whipping cream, stabilizing agents can be added before the heat treatment in order to maximize the effective formation of the fat-protein network when whipping the cream. A partially coalesced cohesive network is necessary in trapping air and water in order to give the desirable texture and stability of whipped cream products.

2.7 ROLES OF MAJOR COMPONENTS DURING WHIPPING

2.7.1 ROLE OF FAT GLOBULES

The stabilization of air bubbles in whipped cream is a dynamic process governed by the coordinated interactions of proteins, fat globules, and emulsifiers at the air-water interface. While proteins initially adsorb to form a temporary protective film, long-term foam structure relies on the partial coalescence of fat globules, where liquid fat spreads to reinforce the interfacial layer (Henderson, 2022; Van Aken, 2001). This mechanism is heavily influenced by globule size and crystallization state; larger droplets typically accelerate partial coalescence and network formation, while smaller droplets regulate crystallization rates and emulsion stability (Ihara et al., 2010; Mohamad Fauzi, 2024). Ultimately, the displacement of proteins by fat agglomerates—facilitated by emulsifiers—and the compression of adhered globules during bubble shrinkage establish a robust, mixed interfacial network that defines the foam's final stiffness and textural quality (Peng et al., 2018; Wei et al., 2023; Xiao, 2020).

2.7.2 ROLE OF FAT CRYSTALS

Partial coalescence in whipped cream is primarily facilitated by fat crystals present in the interface of fat globules, which provide the rigid structure necessary to bridge fat globules during aeration. These crystals protrude from the droplet surface, acting as anchors that interlock upon collision, a mechanism heavily dependent on crystallization conditions and temperature cycling that drive crystal migration to the interface (Fredrick, 2011; Henderson, 2022). The efficiency of this process is further determined by the structural disorder and surface roughness of the globules; specifically, crystalline bulges act as hotspots for aggregation, enhancing the trapping capacity and mechanical interlocking required to form a stable, dense network (Moens et al., 2018).

2.7.3 ROLE OF PROTEINS

While the partial coalescence of fat globules builds the necessary structural framework for air entrapment, proteins are essential for stabilizing this network by establishing a robust viscoelastic film at the air-water interface. This protective barrier is dynamically regulated by competitive adsorption between proteins and low molecular weight surfactants, such as mono- and diglycerides; although these smaller molecules are more surface-active, a high protein-to-surfactant ratio is required to maintain interfacial viscoelasticity and prevent total displacement (Chen et al., 2025; Zhang & Goff, 2004). Furthermore, higher protein concentrations facilitate the formation of thicker lamellae around air bubbles, thereby reinforcing the mechanical barrier against coalescence and enhancing the overall stability and textural integrity of the foam (Rouimi et al., 2005; Xiong et al., 2020).

2.7.4 ROLE OF AIR BUBBLES

The incorporation and stabilization of air bubbles during whipping are fundamental to the structural integrity and sensory attributes of the final product. Primarily, the inclusion of gas is essential to create the characteristic foamy structure typical of these aerated systems. During the process, agitation mechanically entraps air and fractures large voids into a fine dispersion. This phase establishes the initial air volume, while continued whipping primarily serves to refine the bubble size distribution (Dabo et al., 2024).

The size of the air bubbles significantly influences the perceived density and texture of the foam. A distribution of small, uniform air bubbles generally results in a smoother, creamier texture and a more stable foam, whereas larger bubbles can lead to a coarser mouthfeel and reduced stability. This relationship is quantitatively described by the "overrun," which measures the percentage increase in volume caused by the incorporated air. In dairy foams, the overrun and bubble size distribution are critical quality parameters; they directly dictate the lightness of the final product and how the foam behaves both rheologically and on the palate.

However, long term foam rigidity and resistance to drainage are ultimately enforced by a network of partially coalesced fat crystals enveloping the air bubbles and the viscosity-enhancing effects of serum phase are obtained by adding stabilizers like certain hydrocolloids or additional proteins. (Fredrick, 2011; Xiao, 2020).

Chapter 3: MATERIALS AND METHODS

3.1 MATERIALS

The commercial fresh cream used in this research is Pam's fresh cream which was purchased from a local supermarket (PAK'nSAVE) in Palmerston North, New Zealand. The commercial cream was purchased with a minimum of one week remaining before its expiry date. The fresh creams were stored at 4°C, at least for 24hrs, before use.

The compositional information for Pam's fresh cream as provided by manufacturers is shown in **Table 3**.

Table 3: Compositional information of Pam's fresh cream in average quantity per 100ml.

Composition	**Average quantity per 100 mL**
Protein	2.4 g
Fat (total)	36.3 g
Saturated fat	24.0 g
Carbohydrate	3.1 g
Sodium	26 mg

3.2 METHODS

3.2.1 CREAM CHEMICAL COMPOSITION

The composition of fresh cream was measured using a MilkoScan™ FT1 (Foss Electric A/S, Hillerød, Denmark). An aliquot of 50 ml of cream was diluted with water on a weight/weight basis (*i.e.* cream to water ratio of 1:1). The sample was warmed in a water bath at 40°C for 30 minutes prior to the measurement. Fat, protein, TS (total solids) and SNF (solids non-fat) were measured.

3.2.2 WHIPPING PROCEDURE

A benchtop mixer (Kenwood, Kenwood Electronics, KM200) was used for whipping the fresh cream. The fresh cream was whipped at maximum speed. The temperature of the cream was controlled by storing the fresh cream at 4°C, at least for 24 hrs before whipping. To maintain temperature, both the beaker and the whisk were stored inside the walk-in refrigerator at 4°C for at least 30-60 minutes before whipping. The whipping experiments were done in triplicates and were performed until the fresh cream was turned into butter.

3.2.3 TORQUE VS TIME ANALYSIS

The acquisition of torque vs. time graphs was a key target in this research. Monitoring the torque changes helps in quantifying and visualising the mechanical changes happening in the cream during the whipping process. By measuring the resistance (torque) from the cream against the whisk over time, this method captures the real-time shift from a liquid emulsion to a semi-solid foam, and then, to foam destabilisation and butter formation. It offers a straightforward and reliable way to determine essential rheological milestones, as observed from **Figure 8**, where the following parameters can be defined:

- Optimum whipping time (this refers to the optimum duration required to achieve the desired consistency or quality during the whipping process) and it is variable with samples. This determination is based on the formation of defined, firm, sharp peaks in the foam. An ideally whipped sample will possess a firmer, self-sustaining structure supported by a stable foam network, characterized by well-defined rounded edges and mountain-like formations.
- Peak torque (this is the maximum torque exerted during the whipping process).
- Peak width (The peak width was determined based on the temporal profile of the torque measurements. The time required to reach the maximum torque value is designated as t_{peak}. The peak width is defined as the interval spanning 10% before and 10% after this peak time. Shown in **Equation 1** and **Equation 2**. The starting point (t_{start}) and ending point (t_{end})of the peak width are calculated as follows:

$$t_{start} = t_{peak} - (0.10 \times t_{peak}) \qquad \textit{Equation 1}$$

$$t_{end} = t_{peak} + (0.10 \times t_{peak}) \qquad \textit{Equation 2}$$

  Consequently, the Peak Width corresponds to the duration between (t_{start}) and (t_{end}).
- To accurately describe the rheological changes during the whipping process, a mathematical model Y_{fit} (mN.m) was developed to fit the experimental torque (mN.m) data up to the inflection point. The final constitutive equation used to model the torque evolution is:

$$Y_{fit} = A\left(1 - e^{\frac{-t}{\tau}}\right) + B(e^{kt} - 1) \qquad \textit{Equation 3}$$

Where:

- **A**: Height of the asymptote (mN.m) (representing the magnitude of the initial viscosity build-up).
- $\boldsymbol{\tau}$: Exponential time constant (sec), (characterizing the rate of the initial response).
- **B**: Amplitude of the exponential growth component (mN.m).
- **k**: Exponential growth coefficient (s^{-1}).
- **t**: Time (sec).

The development of this equation followed a stepwise refinement process to capture the distinct phases of the whipping curve:

1. **First-Order Response (Early Stage):** Initially, the early portion of the data (0–20 s) was modelled using a standard first-order response, $Y_{fit} = A\left(1 - e^{\frac{-t}{\tau}}\right)$. This term describes an exponential approach to an asymptote, resulting from a first-order differential equation, which effectively captures the initial rapid increase in torque as the whisk engages the fluid.

2. **Limitations of the First-Order Model:** As the whipping duration extended beyond 40 seconds, the simple first-order model proved insufficient. The experimental data did not plateau at an asymptote as predicted; instead, the torque trend continued upwards. Simply adding a linear slope to the model improved the fit for intermediate times but failed to capture the non-linear acceleration of torque observed as the foam structure began to stiffen significantly.

3. **Inclusion of Exponential Growth:** To accurately model the data up to the inflection point (approximately 82 s), shown in **Figure 8**. The linear term was replaced with an exponential growth term: $B(e^{kt} - 1)$. This modification accounts for the phase where torque "sweeps up" at an increasing rate due to the exponential growth of the foam's structural resistance.

4. **Final Combined Model:** The summation of the asymptotic first-order term and the exponential growth term resulted in the final equation. This dual-component model fits the experimental data more accurately than a 3rd-order polynomial (despite having the

same number of parameters) and avoids the over-parameterization associated with higher-order polynomials.

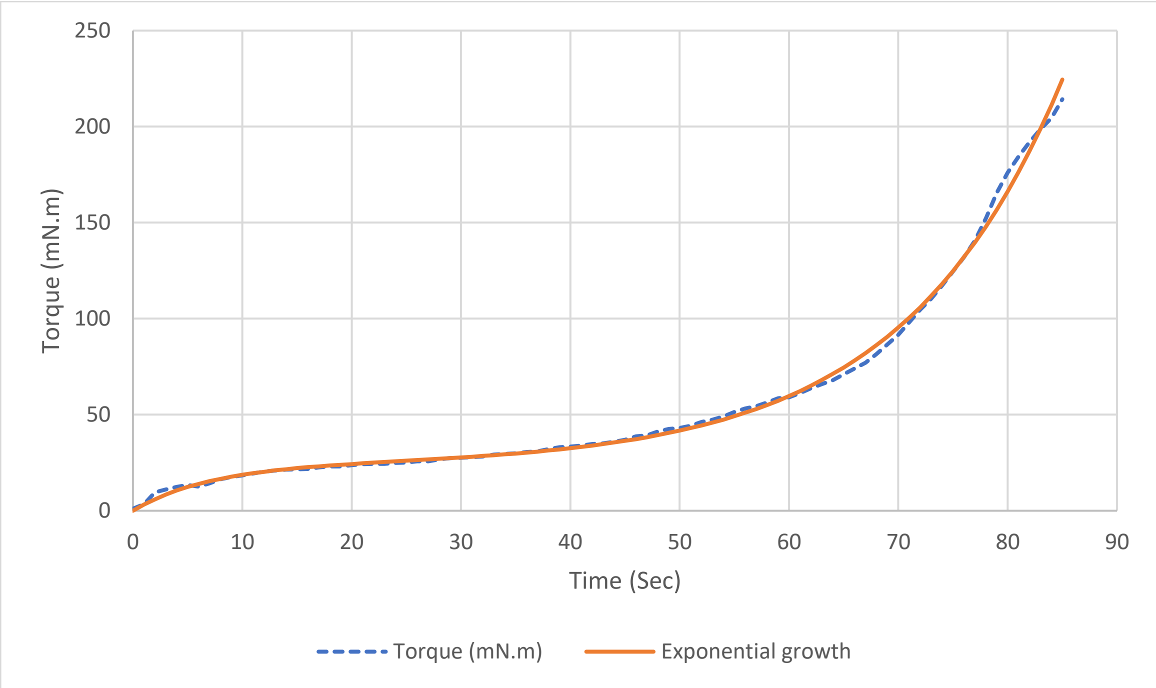


Figure 8 : Mathematical modelling of torque evolution during the whipping of 400ml fresh cream. The solid orange curve represents the fit of the ***Equation 3*** *against the raw torque data (dashed blue line). The plot illustrates the model's ability to capture both the initial viscosity build-up and the subsequent exponential growth in structural resistance.*

These are often difficult to define precisely using only visual or textural assessments. This graph also helps identifying over-whipping limits, which is important for reducing product failure during industrial processing. Combined with microscopy, overrun measurements and texture profile analysis, torque measurements help to correlate physical changes with the corresponding structural changes, such as partial coalescence, air incorporation and developing of the fat network. As a result, it is vital for creating a scientific foundation to improve whipping conditions, compare cream formulations, and understand how factors like fat content and temperature affect whipping behaviour.

3.2.4 FOAM CHARACTERISATION

3.2.4.1 OVERRUN

Overrun was measured after visually determining the optimum whipped cream. This was based on the firm peak structure developed, which was significantly expanded, compared to the starting liquid cream and presumably reaching maximum overrun. Overrun refers to the percentage increase in volume caused by the incorporation of air into the emulsion. Typically, the optimum whipping properties occur with an overrun between 100 and150% (Walstra et al., 2005). Whipped cream was filled into a 120 ml container to the rim, avoiding any small air gaps during filling. The container was levelled using a scraper. **Equation 4** was used to calculate the overrun, based on the weight of the samples at a fixed volume, where the $m_{liquid\ sample}$ was the weight of the initial cream and $m_{whipped\ sample}$ was the weight of the same volume of foam. Overrun was determined in duplicates

$$Overrun\ (\%) = \frac{m_{liquid\ sample} - m_{whipped\ sample}}{m_{whipped\ sample}} \times 100 \qquad \text{Equation 4}$$

3.2.4.2 FIRMNESS

TA.XTPlusC Texture Analyzer (Stable Micro Systems, USA) equipped with a flat cylindrical acrylic probe (diameter 10 mm, height 35 mm) was used to measure the deformation puncture. Whipped cream was filled into 120 ml containers to the rim, and the surface was levelled using a scraper. The penetration tests were performed on the surface of the whipped cream at a rate of 1 mm/s over a distance of 5 mm. The trigger value to start the measurement was set at 0.01 N. The peak force (N) at a depth of 5 mm was defined as the firmness of the whipped cream. The puncture tests were performed in triplicates (Fredrick et al., 2013).

3.2.4.3 FOAM STABILITY

The stability of the foam was determined by piping the whipped cream into shapes like rosettes and measuring any serum loss or loss of shape after 24 hr storage at 4ºC. By evaluating the visual appearance of the rosettes and score can be assigned to each, and the foam stability can be determined. The scores ranged between 1 and 7, “1” being the lowest score and “7” being the highest score.

Table 4: Visual evaluation scoring criteria for whipped cream rosettes, (adapted from Synlait Milk Limited).

Score	Description of Rosette Attributes
7	**Perfect.** Smooth and sharp edges, good height, good surface texture, shiny looking, pointing peak, and no wheying off.
6	One attribute not quite perfect, but still a good rosette. e.g., slightly jaggered edges, only moderate depth in ridges, slightly dull, peak not pointing, etc.
5	Two or three attributes not ideal but still ok rosette. e.g., slightly slumping, edges not as sharp, not shiny, etc.
4	On the verge of being unacceptable with one or two attributes quite average or lots of attributes not ideal. e.g., some pitting or slumping.
3	**Not acceptable**, at least one bad attribute. e.g., significant slumping, slight wheying off, pitted, shallow ridges, very jaggered edges, etc.
2	**Not acceptable**, multiple bad attributes. e.g., completely slumped, wheying off, cracks, severe jaggered edges, etc.
1	None of the attributes is desirable.
0	The cream is not able to whip.

3.2.4.4 FOAM MICROSTRUCTURE

Confocal laser scanning microscopy was used to observe the microstructure of whipped cream after adding the following fluorescent dyes; Nile Red dispersed in Dimethyl Sulfoxide (DMSO) and Fast Green hydrated in distilled water. Before whipping, X µl of 0.02 wt.% Fast Green (Sigma-Aldrich, MA, USA) and 0.05 wt.% Nile Red (Sigma-Aldrich, MA, USA) were added to the cream, to stain the protein and fat, respectively. Using the Kenwood mixer, the stained cream was whipped at under 7°C with controlled parameters. The fresh creams were whipped until a firm peak was attained—at the optimum whipping time as defined above. The stained whipped cream was then placed on a microscope slide for observation (Mohamad Fauzi, 2024). A temperature-controlled stage attached to the confocal was used to maintain the temperature at 4 ºC.

To obtain the images, Zeiss LSM 900 Airyscan 2 high-resolution system (Oberkochen, Germany) equipped with a 10x objective and a 40x oil-immersion objective were used. The excitation wavelengths were 568 nm and 633 nm for Nile Red and Fast Green, respectively. The fluorescence light emitted by the Nile Red was detected at 569-640 nm and for Fast green it was detected at 650-700 nm (Henderson, 2022; Mohamad Fauzi, 2024). The images were processed using ZEN 3.1 (imaging software).

Chapter 4: EFFECT OF THE INITIAL CREAM VOLUME ON THE WHIPPING PROPERTIES

4.1 INTRODUCTION

The food science behind the whipping cream process is key to control industrial processes and develop new products. Whipping involves mechanical incorporation of air into the oil in water emulsion, so the liquid cream can be transformed into a stable foam. It is theorised that the volume of cream that is whipped in the mixer can have a substantial effect on the physical characteristics of the resulting whipped cream such as fat globule stability, size and distribution of air bubbles, and texture and firmness of the whipped cream. These characteristics are important in establishing the applicability of whipped cream in different uses and the information obtained can be used in the design of industrial and kitchen equipment. Therefore, it is necessary to have an in-depth insight into the effect of sample volume on whipping process to maximize the efficiency and quality of the result based on the needs of consistency and scalability.

The whipping process involves the partial coalescence of fat globules which is a mechanism whereby fat droplets are aggregated through mechanical shear to develop a network that stabilizes the air added by trapping the bubbles. The initial volume of cream can potentially affect this network because greater volumes of cream would offer more material for the interactions of fat globules, which could in turn affect the rate and extent to which coalescence takes place. The previous studies, suggested that the milk fat globule membrane and its response to mechanical stress is fundamental to the stability of emulsions and therefore the stability of the foam, which formed the basis of volume related effects (Mulder & Walstra, 1974). Later works by Goff (2013) further clarified the purpose of mechanical energy in the aeration of dairy emulsions, pointing out that the volume of the emulsion may also regulate the distribution of energy and the thereby structural result. Larger volumes might need increased energy input or longer whipping time in order to get homogeneous aeration, and this can result into variability in the size and stability of the air bubbles. Furthermore, Stanley et al., (1996), observed that in case of a large volume or when whipping exceeded a certain time period, over-aeration or phase separation can occur, like in the case of whipped cream becoming butter, which is why it is important to have precise control of the volume to whip.

In this chapter, a systematic study on how varying the volume of cream (200 ml, 400 ml, or 600 ml) will influence the whipping process will be carried out, by analysing the torque versus time graphs and by characterizing the foams formed. The chapter aims at determining the quantitative effect of the volume on the exponential time constant, the peak torque, the optimum whipping time, and the peak width, which give information on the behaviour of fat globule coalescence and incorporation of air bubbles. The study isolates the variable of volume by keeping a controlled temperature range (between 6.7°C and 7.3°C), providing a controlled environment to determine its effect on cream structure. The results should also add to the current body of knowledge by offering empirical evidence that can be used to develop standardized whipping procedures, improve the quality of products, and design equipment to represent different scales of production.

4.2 MATERIALS AND METHODS

4.2.1 MATERIALS

Please refer to Section 3.1

4.2.2 METHODS

4.2.2.1 WHIPPING PROCEDURE

Please refer to Section 3.2.2.

4.2.2.2 TORQUE VS TIME ANALYSIS

Please refer to Section 3.2.3.

4.2.2.3 OVERRUN

Please refer to Section 3.2.4.1.

4.2.2.4 FIRMNESS

Please refer to Section 3.2.4.2.

4.2.2.5 FOAM STABILITY

Please refer to Section 3.2.4.3.

4.2.2.6 FOAM MICROSTRUCTURE

Please refer to Section 3.2.4.4.

4.3 RESULTS AND DISCUSSION

4.3.1 FOAM FORMATION: TORQUE VS TIME ANALYSIS

Data on torque changes over time were obtained when whipping fresh cream samples of 200 ml, 400 ml, and 600 ml using a Kenwood mixer at high speed, conducting the experiment until the cream had turned into butter. The comparative analysis of the average torque of fresh cream is shown in **Figure 9**, and the parameters obtained from the graph analysis are shown in **Table 5.** The cream was chilled overnight (at least 24 hours) at 4°C, and the bowl and whisk were cooled at 4°C for 30–60 minutes before using to ensure that an effective temperature control was maintained during whipping. The study has taken into account only one of the variables, that is, volume, by maintaining a constant temperature range at start of the whipping process (between 6.7°C and 7.3°C), controlling the environment to investigate the influence of volume on cream structure. Repetitions of experiments guarantee reliability.

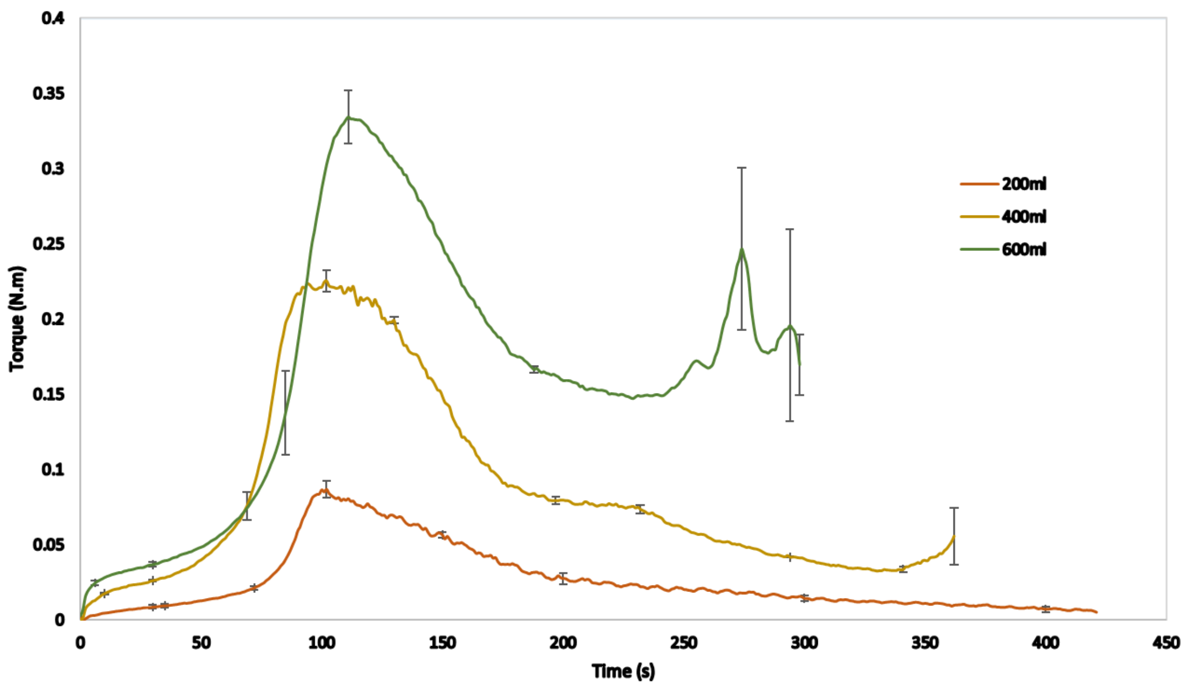


Figure 9: Comparative Analysis of Average Torque Vs Time for Whipping 200ml, 400ml and 600ml of Fresh Cream.

Table 5: Parameters obtained from the Torque Vs Time graph for different volumes of fresh cream used.

Parameter	**200 ml**	**400 ml**	**600 ml**
Exponential Time Constant (sec)	34.58 ± 0.02	9.88 ± 2.4	5.58 ± 1.6
Exponential Growth Coefficient (sec^{-1})	0.08 ± 0.02	0.07 ± 0.006	0.05 ± 0.009

Peak Torque (N·m)	0.08 ± 0.03	0.22 ± 0.03	0.33 ± 0.005
Time to Peak Torque (sec)	102 ± 1.7	102 ± 4.02	111 ± 2.02
Optimum Whipping Time (sec)	70	69	85
Peak Width (sec)	13	38	31
Temperature (°C)	6.8 ± 0.2	7.3 ± 0.1	6.7 ± 0.1

The measured torque profile while whipping shows the changes happening in the cream structure. In all cases a steady increased in torque was detected, followed by an exponential growth up to a peak torque, followed by a torque decrease. The shearing process includes adding air bubbles and destabilizing milk fat globules at the same time. It is well known that the shear force from the whisk removes the milk fat globule membrane layers from the fat globules (Henderson, 2022; King, 1953). This lets the globules come together and create a partially crystalline, three-dimensional network that surrounds and stabilizes the air bubbles. This fat network gives whipped cream its stiffness and structure, and theoretically the torque measured indicates how strong and extensive this network is (Henderson, 2022).

The peak torque increased from 0.08 ±0.03 N.m for the 200 ml sample to 0.22 ±0.003 N.m for 400 ml and further to 0.33 ±0.005 N.m for the 600 ml sample. This result indicates that a greater volume of cream offers more resistance to the whisk once the rigid foam structure is formed. It is not surprising that the peak torque increases with volume. As the sample volume increases, the whisk is more deeply submerged, hence also the increase in torque. A larger amount of cream creates a bigger and stronger fat globule network. This network has greater resistance against the mixer's whisk, which means it needs more energy (torque) to maintain the constant speed. The strength of the network can be best seen on the firmness measurements in the following section. The 200 ml sample which had the lowest peak torque, probably had a lower degree of partial coalescence, leaving smaller intact fat globules, and producing a smoother texture at first. The 400 ml and 600 ml samples presenting higher torques, probably exhibited a greater degree of partial coalescence, creating a rigid network. These changes highlight the importance of increased volumes to increase the fat globules interactions, which are caused by the intense mechanical energy at maximum speed, leading to a more noticeable structural change.

The 200 ml sample exhibited the narrowest peak width (13 sec) whereas the 400 ml sample showed the greatest peak width (38 sec). This could be an indication of a particular structure developed from the partially coalesced fat and air incorporated at intermediate volumes, which made the whipped cream more stable before it turned into butter. The 600 ml sample which had the highest peak torque (0.33 N·m) also exhibited secondary peaks between 250 and 280 sec with noticeable error bars. This peak indicates a high degree of fat globule networking, but the overwhipping, leads to a grainier texture (breaking point, grains floating in buttermilk/butter water) as the complex structure with air bubbles finally collapses into butter. The secondary peaks seem to indicate over-agitation (Stanley et al., 1996)

The initial rate of whipping was also volume dependent. The exponential time constant (τ), which characterises the time taken for the initial exponential rise in torque, decreased significantly as volume increased, from 34.58 ±0.02 sec for 200 ml to 9.88 ±2.4 sec for 400 ml and finally to 5.58 ±1.6 sec for 600 ml. The smaller exponential time constant signifies a more rapid initial thickening of the cream. The quicker initial whipping phase in larger volumes indicates better mechanical efficiency, as the whisk is submerged more effectively. This likely leads to better air incorporation and a larger area of high shear. This causes a more rapid increase in torque due to the acceleration of the initial destabilization of fat globules and the development of the initial foam structure. The growth coefficient (k) slightly decreased from 0.08 sec^{-1} for 200 ml, 0.07 sec^{-1} for 400 ml and 0.05 sec^{-1} for 600 ml, suggesting a slower growth rate in larger volumes after the initial phase.

Interestingly, the time required to attain the peak torque remained relatively consistent in all the volumes, even though there was a large difference in the peak torque and initial whipping rate. The peak torque for 200 ml and 400 ml samples was recorded at 102 sec, and slightly longer for 600 ml (111 sec). Similarly, the optimum whipping time—the point at which it was visually determined to have obtained the ideal whipped cream, which consistently happened before the peak torque—was also similar for the 200 ml and 400 ml samples (70 sec and 69 sec, respectively) and slightly longer for the 600 ml sample (85 sec).

4.3.2 FOAM CHARACTERISATION: ROSETTE STRUCTURE, FIRMNESS, OVERRUN AND MICROSTRUCTURE OF WHIPPEDCREAM

The ideally whipped foams from the 200 ml, 400 ml, and 600 ml cream volumes were characterized by their visual appearance, foam structure, firmness, and overrun. The visual rosettes are shown in **Figure 10**, and the results for firmness obtained from texture analyzer and overrun data are given in **Table 6.**

Cream Volume used for whipping	Rosette made immediately after whipping (a)	Rosette after 24hr (b)
200ml		
400ml		
600ml		

Figure 10 : Foam stability observed by visual rosettes for different whipped cream volumes made (a) immediately after whipping and (b) after 24 hrs of refrigerated storage at 4°C.

Table 6: Firmness (N) and overrun (%) for different cream volumes used for whipping

Cream Volume used for whipping	Firmness (N)	Overrun %
200ml	0.29 ± 0.01	123.97%
400ml	0.4 ± 0.03	101.57%
600ml	0.44 ± 0.04	89.46%

The foam structure from different whipped volumes was assessed by piping the cream into shapes like rosettes and evaluating their structure immediately after whipping and after 24 hrs stored at 4°C. All rosettes, regardless of the initial cream volume, were assigned a sensory score of 4 based on the provided standard scoring guide from a dairy company. A score of 4 is described as "on the verge of being unacceptable with one or two attributes quite average or lots of attributes not ideal, e.g., some pitting or very jagged edges, slight slumping." Visually, all rosettes successfully held their general shape both initially and after 24 hours, indicating good stability against collapse or significant wheying off (syneresis). However, these rosettes lacked the sharp, well-defined ridges and smooth texture characteristic of a higher scoring rosette (score 4).

The data obtained using the Texture Analyzer (TA), provided a quantitative measure of the foam firmness. The foam made from 200 ml had the lowest firmness at 0.29±0.01 N. This increased significantly to 0.40±0.03 N for the 400 ml volume, reaching the highest value of 0.44±0.04 N for the 600 ml. The overrun, which shows the percentage increase in volume due to air, had a clear inverse relationship with the initial cream volume. The 200 ml sample had the highest overrun at 123.97%. This decreased to 101.57% for the 400 ml sample, with the lowest being 89.46% for the 600 ml sample.

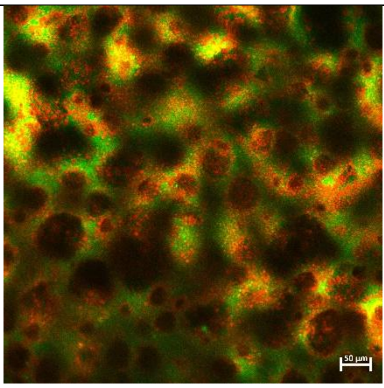
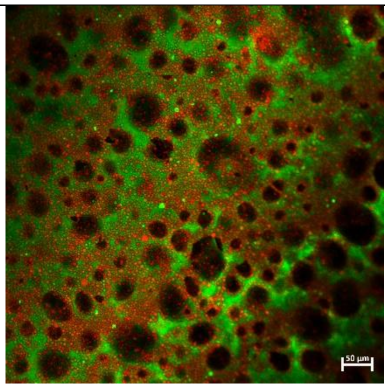
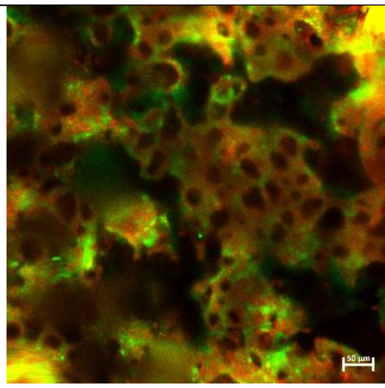
200 ml (70 sec)	400 ml (69 sec)	600 ml (85 sec)
		

Figure 11: CLSM micrographs at ideally whipped of whipping cream whipped with different initial cream volume.

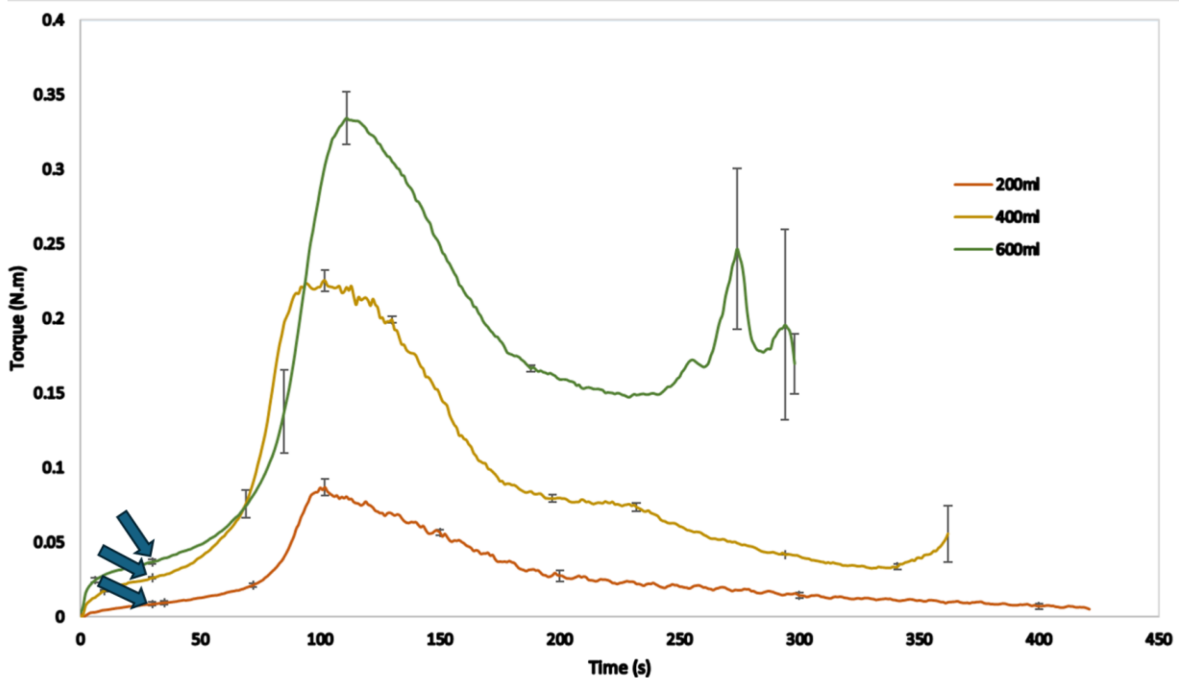
The high overrun (123.97%) and low firmness (0.29 N) after whipping 200ml of cream shows that the lowest volume whipped efficiently, incorporating a lot of air. This creates a light foam with larger or more numerous air bubbles, Shown in **Figure 11**. To stabilize this large volume of air, the available fat globules must form a network that is spread more thinly. This probably leads to a weaker, less dense structure, which corresponds to a lower firmness and as mentioned earlier, to a lower degree of partial coalescence.

However, the low overrun (89.46%) and high firmness (0.44 N) when using 600ml suggest a different process. Whipping a larger volume may be less effective at incorporating air compared to the total liquid mass. The longer mechanical action needed works the fat globules harder, causing more partial coalescence. This results in a denser and stronger fat network that surrounds a smaller volume of trapped air. The air bubbles are probably smaller and more compact. This dense structure leads to a much firmer product. The 400 ml sample is in an intermediate state between these two extremes, with overrun (101.57%) and firmness (0.4 N). An ideally whipped cream shows an important balance between overrun and firmness, both of which are affected by the volume of cream used for whipping. This relationship comes from the foam microstructure, mainly the size and distribution of air bubbles and the strength of the fat network that helps in stabilizing them (Henderson, 2022). It seems a volume of 400ml achieves a good compromise of gas entrapment and strong network (**Figure 11**).

4.3.3 MONITORING THE WHIPPING OF CREAM TO OBSERVE THE EFFECTS OF THE INITIAL CREAM VOLUME ON THE WHIPPING PROCESS

A comparative analysis of the CLSM micrographs for the 200ml, 400ml, and 600ml samples, provides crucial insights into the effect of the initial cream volume and the associated shear forces on the final foam structure. The images show a clear progression in air bubble morphology and the development of the fat network as the volume increases.

CLSM micrographs shown in **Figure 12,** captured at 30 seconds reveal that the initial phase of whipping is defined by rapid air incorporation and the fat globules adsorbing to the air-water interface while remaining predominantly as discrete, non-coalesced droplets. Utilizing Nile red and fast green staining, the imagery confirms that while fat globules coat the newly formed air voids, they remain largely spherical and non-fused. At greater volume samples, such as 600 mL, there was a clear separation of phases, with distinct areas that were either protein or fat dominant, suggesting greater levels of aggregation. The fat globules are coating and aggregating around the air bubbles, yet they still remain largely as individual spheres instead of fusing into bigger and irregular forms. This micrograph aligns with the initial rise in torque seen in the **Figure 12(a)**, as the foam structure begins to resist the whipping action.



(a)

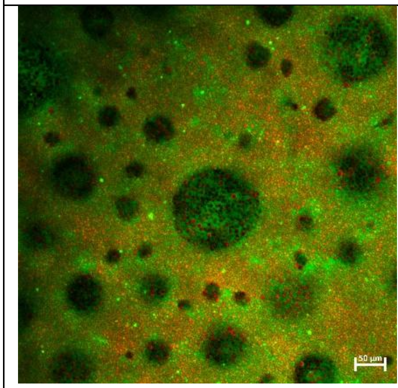
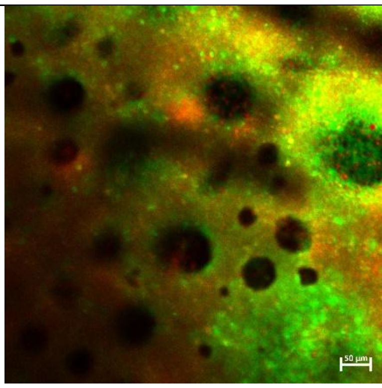
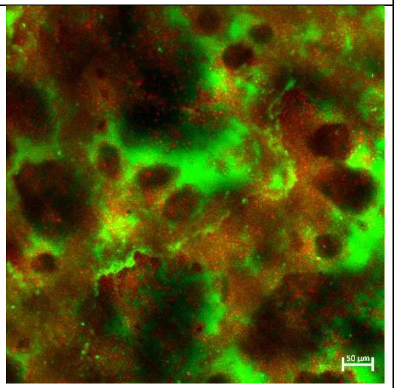
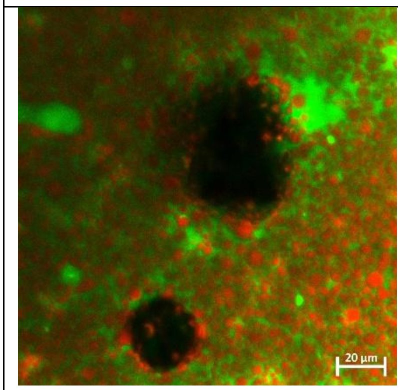
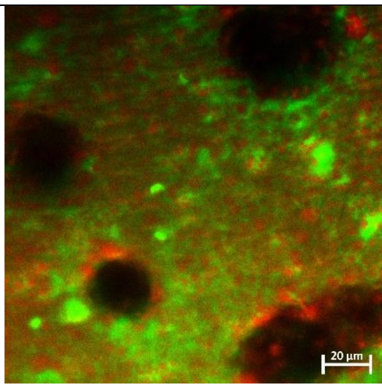
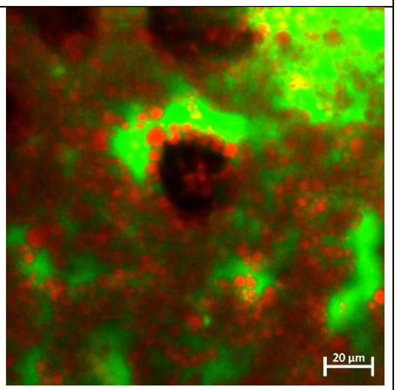
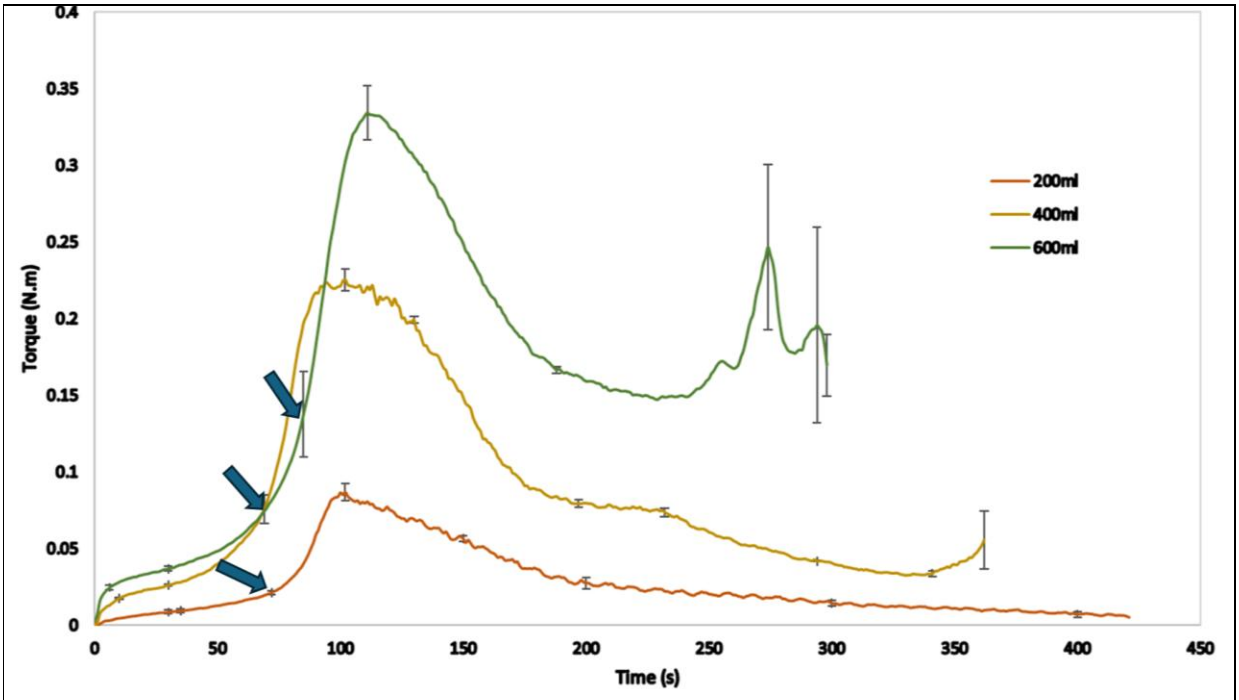
Observed under 10X		
200 ml (30 sec)	400 ml (30 sec)	600ml (30 sec)
		
Observed under 40X (oil immersion)		
200 ml (30 sec)	400 ml (30 sec)	600ml (30 sec)
		
(b)		

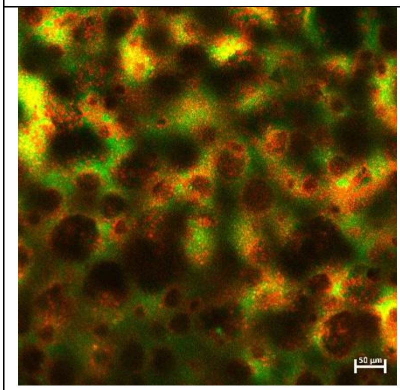
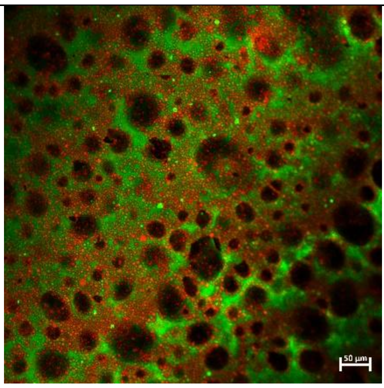
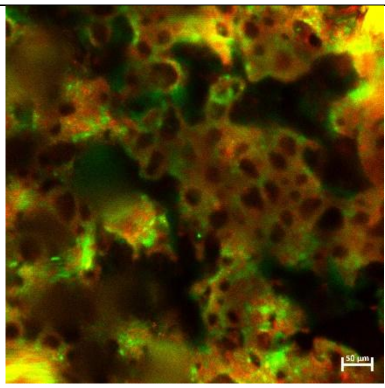
Figure 12: (a) Torque Vs Time developed during whipping of 200ml, 400ml, 600ml of cream. The arrows indicate the exact point (30 sec) when the samples were collected to observe under microscope (b) CLSM foam micrographs observed at the early stage of whipping (30 sec), for different initial cream volumes.

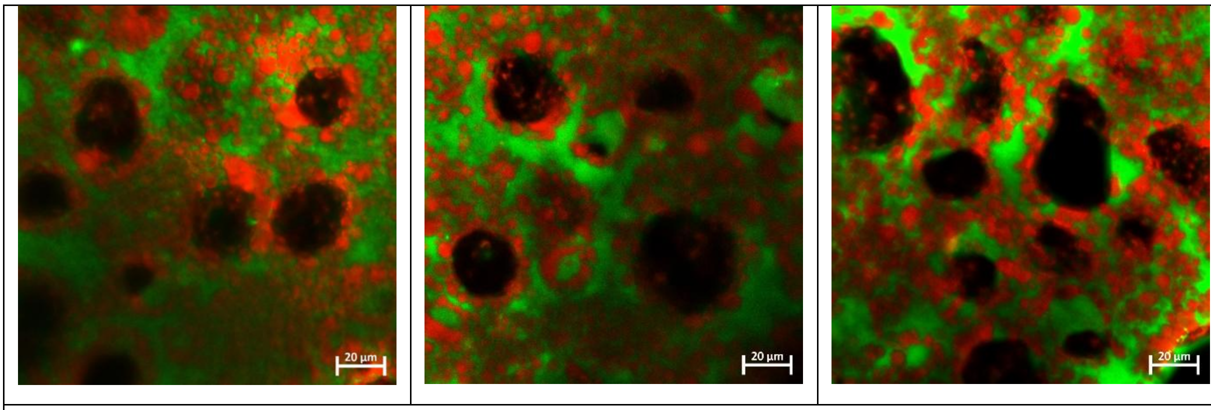
CLSM micrographs captured at the ideally whipped stage (**Figure 13b**), correlated with the torque profiles in **Figure 13a**, The micrographs revealed that whipped cream is not a simple dispersion of air in liquid but a complex, interlinked biopolymer network. The visual evidence supports the conceptual model of a two-network interlinked system.

At 400 ml, the air bubbles were mostly small and round. With a 200 ml volume, the air bubbles became bigger and more irregular, connected into air channels, while the red fat network became more prominent and interconnected, and the semi coalescence more visible. At 600 ml, the air bubbles were large and highly irregular, losing their round shape and often forming interconnected channels. The red-stained fat created a thick, continuous network that surrounded and encapsulated these highly deformed air pockets. The larger volume (600 ml) likely leads to a higher effective shear rate. This increased volume (600 ml) presumably corresponds to an increased effective shear rate that would not only increase the rate at which fat and protein are adsorbed, but also more violently deform the bubbles allowing them to form the noticeable channel formation observed in the micrographs. This shows the interaction of physical forces and the chemical composition of the cream.



(a)

Observed under 10X		
200 ml (70 sec)	400 ml (69 sec)	600ml (85 sec)
		
Observed under 40X (oil immersion)		
200 ml (70 sec)	400 ml (69 sec)	600ml (85 sec)



(b)

Figure 13: (a) Torque vs Time during whipping of 200ml, 400ml, and 600ml cream volumes. The arrows indicate the exact point at the Ideally whipped stage when the samples were collected to observe under microscope (b) CLSM foam micrographs observed at the ideally whipped stage, at different initial cream volumes.

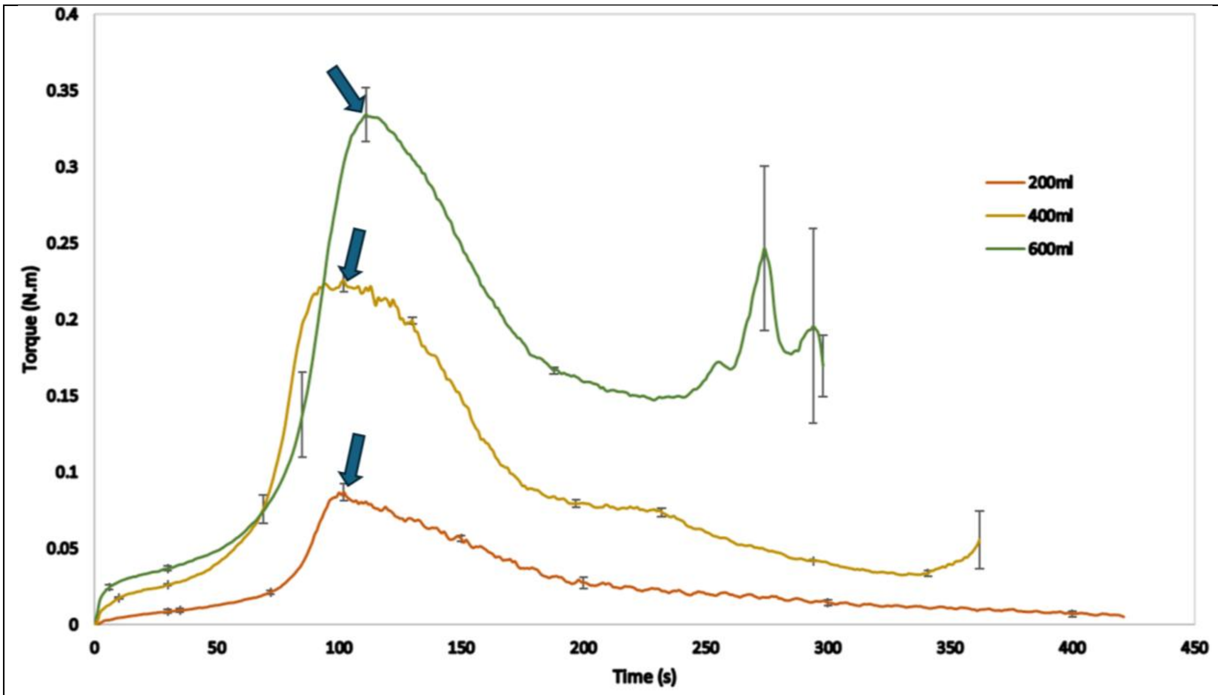
Figure 14a indicates the points of sample collection using the arrows to signal the peak torque (maximum torque) during whipping, with the corresponding microstructures in **Figure 14b** for the three cream volumes. The CLSM image for the 200 ml sample revealed a varied microstructure. It depicted a web of individual, typically spherical air bubbles of different sizes. These bubbles were well-spaced and were surrounded by an organized fat network. At this maximum torque, the mechanical shear had caused all the fat globules to partially merge into a network that surrounds the air bubbles. This network depicted in bright red shows a high level of fat destabilization, where all the globules have merged losing the individual spherical appearance. This almost continuous fat phase is now very distinctive from the protein phase in bright green. This indicates a stable but not overly stressed foam structure being the weakest of the three networks given the low torque.

In contrast, the microstructure of the 400 ml sample showed a more noticeably dense foam with a higher concentration of air bubbles and structural fat network. The fat globules still exhibited some individual spherical shape, though all of them had semi-coalesced into a stable and interconnected network. This interconnected strong fat network likely contributed directly to the higher torque observed for this sample. While the air bubbles mostly kept a spherical shape, there is evidence of more confinement by the surrounding network. This suggests that the foam is under more mechanical stress than the 200 ml sample. Such a condition reflects a major rise of the foam's elastic modulus and rigidity because of the organized connected fat network.

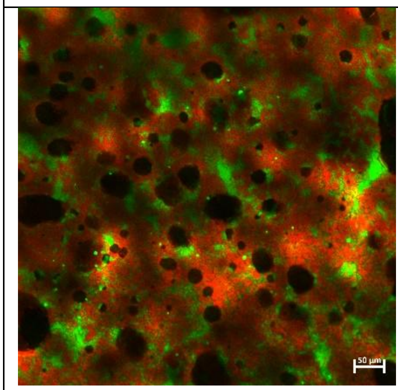
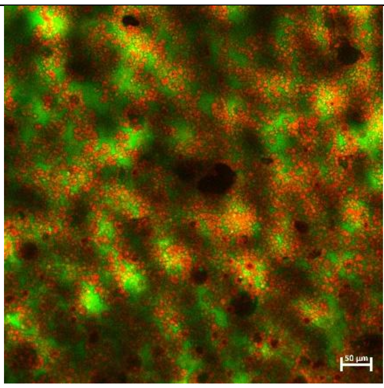
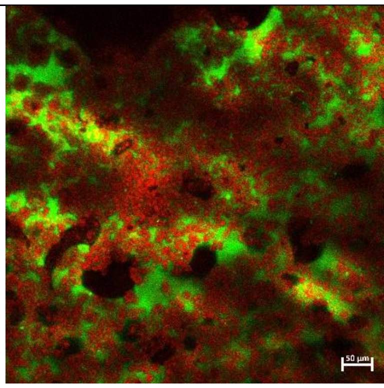
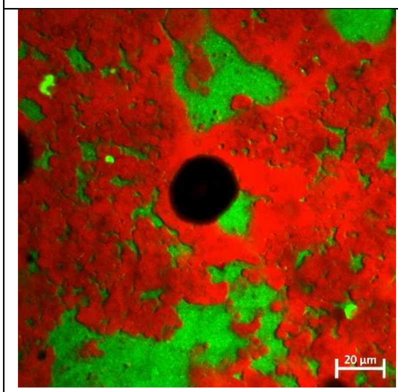
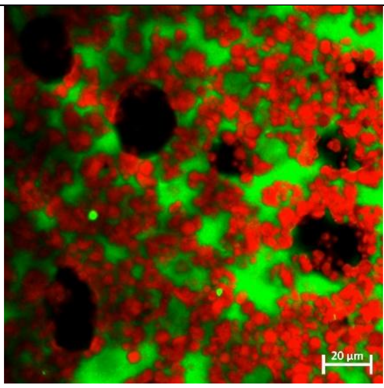
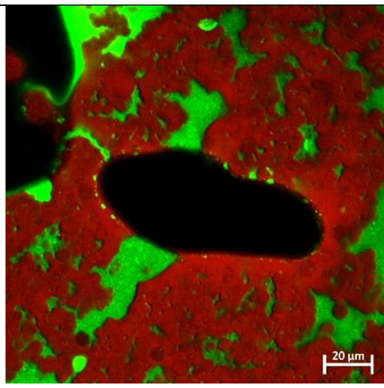
The microstructure of the 600 ml sample at peak torque had a radically different and more intricate morphology. Important microstructural observations include a highly distorted and non-spherical air bubble morphology, and a dense and extensively interconnected fat network, where the fat seems more destabilized again than at 400ml.

The CLSM images (**Figure 14b**) indicated that the bubbles in the 600 ml sample are no longer spherical this was already detected at the ideally whipped stage; instead, they are elongated and flattened. This change suggests that the mechanical force from the rigid and interconnected fat-protein network is now stronger than the Laplace pressure that tries to maintain bubble sphericity. This clearly shows that the foam has reached its maximum structural capacity and is under extreme mechanical stress, close to breaking down.

Furthermore, the images revealed a highly concentrated fat network with a distinct, separate protein phase. This is consistent with the observation of incipient phase separation. The high level of mechanical shearing had caused large aggregation and partial coalescence of the fatty globules, forming a rigid structure due to the destabilization of the O/W emulsion. The observed leakage of the aqueous phase, or serum, is a phenomenon known as syneresis. This expulsion of the liquid phase happens due to the contraction and tightening of the rigid fat-protein network, which can no longer hold the serum phase within it. The presence of both distorted bubbles and visible syneresis (observed during sampling) at peak torque, provides strong microstructural evidence that the system is under maximum stress and on the verge of rheological failure.



(a)

Observed under 10X		
200 ml (102 sec)	400 ml (102 sec)	600ml (111 sec)
		
Observed under 40X (oil immersion)		
200 ml (102 sec)	400 ml (102 sec)	600ml (111 sec)
		

(b)

Figure 14: (a) Torque vs Time during whipping of 200ml, 400ml, and 600ml cream volumes. The arrows indicate the exact point at peak torque (maximum torque) when the samples were collected to observe under microscope (b) CLSM foam micrographs observed at peak torque (maximum torque), at different initial cream volumes.

4.4 OVERALL DISCUSSION

In this chapter it was examined how the different cream volumes affect the whipping process. The study focused on the physical changes while whipping 200 ml, 400 ml, and 600 ml of cream. The investigation revealed that increasing the whipping volume from 200 ml to 600 ml leads to a more rapid initial thickening and required significantly more energy, as shown by the higher peak torque.

In the initial phase of shear-induced fat aggregation also large air bubbles that are incorporated, are turned into small-sized air bubbles by shear. This results in changes in the viscosity and an increase in semi-coalescence which makes the structure of cream firmer by increasing fat connectivity (Goff, 2013; Mulder & Walstra, 1974). However, regardless of the cream volume whipped, the total time required to achieve maximum firmness remained remarkably consistent across all volumes.

Moreover, a definite inverse correlation was defined between the ideally whipped foam firmness and its overrun (Camacho et al., 2005). Larger volumes (600 ml) produced a firmer, denser cream with less incorporated air. In contrast, the smallest volume (200 ml) resulted in a lighter, softer foam with a high overrun. The 200 ml rosette had a high overrun and low firmness, making it too soft to form and hold sharp edges. This led to "pitting" or had "slight slumping." On the other hand, the 600 ml rosette, which was firm and dense due to low overrun, was likely too stiff and heavy. A very dense foam can be hard to pipe smoothly, causing "jagged edges" instead of the desired smooth, glossy finish. Therefore, both the weakest and the firmest creams failed to achieve an ideal visual score, though for different underlying microstructural reasons.

The excellent 24-hour stability of all samples indicates that in all cases, a sufficient fat network was formed to prevent syneresis, which is a critical quality attribute. However, the initial whipping volume fundamentally dictates the final balance of properties, with smaller volumes favouring a lighter, high-overrun foam and larger volumes producing a denser, firmer foam (Goff, 2013).

One of the most notable findings is the almost constant time needed to reach peak torque in different volumes. This suggests that the basic process of fat network formation happens at a similar rate, no matter the total volume, under the specific conditions of this experiment, such as constant whisk speed and bowl geometry. Peak torque (maximum torque obtained) represents the point just before over-whipping begins. The data imply that it takes approximately 102-111 seconds of mechanical agitation to process the fat globules to this critical point. Although larger volumes need more total energy and higher torque, the time to reach this state does not increase proportionally. This may mean that the rate limiting step is the time it takes for fat globules to be pulled into the high-shear zone of the whisk, where they destabilize, a process that occurs at a fairly constant rate.

The results from this study emphasize that getting the perfect whipped cream texture requires a careful balance between incorporating air and building a strong fat network (Dabo et al., 2024). Therefore, controlling the initial volume is one of the most important strategies for influencing the final microstructure and obtain the desired sensory and functional qualities in whipped cream (Cui et al., 2025).

4.5 CONCLUSION

In summary, the 400 ml sample achieves an even distribution of smaller, more stable air bubbles. Also, the 400 ml volume provides an optimal balance for whipped cream stability, firmness, and rosette quality. With firmness of 0.4 N and an overrun of 101.57%. Using 400 ml of cream will be the best option in the moderate batch production of whipped cream. Hence, the 400ml of cream was used for further studies in this research.

Chapter 5: EFFECT OF INITIAL CREAM TEMPERATURE ON WHIPPING PROPERTIES

5.1 INTRODUCTION

Temperature is one of the most crucial processing factors in cream whipping and it has a significant impact on the state of milk fat. Specifically, it controls how much fat crystallizes and the shape of the fat crystals. These aspects are essential for breaking down fat globules and forming the foam structure (Brooker, 1993). The solid fat content (SFC) in the cream depends heavily on temperature. This directly influences the flow properties and how well the whipping process works. Low temperature conditioning of cream is essential to ensure that the right proportion of solid to liquid fat is obtained to allow optimum whipping (Lee & Martini, 2018; Nguyen et al., 2015).

Fat crystallization in whipping cream is greatly influenced by temperature. It influences the rate of the process as well as the network of fat crystals. The rate of decrease in temperature during processing also determines the size, shape and purity of fat crystals. These small crystals help in a stiffer fat matrix. This is due to greater content of solid fat and smaller crystal size, which produces a stiffer structure. Conversely, with slow cooling, bigger and purer crystals can be obtained with less liquid fat. This results in a softer texture, though it may be grainier because of the larger crystal size (Campos et al., 2002; Henderson, 2022).

Manipulation of temperature profiles does not only influence the rate of crystallisation but also the solid and liquid phases distribution in the fat, which influences the whipping performance and the stability of the cream. At molecular level, temperature influences the pack and growth of fat crystals, particularly at nano-domains in which fat globules exist. The sharp curvature and limited volume of small droplets, change the molecular arrangement in the crystalline structure, resulting in physical properties that differ from those of larger crystals. Such differences are most strongly evident in the conditions of rapid cooling when they are further limited by the size of the droplet and its high surface curvature (Campos et al., 2002).

Temperature has a strong effect on the whipping speed and overrun of cream, mainly through its effect on the physical state of the fat phase and the nature of fat globule interactions in the context of aeration (Fredrick et al., 2010; Ihara et al., 2010). Whipping rate, which may be expressed as the time to achieve optimum foam structure, is easily affected by temperature changes. At lower temperatures, the solid fat content in the cream increases. This helps fat globules to partially merge. This process is important for stabilizing air bubbles and forming a strong foam network. The higher solid fat content in cooler temperatures speeds up the formation and clumping of fat crystals. This reduces whipping time and promotes quick foam formation (Ihara et al., 2010).

On the other hand, as the temperature rises, more fat becomes liquid. This reduces fat globule clumping and extends the whipping time. The connection between temperature and overrun, which measures the increase in cream volume from incorporating air, is also complex (Ihara et al., 2010). Overrun reaches its peak when there is a good balance between solid and liquid fat that allows for effective partial merging without making the fat too stiff or too fluid. At ideal temperatures, specifically the melting range of the low- and medium-melting point triglycerides (typically between 5°C and 15°C) the cream shows a high level of partial coalescence, which is high level of fat globule clumping. This supports the trapping and stabilization of air bubbles, leading to higher overrun values (Wang et al., 2019).

The aim of this chapter is to carry out an extensive study on how the different whipping temperature (7°C, 10°C, and 13°C) can influence the whipping process, by analysing the torque versus time graphs and by characterizing the foams formed. The chapter aims at determining the effect of the initial temperature on the exponential time constant, the peak torque, the optimum whipping time, and the peak width, which give information on the behaviour of fat globule coalescence and incorporation of air bubbles. The study isolates the variable of volume by keeping volume at 400ml, providing an equal volume to determine its effect on cream structure. The results should also add to the current body of knowledge by offering empirical evidence that can be used to develop standardized whipping procedures, improve the quality of products, and design equipment to represent different scales of production.

5.2 MATERIALS AND METHODS

5.2.1 MATERIALS

Please refer to Section 3.1

5.2.2 METHODS

5.2.2.1 WHIPPING PROCEDURE

Please refer to Section 3.2.1.

5.2.2.2 TORQUE VS TIME ANALYSIS
Please refer to Section 3.2.3.

5.2.2.3 OVERRUN
Please refer to Section 3.2.4.1.

5.2.2.4 FIRMNESS
Please refer to Section 3.2.4.2.

5.2.2.5 FOAM STABILITY
Please refer to Section 3.2.4.3.

5.2.2.6 FOAM MICROSTRUCTURE
Please refer to Section 3.2.4.4.

5.3 RESULTS AND DISCUSION

5.3.1 FOAM FORMATION: TORQUE VS TIME ANALYSIS

All three experimental temperatures produced a characteristic torque vs time curve that shows three distinct phases: an initial lag phase, a rapid increase phase that peaks, and a subsequent decay phase, shown in **Figure 15.** The parameters obtained from the torque vs time graph are given in **Table 7**. The sudden rise in torque indicates the gradual destabilization of fat globules, their partial coalescence, and the creation of a continuous fat network around the trapped air bubbles, this leads to increased viscosity and stiffness in the cream. The peak torque marks the maximum structural development and stiffness in the foam, indicating the start of over-whipping. In contrast, the decay phase reveals over-whipping. During this phase, excessive partial coalescence forms large, unstable fat clusters (butter granules) and causes serum separation. This process results in a collapse of the foam structure and a decrease in its resistance to shear.

The cream whipped at 7°C showed a relatively higher peak torque value of 0.22 N.m ± 0.003, compared to 0.204 N.m ± 0.003 at 10°C and 0.212 N.m ± 0.004 at 13°C. Although the peak torque of the cream whipped at 7°C was slightly higher, the differences at all three temperatures are relatively small, which indicates that the highest attainable stiffness of the whipped cream is relatively the same within this temperature range. However, the speed at which this stiffness was achieved widely differed.

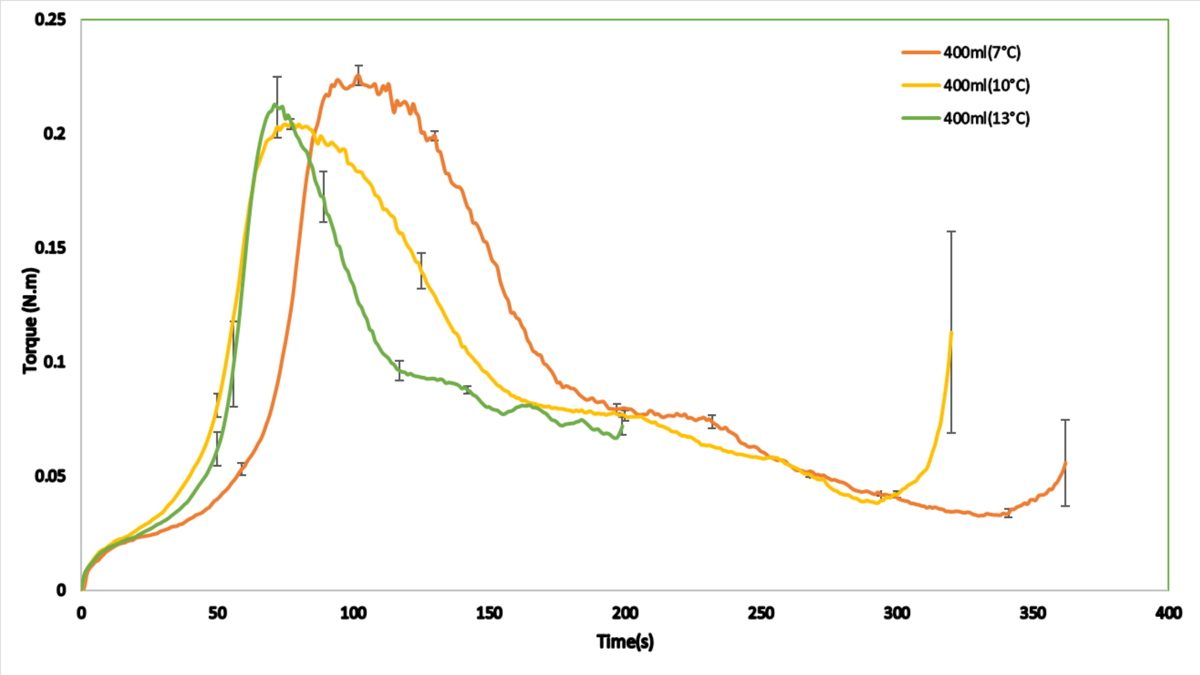


Figure 15: Comparative analysis of Torque vs Time during the whipping of 400ml fresh cream at different temperatures (7°C, 10°C, and 13°C).

Table 7: Parameters obtained from the Torque Vs Time graph during the whipping of 400ml fresh cream at different temperatures (7°C, 10°C, and 13°C).

Parameter	**400ml (7°C)**	**400ml (10°C)**	**400ml (13°C)**
Exponential Time Constant (sec)	9.88 sec ± 2.4	4.59 sec ± 1.2	8.00 sec ± 1.3
Exponential Growth Coefficient (sec⁻¹)	0.07 ± 0.006	0.07 ± 0.002	0.1 ± 0.005
Peak Torque (N·m)	0.22 N.m ± 0.003	0.204 N.m ± 0.003	0.212 N.m ± 0.004
Time to Peak Torque (sec)	102 sec ± 4.02	77 sec ± 1.5	71 sec ± 1.02
Optimum Whipping Time (sec)	69 sec	55 sec	56 sec
Peak Width (sec)	38 sec	36 sec	19 sec

The time of achieving peak torque (sec) clearly showed the accelerating nature of increasing temperatures on the whipping process. It took 102 seconds at 7°C, 77 seconds at 10°C, and 71 seconds at 13°C. The cream at 13°C reached its peak torque nearly 30 seconds faster than at 7°C.

The optimum whipping time (sec) was consistently shorter than the "time taken to reach peak torque" across all conditions and not significantly different between 10°C and 13°C: 69 seconds at 7°C, 55 seconds at 10°C, and 56 seconds at 13°C. This means that the cream was perceived as "ideally whipped" before it reached its maximum stiffness in a region where the torque curve is still very steep. This indicates that the highest torque may coincide with the stage at which the cream is already very stiff and may be approaching the over whipping stage, especially at higher temperatures where the process speeds up.

The peak width (sec) is a critical parameter; it shows the transition from optimally whipped state to overwhipped state. It was 38 seconds at 7°C, 36 seconds at 10°C, and a significantly narrower 19 seconds at 13°C. This provides robust quantitative evidence for the rapid transition from optimal whipping to over-whipping at 13°C.

The exponential time constant (sec) and exponential growth coefficient (sec^{-1}) characterise the rate of the initial growth phase of the torque curve. A smaller time constant indicates a faster initial rise in torque. In this regard, 10°C exhibited the smallest time constant (4.59 sec), suggesting the most rapid initial structural development, followed by 13°C (8.00 sec), and then 7°C (9.88 sec). Although the exponential growth coefficients for 7°C and 10°C are quite similar, the large differences in their time constants highlights that, despite having similar rates of change at certain points, the overall behaviour of the whipping process varies greatly due to the different starting temperatures and how things progress from there.

5.3.2 FOAM CHARACTERISATION: ROSETTE STRUCTURE, FIRMNESS, OVERRUN AND MICROSTRUCTURE OF WHIPPEDCREAM

The whipping temperature was very critical to the visual quality and stability of the whipped cream. The cream that was whipped and kept at 7°C produced the best rosette which scored 4 in the sensory score. As per the guide offered by a dairy company in New Zealand, this means a usable but not perfect structure, with some pitted or jagged edges observed in the rosette. In comparison, creams whipped at higher temperatures of 10°C and 13°C received lower scores of 3. This means their quality was "unacceptable" due to "significant slumping" and poorly defined ridges.

Figure 16 shown below, indicates that the rosette made at 7°C held its shape well, both right after whipping and after 24 hours. The rosettes from 10°C and 13°C creams, showed a clear lack of definition and jagged edges. Immediately after whipping, the 7°C rosette looked well-defined, with distinct ridges and good height, although the score of 4 indicates it is on the edge of being unacceptable with one or two attributes quite average or lots of attributes not ideal, e.g., some pitted or very jagged edges. This means that it may not have a perfect aesthetic although it is structurally sound. The rosette at 7°C mostly remained the same in terms of shape and definition after 24 hours, which shows good structure stability over time.

The rosette whipped at 10°C received a score of 3 immediately after whipping and after 24 hours. This score indicates it is "not acceptable," as it has "at least one bad attribute, e.g., significant slumping, pitted or shallow ridges. Visually, the initial rosette appeared less defined and somewhat softer than the 7°C counterpart. After 24 hours, it still retained its shape.

Similar to 10°C, the 13°C rosette also scored 3. Immediately after whipping, it appears to have a less stable structure, with less distinct ridges compared to 7°C. The image taken after 24 hours shows that this rosette maintained its shape.

Temperature at which the cream was whipped	**Rosette made immediately after whipping**	**Rosette after 24hr storage**
7°C		

10°C		
13°C		

Figure 16: Rosettes formed at different whipping temperatures, made right after whipping to the "ideally whipped point" and after 24 hrs storage at 4°C.

The results for firmness obtained from the texture analyzer and the measured overrun percentages are given in **Table 8.** When the temperature was raised from 7°C to 10°C and 13°C, the amount of solid fat crystals is reduced and the fat globules are softer as more liquid fat is formed. These softer, more liquid fat globules were clearly less effective at forming a robust network. The network became too weak to trap air effectively. As a result, the air bubbles that get incorporated are more likely to escape, explaining the steady and dramatic decrease in overrun as temperature increased (from ~101% at 7°C to ~73% at 13°C). This weak foam at higher temperature cannot support its own weight, which leads to the poor definition seen in the rosettes.

The findings also showed that the product with the highest firmness value of 0.4 ± 0.03 N was obtained at 7°C whipped cream, which agrees with the better visual stability in this product. The reduced firmness at 10°C (0.25 ± 0.0 N) and 13°C (0.29 ± 0.01 N) indicates that fat network structure established at the higher temperatures is less rigid or robust, such that the cream is more easily deformed.

Table 8: Texture Analyzer results i.e. firmness (N) and overrun percentages for different temperature used for whipping

Whipping done for different temperature (°C)	Firmness (N)	Overrun %
400ml (7°C)	0.4 ± 0.03	101.57%
400ml (10°C)	0.25 ± 0.0	94.52%
400ml (13°C)	0.29 ± 0.01	73.25%

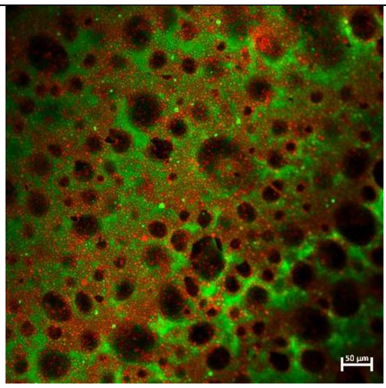
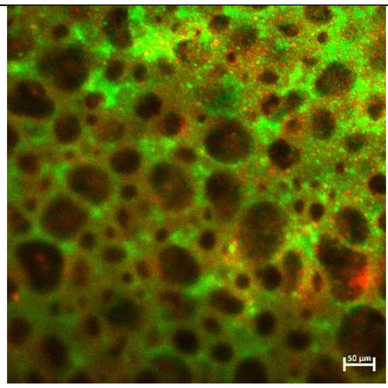
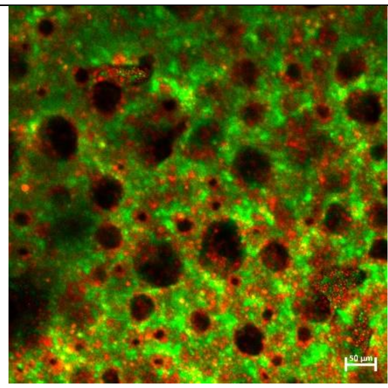
7°C (69 sec)	10°C (55 sec)	13°C (56 sec)
		

Figure 17: CLSM micrographs at ideally whipped of whipping cream whipped at different temperatures.

The sharp drop in firmness from 7°C to 10°C was expected; the weaker network does not resist compression well. However, the slight increase in firmness from 10°C to 13°C, despite the foam looking worse and being less aerated, indicated a different issue. At 13°C, the fat is very liquid, and the mechanical action can cause too much of the uncontrolled merging of the fat globules, which is more like churning butter than whipping cream. This resulted in larger, denser fat aggregates or more of the fat being damaged as being detected by the merged bigger red fat areas detected at 13°C in the confocal micrographs surrounding the gas bubbles in **Figure 17**. While the foam structure was poor, this denser, more compacted, and grainy mass offered slightly more resistance to the texture analyzer's probe. Therefore, this higher firmness is not an indicator of a quality foam structure but rather a symptom of the foam's collapse into a denser, semi-buttery state. At colder temperatures the higher fat crystal content resulted in a stronger network and hence a firmer product where the aggregated fat globules retain much of the intact small spherical shape forming the fat network (**Figure 17**).

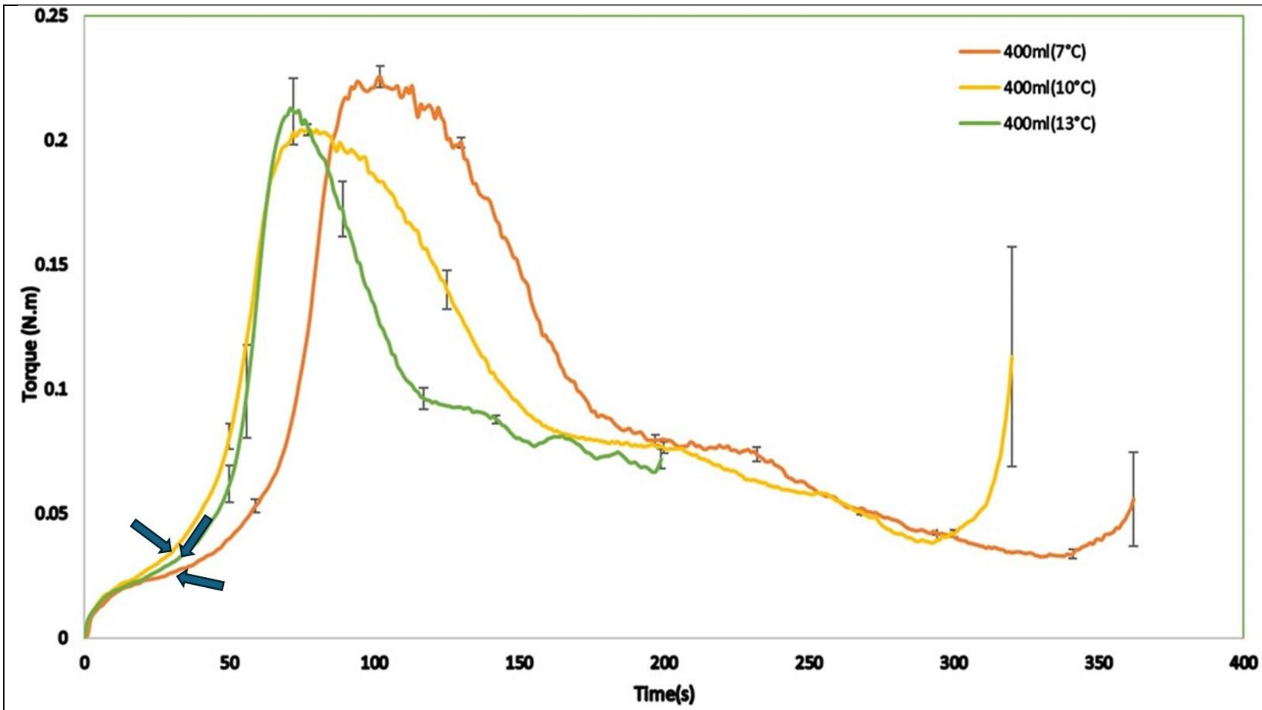
The overrun as a measure of the quantity of air added was highly correlated with temperature. The maximum overrun of 7°C (101.57%) shows that it is the optimal temperature to obtain the most efficient incorporation and retention of air bubbles resulting in a lighter and voluminous product. The much reduced overrun at 13°C indicates that the whipping process at this temperature is less efficient in trapping air, or the air that is trapped is easily lost through structural instability, as shown in **Figure 17**.

5.3.3 MONITORING OF WHIPPING CREAM TO OBSERVE THE EFFECTS OF TEMPERATURE ON THE WHIPPING PROCESS

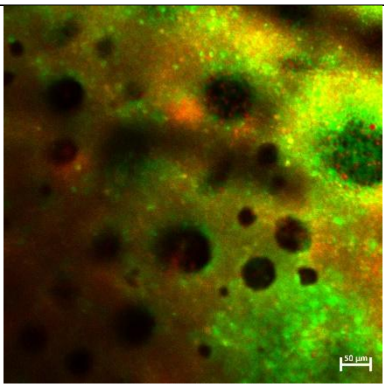
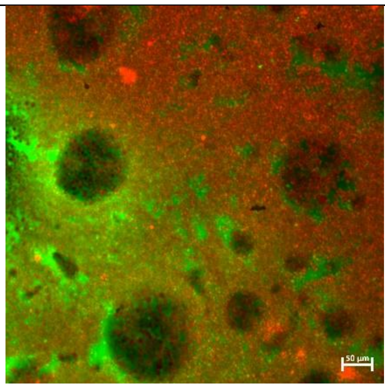
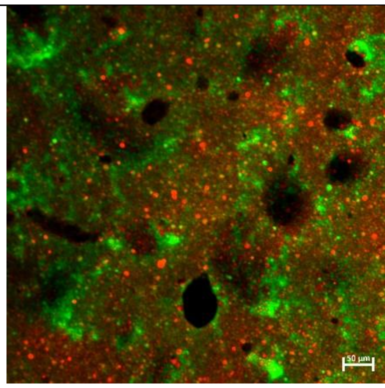
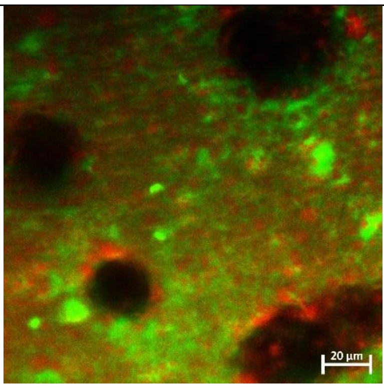
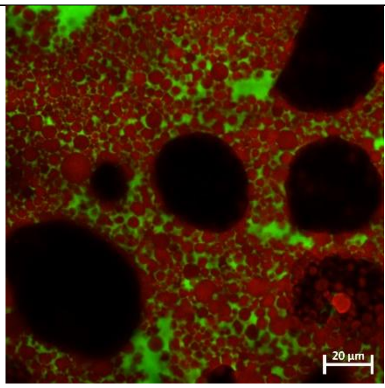
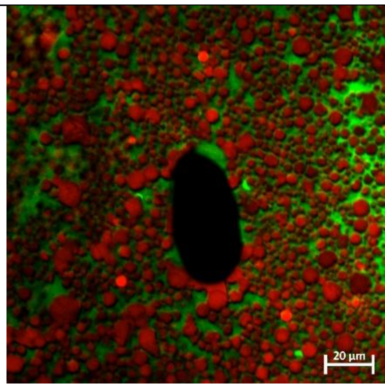
Figure 18b shows the microstructures after 30 sec of whipping at 7°C, 10°C and 13°C. The micrograph of whipped cream at 7°C, showed the spherical bubbles incorporated into the system, with both protein and fat at the air-water interface. The image taken at 10× magnification revealed the discrete, spherical fat globules, stained green and red, and therefore producing the yellowish areas. This means that at this lower temperature, the fat globules mostly kept their individual shape. There was little fat semi-coalescence, indicating that the mechanical forces of whipping had not caused much damage or clumping of the globules.

A distinct change in the microstructure became evident as the temperature increased to 10°C. The CLSM images (**Figure 18b**) demonstrated a greater degree of fat aggregation than at 7°C. The fat globules were clumped into dense aggregates suggesting that the emerging fat network was starting to become the main structural element. At the more detailed 40× magnification, the aggregates were clearly visible as tightly packed groups of bigger clumps of fat, holding big air bubbles of around 40 µm size.

The most dramatic microstructural transformation occurred at 13°C. The CLSM images at both magnifications showed widespread fat aggregation. The fat globules looked much larger and displayed a high level of coalescence and semi-coalescence, where some globules seemed to have partially fused. The network formed at this temperature was rougher and less defined than the one seen at 10°C.



(a)

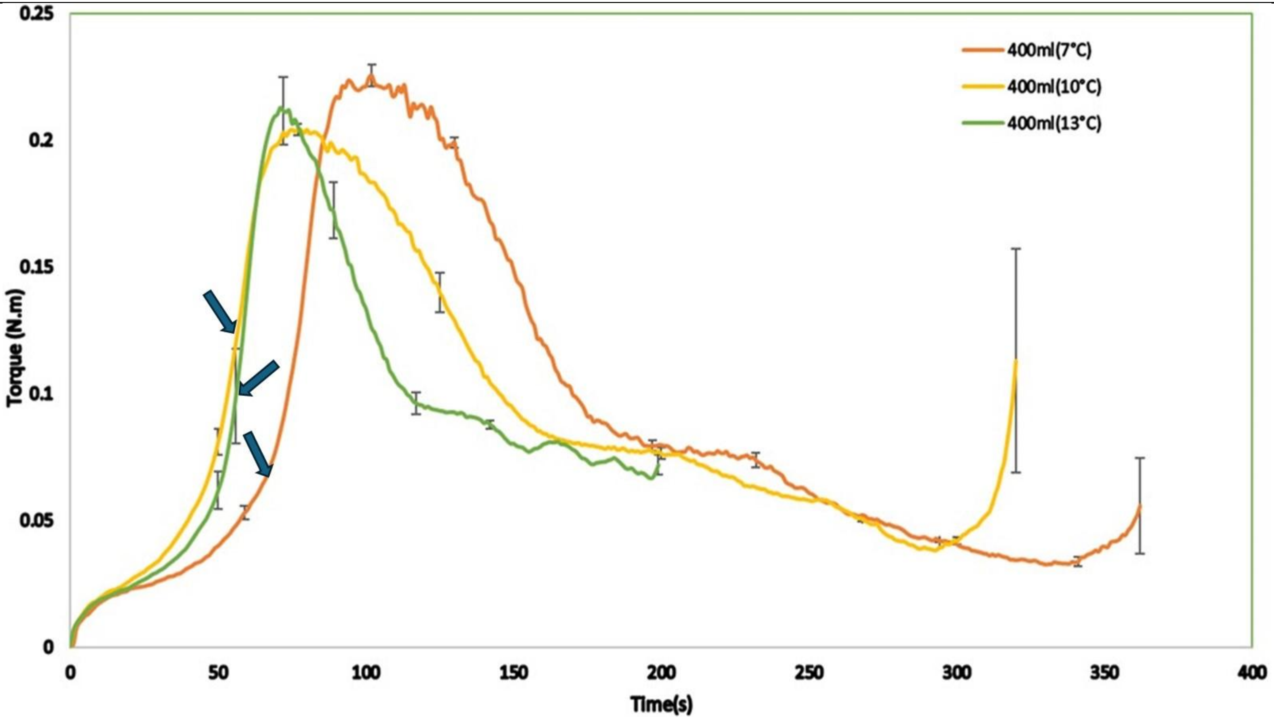
Observed under 10X		
7°C (30 sec)	10°C (30 sec)	13°C (30sec)
		
Observed under 40X (oil immersion)		
7°C (30sec)	10°C (30 sec)	13°C (30 sec)
		

(b)

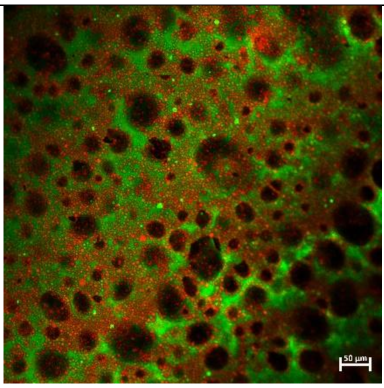
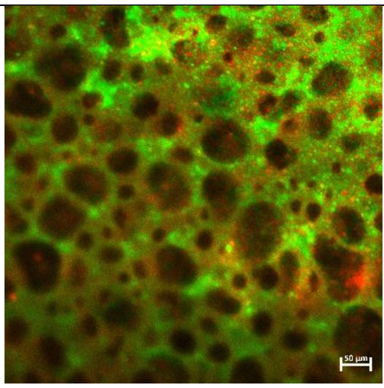
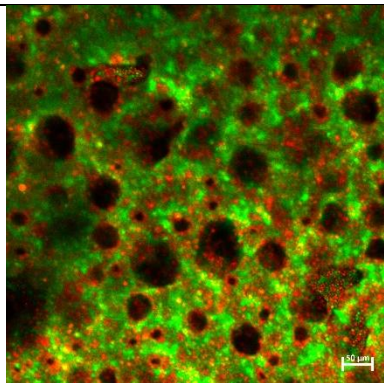
Figure 18: (a) Torque Vs Time developed during whipping cream at 7°C, 10°C and 13°C. The arrows indicate the exact point (30 sec) when the samples were collected to observe under microscope (b) CLSM foam micrographs observed at the early stage of whipping (30 sec), for different temperature.

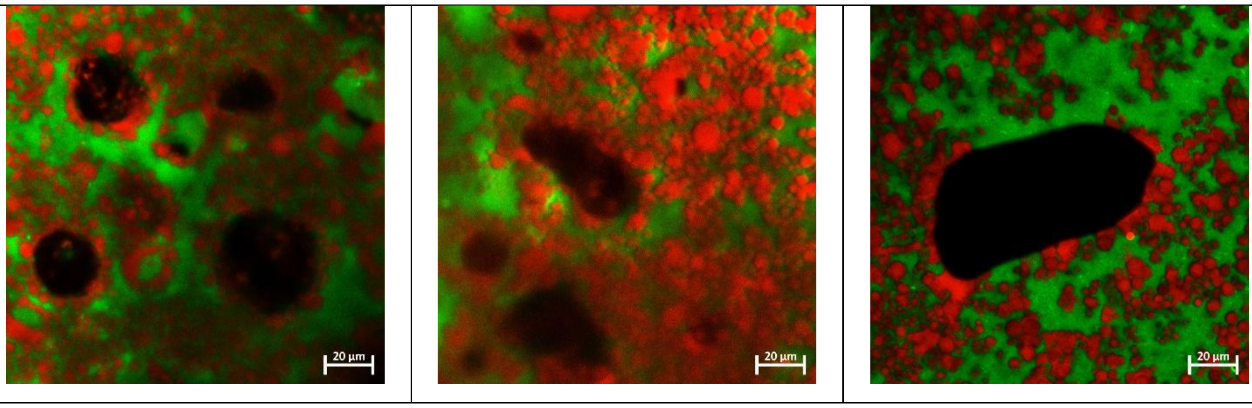
The microstructure of whipped cream at the ideal whipped stage is shown in **Figure 19b**. The images clearly showed the differences in overrun and torque. At 10x magnification, the samples whipped at 7°C and 10°C have a high density of fine, evenly distributed air bubbles. In contrast, the image of the sample at 13°C shows fewer, larger, and more scattered air bubbles. The overrun data confirms that a lower whipping temperature traps more air in a finer, more stable distribution.

Looking closer at 40x magnification provides important insight into the air bubble shapes and the stabilizing fat network. The images for 7°C and 10°C show air bubbles with clear non-spherical shapes. The fat phase, marked in red, and the protein, marked in green, form a large, interconnected network that fully surrounds the air bubbles. In the 13°C image, the structure looks less organized, featuring a very large, irregular bubble and a less cohesive fat network made up of more separate, less merged globules. This microstructural evidence supports the idea that the foam structure at higher temperatures is weaker and not as effective at trapping and stabilizing air.



(a)

Observed under 10X		
7°C (69 sec)	10°C (55 sec)	13°C (56 sec)
		
Observed under 40X (oil immersion)		
7°C (69 sec)	10°C (55 sec)	13°C (56 sec)

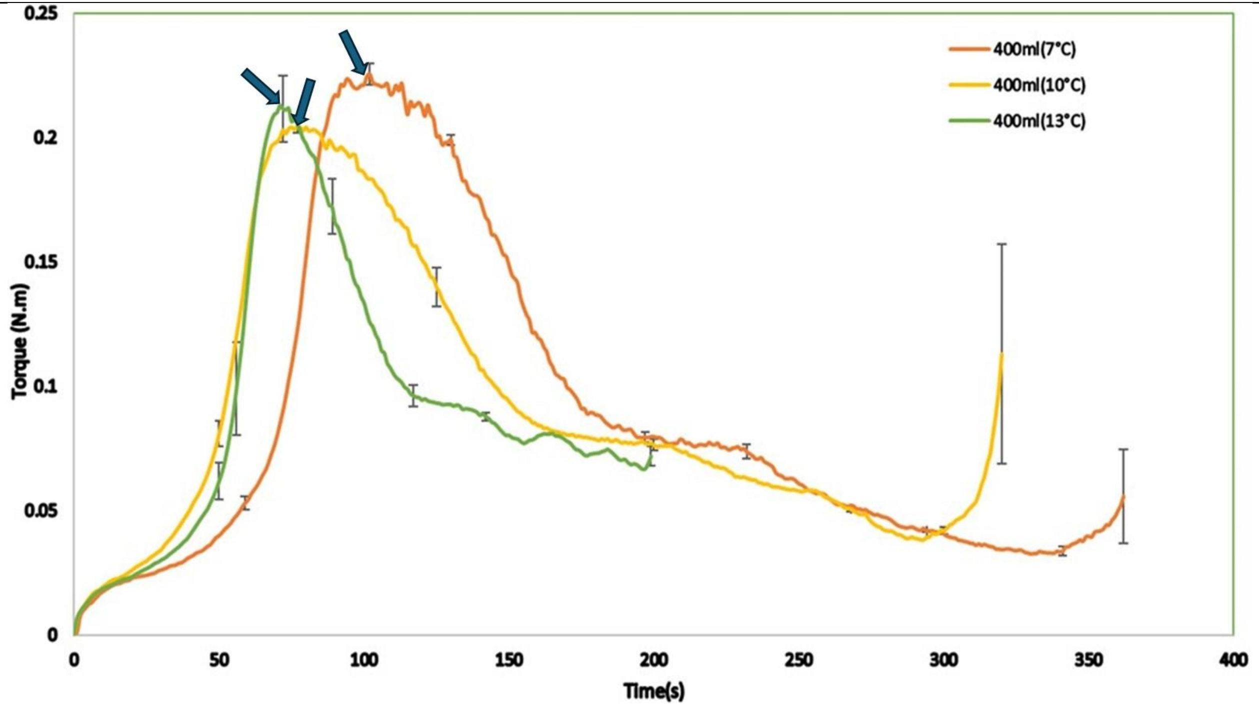


(b)

Figure 19: (a) Torque Vs Time developed during whipping cream at 7°C, 10°C and 13°C. The arrows indicate the exact point at the Ideally whipped stage when the samples were collected to observe under microscope (b) CLSM foam micrographs observed at the ideally whipped stage, for different temperature.

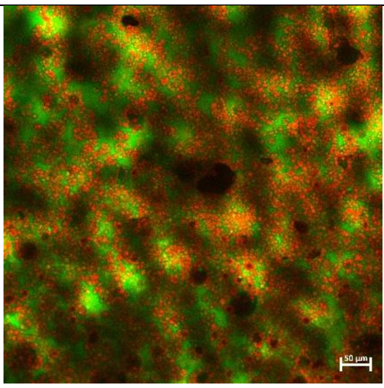
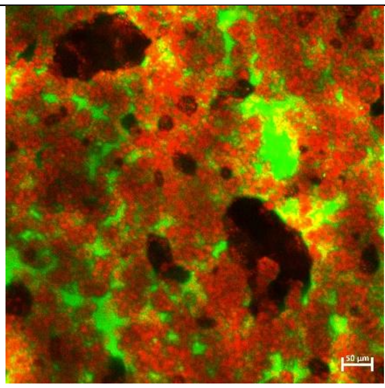
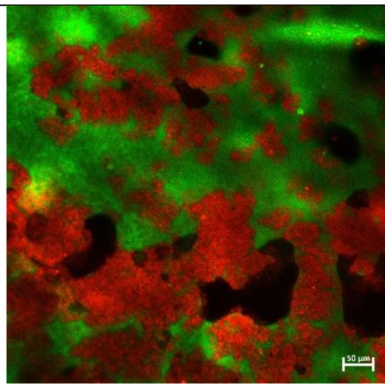
Figure 20 shows the microstructures at the maximum torque developed during whipping. The micrographs of the 13°C sample shown in **Figure 20**, revealed a highly developed, yet compromised, structure at its peak torque. Consistent with the provided observations, there was evidence of extensive aggregation of the fat globules, which appeared as damaged fat where the fat has lost connectivity. Two very distinctive phases (fat and protein) were also observed in the images, which demonstrate that there is a high degree of phase separation. Also, the air bubbles trapped are characterized as non-homogenous and non-spherical implying that the vigorous whipping of the mixture at this temperature had resulted in a chaotic and unsteady foam structure. The advanced fat aggregation and phase separation seen at 13°C directly caused the high torque peak and the quick decline, meaning the structure had reached a critical point of over-whipping and is about to collapse into a churned state.

In contrast, the micrographs of the 7°C and 10°C samples shown in **Figure 20** presented a distinctly different microstructure. These samples had fewer air bubbles compared to the ideally whipped micrographs. The air bubbles were also much larger than those in the ideally whipped cream, and their shape was non-spherical. This microstructural state suggests that at peak torque, the cream had started overwhipping. The colder temperatures likely slowed the incorporation of air and the fragmentation of large bubbles into smaller, more uniform ones, a key feature of stable whipped cream foam. This contrast shows a fundamental difference in the whipping process: the 13°C sample had reached a point of structural failure, while at 7°C and 10°C there was lots of fat globules aggregated but had not yet attained their phase separation.

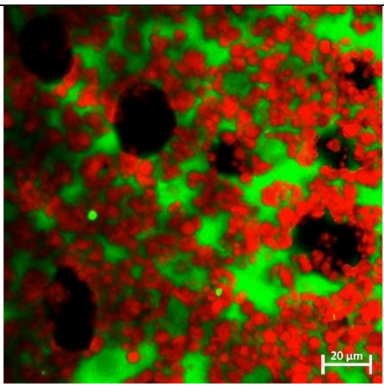
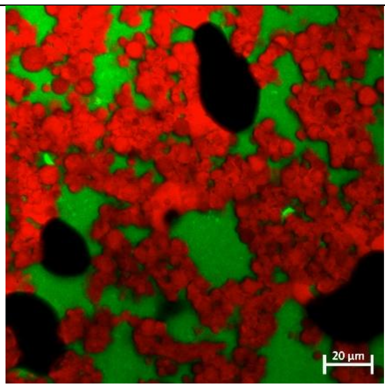
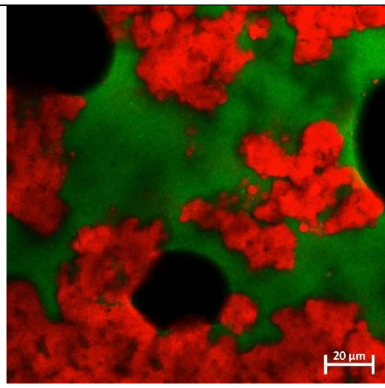


(a)

Observed under 10X

7°C (102 sec)	10°C (71 sec)	13°C (77 sec)
		

Observed under 40X (oil immersion)

7°C (102 sec)	10°C (71 sec)	13°C (77 sec)
		

(b)

Figure 20: (a) Torque Vs Time developed during whipping cream at 7°C, 10°C and 13°C. The arrows indicate the exact point at peak torque (maximum torque) when the samples were collected to observe under microscope (b) CLSM foam micrographs observed at peak torque (maximum torque), for different temperature.

5.4 OVERALL DISCUSSION

Temperature has a direct and extreme effect on both, the solid fat content (SFC), as well as on the fat crystal morphology in the milk fat globules (Rybak, 2016). At lower temperatures, like 7°C, the SFC is higher, this means a larger portion of the milk fat is in a solid state. While this can create a stiffer fat network, it may also slow down the initial partial coalescence because fat globules move less (also due to the higher viscosity in the system) and the milk fat globule membrane (MFGM) becomes more resistant to the initial shear (Nguyen et al., 2015). However, once this network is formed, it is often stronger and more stable. In contrast, at higher temperatures, such as 13°C, the SFC is lower, this indicates that there are fewer fat crystals and that there is a higher liquid fat content. In this situation, the initial partial coalescence can speed up because globule mobility increases and the MFGM is more likely to break down (Fredrick, 2011). Still, if the SFC drops below a certain point, the resulting crystal network could be weak or easily fall apart when under continuous mixing. This can lead to over-whipping and emulsion breaking too soon (Viet, 2013). Fat crystal polymorphs, SFC and partial coalescence are important in the formation of whipped cream and are widely described in scientific literature. In general, with time and appropriate holding/tempering, the less stable α-crystals (small crystals) tend to transform toward more stable β'-crystals, so at 13°C the system would be more β'-rich and structurally more ordered than at 7°C, even though the total SFC is lower. It is generally noted that larger crystals are needed to start coalescence (Brooker, 1993). Yet, if the fat crystals grow too large at low storage temperatures, they can actually prevent normal fat globule adsorption (Nguyen et al., 2015). This shows the need for an ideal size and distribution of crystals, rather than just "more" or "bigger" crystals. At 13°C, despite being the fastest at whipping, results in an extremely narrow processing window (manifested by a short peak width and rapid emulsion breaking). This indicates that the fat state at this higher temperature promotes partial coalescence too aggressively, or leads to the formation of a less stable network.

The rate and efficiency at which fat globules adsorb to the air/water interface and subsequently stabilize the air bubbles are highly dependent on the prevailing temperature. At

7°C, the slower process of fat globule destabilization and partial coalescence, shown by longer whipping times, suggests a gradual shift from protein-stabilized to fat-stabilized air bubbles. This slower and more controlled method may create a more even air cell distribution and a stronger fat network, as reflected in the wider peak width and better stability against over-whipping. At 13°C, cream starts with a lower SFC and more liquid fat. As whipping continues and temperatures increase, the fat globules are ready for fast and possibly excessive partial coalescence. The mechanical shear applied at this higher temperature pushes the system past the ideal stage of partial coalescence into irreversible over-whipping or emulsion breaking. On the other hand, creams that start at 7°C and 10°C have a higher SFC and a more stable fat crystal structure, this helps them endure longer whipping times without excessive aggregation or emulsion breaking, even as their temperatures rise to similar levels (Henderson, 2022).

At 13°C, the quick partial coalescence means fat globules rapidly take control of the air/water interface. While this leads to a swift formation of structure, if the partial coalescence is excessively aggressive, it can result in the formation of larger, less uniformly distributed air bubbles or a less stable fat network, this makes the foam more susceptible to structural collapse or disproportionation (Goff, 2013; Viet, 2013). The high rate of emulsion breaking at 13°C is a direct result of this excessively vigorous aggregation of fat globules, which results in the extrusion of serum and the final breakdown of the foam structure (Goff, 2013).

The differences in whipping time and overall foam stability are greatly affected by temperature. The air bubble stabilization of whipped cream is a dynamic multi-phase process with the initial stabilization of air bubbles done by proteins which then get replaced by fat globules that create the more stable stabilizing network (Brooker, 1993). The rate at which this fat globule adsorption will take place is, in turn, reliant on the proportion of solid-to-liquid fat which is, in turn, temperature-dependent (Brooker et al., 1986).

At colder temperatures (e.g., 7°C), the slower kinetics lead to more controlled and gradual protein displacement, creating a more consistent and stronger fat network, likely leading to a more stable air bubble structure. On the other hand, the destabilization of fat globules at higher temperature (e.g., 13°C) is very fast resulting in very fast displacement of proteins. When this is done too fast and out of control, this may produce less uniform sizes of air bubbles, or the creation of an unstable fat network that can no longer properly support the foam structure when subjected to further shear, and the foam collapses prematurely (emulsion breaking) (Han et al., 2018). Such a quick transition at 13°C may also leave less time to allow maximum air incorporation or may also lead to the creation of bigger less stable air bubbles. A complete picture of this equilibrium balance between protein displacement and fat network construction is vital in order to accurately regulate the overrun (volume increase) and the end result texture of whipped cream (Han et al., 2018). Interestingly, 12-14°C is a common temperature used in industry for cream crystallization prior to churning into butter. A narrow peak width may be desirable in this application.

5.5 CONCLUSION

Based on the results presented here, 7°C was the optimum temperature for whipping dairy cream. At this point, there seemed to be a good balance of solid and liquid fat in the globules. This balance let the whisk apply shear forces that break the globule membranes and encourage partial coalescence. This process created a strong, continuous, and rigid network around the air bubbles. This sturdy network accounted for the high firmness of 0.4 N and the impressive overrun of 101.57%. The whipping cream obtained was a very stable foam that retained its shape very well, which is why received the best visual score (though it is still not perfect—as it could be with perhaps optimized whipping UHT cream). The visual observations indicated that the use of lower whipping temperatures (7°C) produces a more stable and visually appealing structure especially in the long-run, although it is not free of initial flaws. The less stable structures formed at higher temperatures (10°C and 13°C) are also more likely to degrade quickly and 13°C is the most obvious one where the visual quality and stability are compromised most.

Chapter 6: EFFECT OF DIFFERENT FAT CONTENT IN THE WHIPPING PROPERTIES OF DAIRY CREAM

6.1 INTRODUCTION

The process of turning liquid cream into a viscoelastic foam is complex. It involves the interplay of its main components: fat globules, proteins, water, and air (Walstra et al., 2005). The stability, texture, and sensory appeal of the whipped product depend on creating a strong, three-dimensional network that traps the air bubbles in the liquid phase.

Cream is an oil-in-water emulsion, the milk fat globules are oil-droplets suspended in a liquid serum that is full of proteins, lactose, and minerals. Each fat globule is surrounded by a biological membrane called the milk fat globule membrane (MFGM), which consists of phospholipids, proteins, and enzymes (Dickinson, 2003). This membrane is essential for keeping the fat globules from merging with each other, in the liquid cream.

During the whipping process, the applied forces cause many significant changes. Air is incorporated vigorously and creates many air bubbles and the mechanical forces from the whipping action itself are sufficient to disrupt the MFGM sufficiently so that the fatty core of the globules is exposed. Since fat no longer is supported by the membrane, the globules are prone to partially coalesce, this process leads to fat globules grouping together and combining imperfectly, so they keep some of their original round shape while forming larger, irregular clusters (Rousseau, 2000).

The amount of fat content in cream is important for its functional and physical traits, particularly when it comes to whipping cream. The important characteristics of whipped cream, such as its texture, foam stability, and ability to trap air, depend largely on the fat content and its composition. The fatty acid composition of milk fat varies among species, which is also important. Bovine milk usually has less of the medium-chain fatty acids like lauric acid (C12:0), and myristic acid (C14:0), compared to human milk. The compositional differences in milk are also evident in components like gangliosides GD3 and GM3, with lower concentrations of these fatty acids at the hydrophobic end of gangliosides in bovine milk (McSweeney et al., 2020).

The different variations in bovine milk fat emphasize its unique structural characteristics, which influence its particular functionality in dairy products. The solid fat content (SFC) in whipped cream production is a significant factor, that influences the consistency of the foam. Whipped cream's structural integrity is compromised due to insufficient fat globule adsorption at the air-water interface, causing destabilization of the foam (Brooker, 1990). Temperature also plays an important role in modulating the behaviour of fat during whipping process. An increase in temperature can cause solid fats to partially melt, which in turn affects their crystallization pattern. Excessive high temperatures can lead to undesirable flavours like scorching, negatively affecting product quality (Templeton & Sommer, 1933). By maintaining the temperature at an ideal range, this allows solid fats to participate fully in the formation of the foam without affecting sensory attributes (Henderson, 2022).

Many defective whipped creams display morphological abnormalities resulting from inadequate interactions between fat crystals and air bubbles. The penetration of needle like fat crystals across air-water interface can impede the adsorption of fat globules, resulting in decreased foam stability. The presence of such defects highlights the need to optimise fat composition and processing conditions to achieve the desired product characteristics (Brooker, 1990).

Seasonal variations add complexity to the consistency of whipped cream functionality. Seasonal changes impact solid fat content (SFC), which in turn influences emulsification and crystallization behaviours (Henderson, 2022). The formulations need to be tailored by taking environmental factors into account, which impact dairy production. Advances in process technology have allowed for major changes in dairy operations, such as improvements in maintaining fat content during production. Ensuring consistent quality across different applications involves using technical knowledge in these production systems (Tamime, 2009). Understanding how fat content and composition impact at molecular level, the whipping process, can provide insights into optimizing dairy formulations for industrial applications (Truong et al., 2020; Zhang et al., 2024). When considering the factors that contribute to the success of whipping cream, fat content is one of the most important factors. The amount of fat determines how many fat globules are available to form the stabilizing network. Higher fat content usually results in a greater volume of dispersed fat, this leads to more frequent collisions between globules and increases the chances of partial coalescence (Hinrichs & Kessler, 1997). Currently in the dairy industry, a level of 36% of fat content is used.

In this chapter, how whipping performance and the appearance of fresh cream change at different fat contents of 32%, 36%, and 40% was examined. Key parameters like torque development during whipping, the time required for the best whipping consistency, and peak torque values during this process, were all monitored. The goal was to measure how fat concentration affects the whipping process. This chapter also addresses the challenges that arise when whipping high fat content creams, focusing especially on the 40% fat cream.

6.2 MATERIALS AND METHODS

6.2.1 MATERIALS

Please refer to Section 3.1

6.2.2 METHODS

6.2.2.1 SAMPLE PREPARATION

In order to prepare 400 ml of 32% and 40% fat content creams, using 36% fat cream, centrifugation and careful recombination were used. A quantity of 400 ml of 36% fat cream (store bought) was placed in a water bath at 40°C for 5 minutes to create the best separation conditions. After that, the cream was spun in a centrifuge (Multifuge X4R Pro, ThermoFisher Scientific, Germany) at 4000 × g for 5 minutes with temperature set at 40°C. This process formed a fat-rich layer at the top, which contained about 50-60% fat, while the bottom had a skim milk phase with approximately ≤1% fat, as shown in **Figure 21**. This separation uses centrifugal force to concentrate fat globules and is a common method in dairy processing for fractionating and standardizing cream.

After centrifugation, the two distinct layers were carefully separated. The aim was to create two new mixtures, each with a specific fat percentage. For the preparation of 400 ml of 32% fat cream, 356 ml of the original 36% fat cream was combined with 44 ml of the skim milk obtained from the centrifugation process. This mixture adjusts the fat concentration downward by incorporating the lower-fat skim phase.

In order to obtain 400 ml of 40% fat cream, 308 ml of the original 36% fat cream was mixed with 92 ml of the fat-rich layer (~ 55% fat) derived from the centrifugation. This approach increases the overall fat concentration by adding the enriched cream phase, consistent with methods used in laboratory and industrial settings for precise fat content adjustment through recombination of separated dairy fractions.

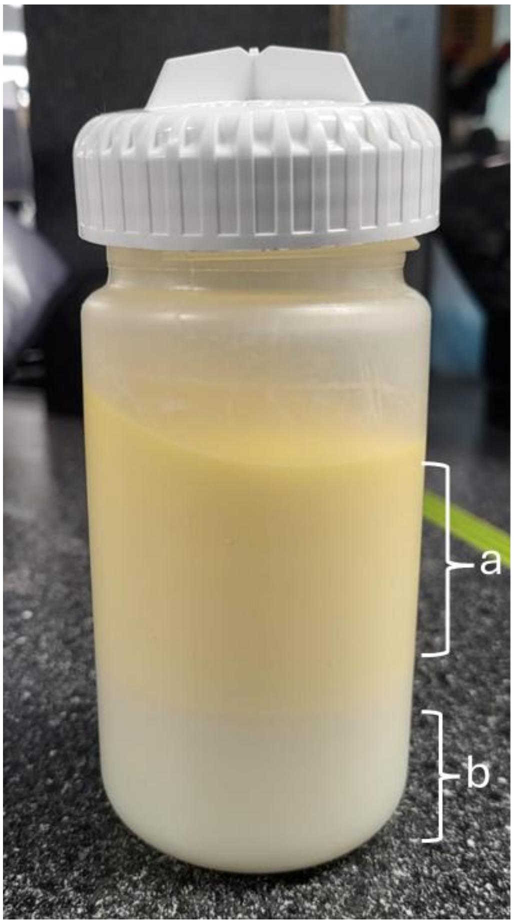


Figure 21: Centrifuged 36% fat cream; the top layer (a) is the fat rich layer, and the bottom layer (b) is the skim milk.

Commercial cream bought on different days was centrifuged in two separate trials. The trials showed that the cream was always damaged to some degree after centrifugation, given the yellowish colour of the top cream layer shown in **Figure 21**. It is acknowledged here that the cream may suffer damage to the milk fat globule membrane (MFGM) due to pretreatment with the water bath and centrifugation. It is known that this damage affects the fat globules' ability to stick together. As a result, the fat can whip faster but also become more susceptible to over-whipping and structural breakdown (Dickinson, 2003).

6.2.2.2 WHIPPING PROCEDURE

Please refer to Section 3.2.2.

6.2.2.3 TORQUE VS TIME ANALYSIS

Please refer to Section 3.2.3.

6.2.2.4 OVERRUN

Please refer to Section 3.2.4.1.

6.2.2.5 FIRMNESS

Please refer to Section 3.2.4.2.

6.2.2.6 FOAM STABILITY

Please refer to Section 3.2.4.3.

6.2.2.7 FOAM MICROSTRUCTURE

Please refer to Section 3.2.4.4.

6.3 RESULTS AND DISCUSSION

6.3.1 FOAM FORMATION: TORQUE VS TIME ANALYSIS

Figure 22, shows the torque measurements versus time obtained during the whipping of various fat content creams (32%-40%) with the calculated parameters given in **Table 9**. At 32% fat content, the whipping process showed a gradual increase in torque, peaking at 190 seconds at about 0.10 N.m. The "ideally whipped" state occurred at 158 seconds. This slower development is likely to happen because of the lower concentration of fat globules, taking therefore more time to create a stable network around the air bubbles. In contrast, the whipping process at 36% fat content was much faster. Peak torque was reached at 77 seconds, at a doubled torque value (0.204 N.m), even though the peak width was not significantly different. The optimum whipping time (or time to reach the “ideally whipped state”) was 55 seconds. This is a direct consequence of the higher fat content, which allows for faster aggregation of fat globules and a more rapid formation of the three-dimensional foam structure. This faster rate of network formation can be quantified by the higher value of the exponential growth coefficient (k) at 36% fat cream (0.04 sec^{-1}) compared to the 32% fat cream (0.025 sec^{-1}). However, the reduction in whipping time was not linear and when the fat content was increased to a 40% fat level, the time to reach peak torque (0.6 N.m), increased again to 116 seconds, taking 60 sec to reach the “ideally whipped” state. The increase in fat content to 40% translated into a three times higher peak torque reading due to the stronger fat network created, presumably due to the additional fat particles that can now be incorporated into the foam structure. However, this came to a cost, the optimum whipping time was slightly slowed down, from 55 to 60 sec.

The profile at 40% fat content in **Figure 22**, can't be only attributed to the amount of fat present, but also to the likely presence of damaged MFGM, as indicated in Section 6.2. Damaged MFGM would make the fat globules stickier and more likely to clump together, even before whipping starts. This tendency to stick probably also led to the very high peak torque seen with the 40% cream. The sharp vertical increase in torque likely reflects the network being formed at high speed, creating a rigid structure that would also make the cream very sensitive to over-whipping. This would explain the sharp rise and fall of the torque curve, with no plateau, and the torque variations after 150 sec. The cream rapidly changes from a liquid to a very stiff foam and then rapidly breaks up as the fat globules merge into butter completely by releasing water and air. This fast and unstable transition is likely to be the reason why it was not possible to calculate some of the time constants parameters of this cream correctly—therefore their absence in the table.

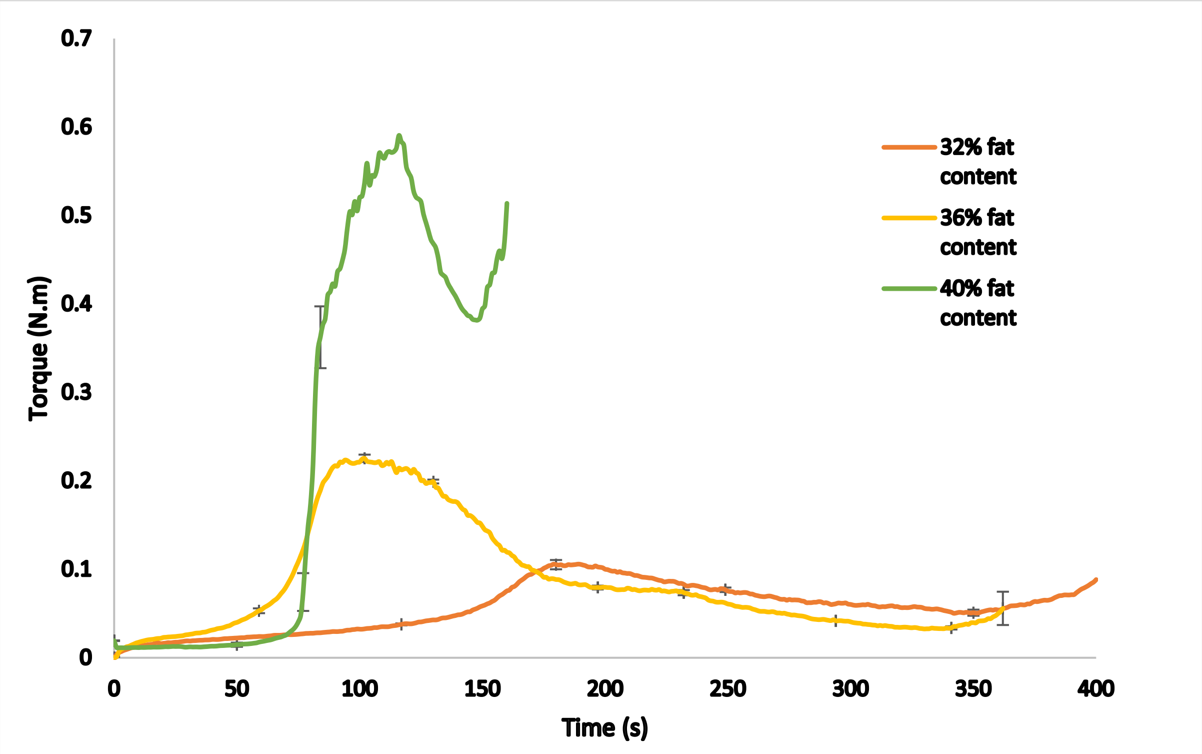


Figure 22: Comparative analysis of the torque developed over time during the whipping of 400ml fresh cream with different fat content (32%, 36% and 40%).

Table 9: Parameters obtained from the Torque Vs Time graph for whipping 400ml fresh cream with different fat content (32%, 36% and 40%).

Parameter	400ml (32%)	400ml (36%)	400ml (40%)
Exponential time constant (s)	9.56 sec ± 1.1	1.704 sec ± 1.16	-
Exponential growth coefficient (sec^{-1})	0.025 ± 0.006	0.04 ± 0.005	-
Peak torque (N.m)	0.10 N.m ± 0.003	0.204 N.m ± 0.003	0.590 N.m ± 0.02
Time taken to reach peak Torque (s)	190 sec ± 4.02	77 sec ± 1.5	116 sec ± 3.0
Optimum whipping time (s)	158 sec	55 sec	60 sec
Peak width	37 sec	36 sec	-

6.3.2 FOAM CHARACTERISATION: ROSETTE STRUCTURE, FIRMNESS, OVERRUN AND MICROSTRUCTURE OF WHIPPED CREAM

The visual rosettes are shown in **Figure 23**, and the results for firmness obtained from texture analyzer and overrun percentages are given in **Table 10.**The visual rosette scoring, the firmness and overrun, all showed similar trend: the 36% fat cream exhibited the best whipping qualities, whereas both the 32% and the 40% fat creams were lacking in several aspects, even though for different reasons. This is specifically due to the nature of the interaction of the fat globules and air bubbles in the process of whipping.

The visual appearance of the whipped cream rosettes directly correlates with the quality of the internal foam structure. The 32% fat cream received a score of 3, and the image shows a soft, slightly slumped rosette. This score matches the lower firmness (0.15 N) and lower overrun (93.35%), indicating a less rigid foam. The concentration of fat globules is lower, and as a result, the development of the supporting fat network is less dense, which makes it softer and less defined in shape.

In contrast, the 36% fat cream received an excellent visual score of 4, which corresponds to being "on the verge of being unacceptable". Visually, the photos show a well-defined, stiff rosette with sharp edges, a pointing peak, and minimal slumping. This difference is significant. The strong visual structure comes from the high concentration of fat globules, which form a dense, stable network that effectively traps and stabilizes the air bubbles. This is also confirmed by the high overrun (101.57%), meaning there is great incorporation of the air and a much greater firmness value (0.4 N)— more than twice of the values obtained with 32% cream. Just for clarification, the rosettes were scored with the help of technical staff who scores this on daily basis within a dairy company. Higher scores would correspond to rosettes produced from optimized formulations like those found for UHT whipping cream.

The 40% fat cream shown in **Figure 23,** received the lowest score of 1, indicating an undesirable structure with no desirable attributes. The figure shows a very coarse, grainy, and severely slumped rosette. This result is a clear manifestation of the fact that the fat globules were likely damaged during the concentration process (water bath heating and centrifugation). This damage caused a rapid and uncontrolled semi-coalescence of fat globules during whipping and likely phase-inversion, leading to the formation of small butter lumps instead of a fine, interconnected fat network. The resulting structure is not a stable foam, it is the result of an over-damaged emulsion which can't form the correct network to trap effectively the gas. This explains the very low overrun of 42.85% and low firmness of 0.18 N, which is only slightly higher than the 32% cream, even though it has a much higher fat content.

Fat content in the cream was used for whipping	**Rosette made immediately after whipping**	**Rosette after 24hr storage**
32% fat content		

36% fat content		
40% fat content		

Figure 23: Rosettes formed at different fat contents made right after whipping to the "ideally whipped point" and after 24 hrs storage at 4°C.

Table 10: Texture Analyzer results i.e. firmness (N) and overrun percentages for different fat content cream used for whipping

Whipping done at different fat contents	**Firmness (N)**	**Overrun %**
400ml (32%)	0.15 ± 0.00	93.35%
400ml (36%)	0.4 ± 0.03	101.57%
400ml (40%)	0.18 ± 0.00	42.85%

Overall, the firmness results matched the visual scores. The 36% fat cream was the firmest at 0.4 N, which aligns with its better foam structure and high overrun. The 32% fat cream was considerably softer (0.15 N), reflecting its weaker fat network. The 40% fat cream had a firmness of only 0.18 N, which, while slightly higher than the 32% cream, is still a very poor result considering its high fat content, this low firmness shows that the high fat content did not create a stable foam, as explained above, due to probably the presence of damaged fat while standardizing the fat content to 40%.

The overrun data gives important information on the efficiency of air incorporation. Overall, the 36% fat cream achieved an impressive overrun of 101.57%, indicating an efficient process for capturing and stabilizing air, this high overrun is a direct consequence of a well-formed fat network that can effectively encapsulate a large volume of air. The 32% fat cream had still a respectable but lower overrun of 93.35%. The most telling result is the very low overrun of 42.85% for the 40% fat cream, confirming that the mechanical action, instead of creating a stable foam, caused quickly overwhipping, easily collapsing the foam structure which could not hold the air effectively.

The confocal microstructures in **Figure 24** confirm that the structure with the best fat connectivity and with fat globules maintaining very native spherical shapes surrounding the bubbles, corresponded to 36% fat. This foam showed a very good air gas distribution detected as the black areas. Similar gas distribution was evident at 32% fat content; however the fat seemed to have a greater degree of semi-coalescence as observed by the red areas in the microstructure, which would indicate a greater tendency to overwhipping. Clearly at 40% fat, massive coalescence was evident, reflected in the size of the fat droplets detected, lacking connectivity, and with very poor gas trapped—or lack of black areas observed.

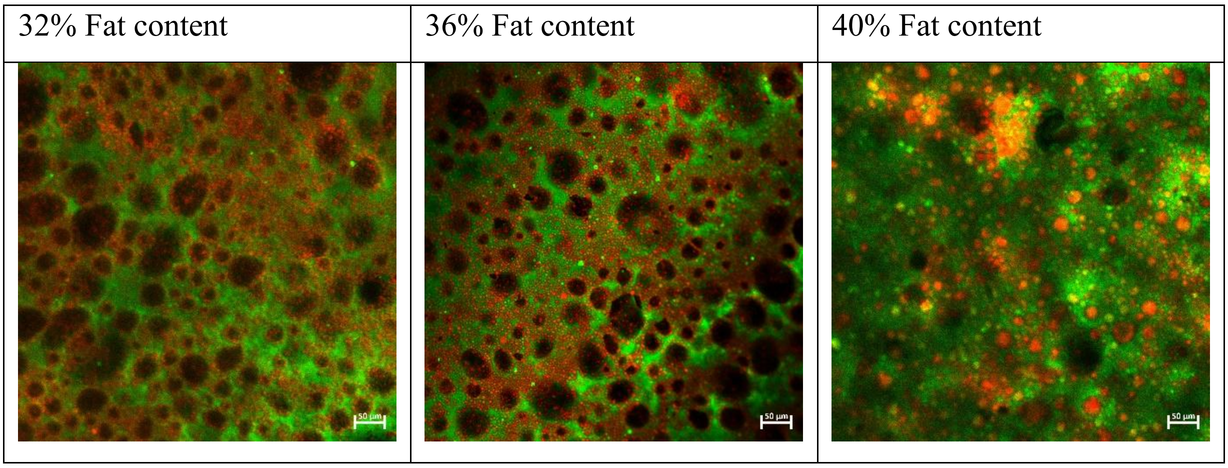
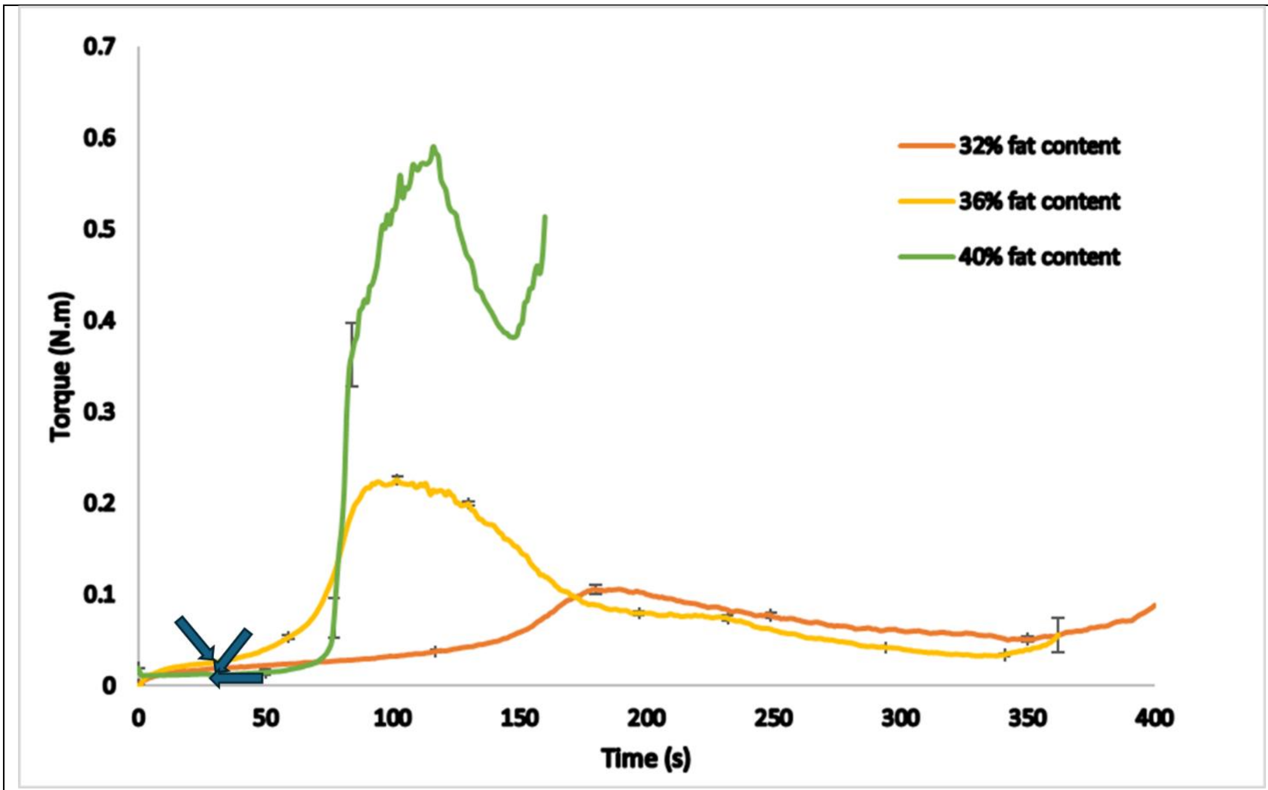


Figure 24: CLSM foam micrographs observed at the ideally whipped points, after whipping cream with different fat contents.

6.3.3 MONITORING OF WHIPPING CREAM TO OBSERVE THE EFFECTS OF DIFERENT FAT CONTENT ON THE WHIPPING PROCESS

Figure 25 shows the micrographs after whipping cream for 30 sec with various fat contents. The 10x micrographs at 32% fat content showed a continuous serum phase with dispersed fat globules and the initial formation of big air bubbles. High-magnification observations at 40x revealed that the air-serum interface was defined by the adsorption of discrete fat globules with some areas of protein. This result shows that at lower fat concentrations, the main process at 30 seconds is the movement of fat to the interface, without significant clumping or network formation.

In contrast, at 40% fat, the foam showed signs of substantial structural change even at this early stage of whipping (30 seconds). The CLSM images shown in **Figure 25** reveal a microstructure that looks "damaged" or highly unstable. Unlike the discrete globules seen at 32% fat, the 40% sample displayed large, irregular fat aggregates in the 10x view, which indicates fat globule clustering. At 40x magnification, the fat appeared packed closely together and partially coalesced with a substantial increase in droplet size.



(a)

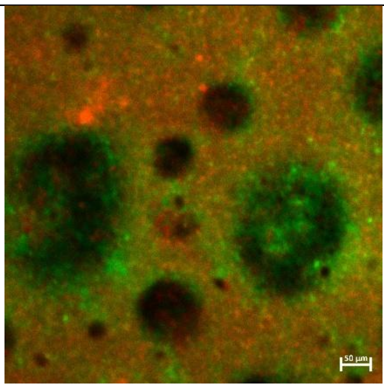
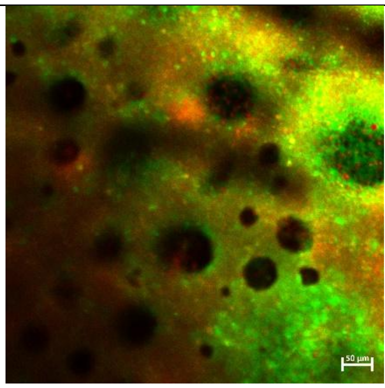
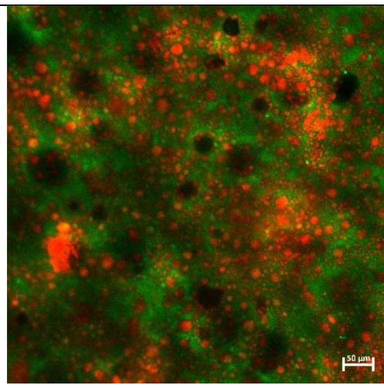
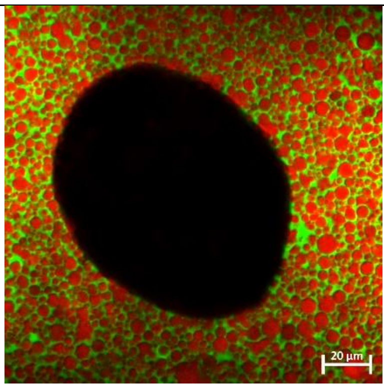
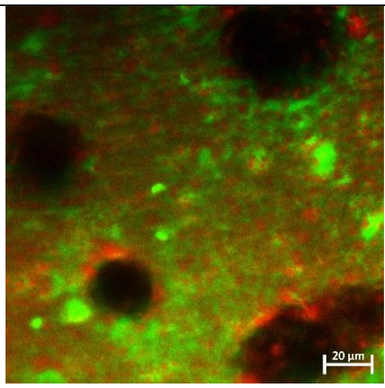
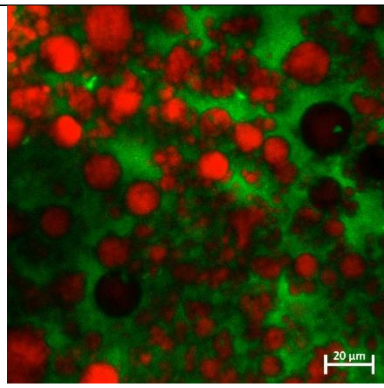
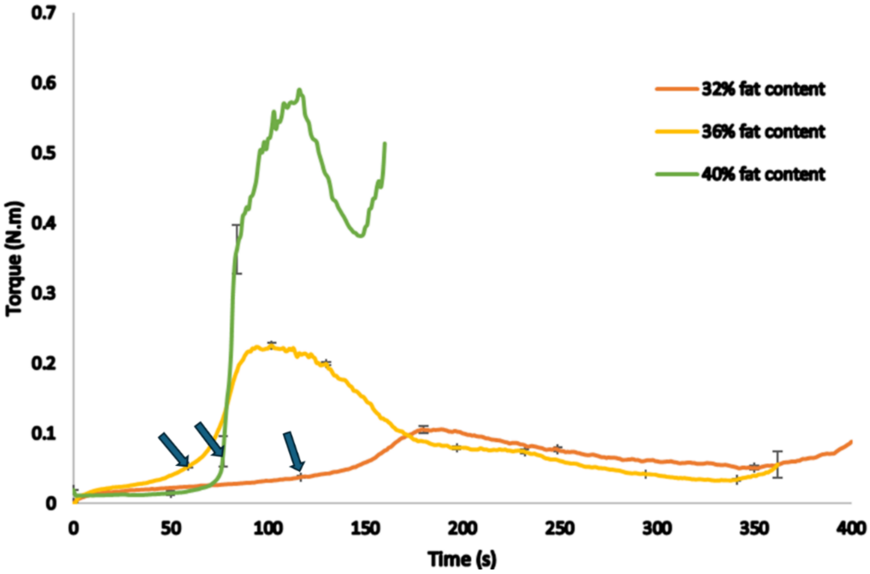
Observed under 10X		
32% fat content (30sec)	36% fat content (30sec)	40% fat content (30sec)
		
Observed under 40X (oil immersion)		
32% fat content (30sec)	36% fat content (30sec)	40% fat content (30sec)
		
(b)		

Figure 25: (a) Torque Vs Time developed during whipping cream with different fat content of 32%, 36% and 40%. The arrows indicate the exact point (30 sec) when the samples were collected to observe under microscope (b) CLSM foam micrographs observed at the early stage of whipping (30 sec), for different fat content.

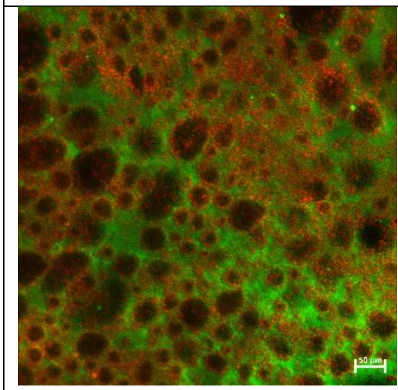
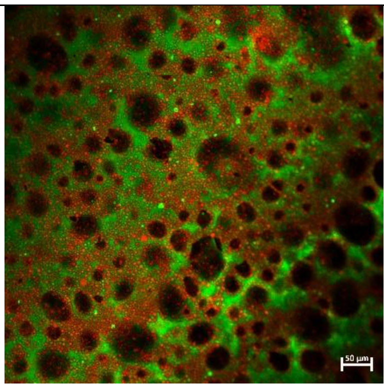
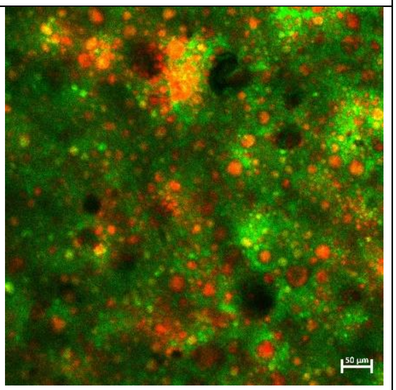
In **Figure 26**, the micrographs at the ideally whipped stage, showed that at both 10x and 40x magnifications the foam microstructures at 32% and 36% fat contents, were morphologically similar. A network of fat globules stabilised the air bubbles in both samples, but the distribution is noticeably uneven. The images revealed distinct phase separation, marked by separated bands in the serum phase (green) and fat globules (red). This variation indicated that, although a foam structure formed, the emulsion stability in these lower-fat versions allows a significant pooling of the serum phase between the air cells. The bubble size also seemed smaller than at the earlier stages of whipping confirming a reduction in air bubbles during whipping.

The foam microstructure at 40% fat cream was very different; as seen in the 40x (oil immersion) micrographs, the fat phase appeared densely clustered with larger, irregular groups of fat globules. Unlike the distinct globule networks seen at 32% and 36% samples, the 40% fat content sample showed signs of "damaged fat" or excessive partial merging with very low concentration of air bubbles observed. This structure implies that the sudden increase in torque shown in the rheological data relates to an aggressive clumping of fat globules. While this structure provides high stiffness, the presence of these large, merged fat globules suggests the sample has entered the early stages of churning (phase inversion) even at the ideally whipped point.

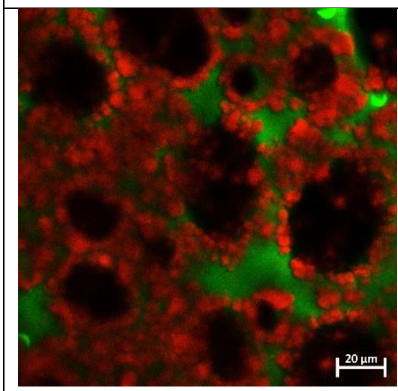
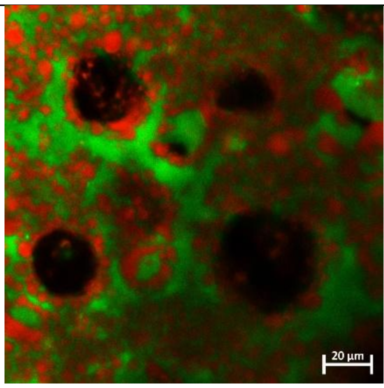
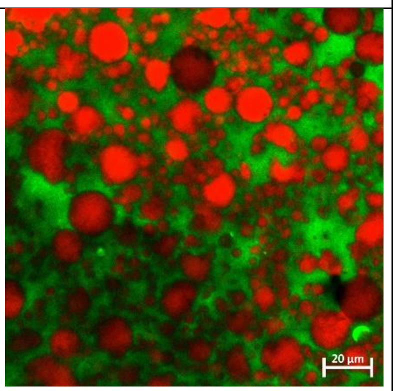


(a)

Observed under 10X

32% fat content (158 sec)	36% fat content (55 sec)	40% fat content (60 sec)
		

Observed under 40X (oil immersion)

32% fat content (158 sec)	36% fat content (55 sec)	40% fat content (60 sec)
		

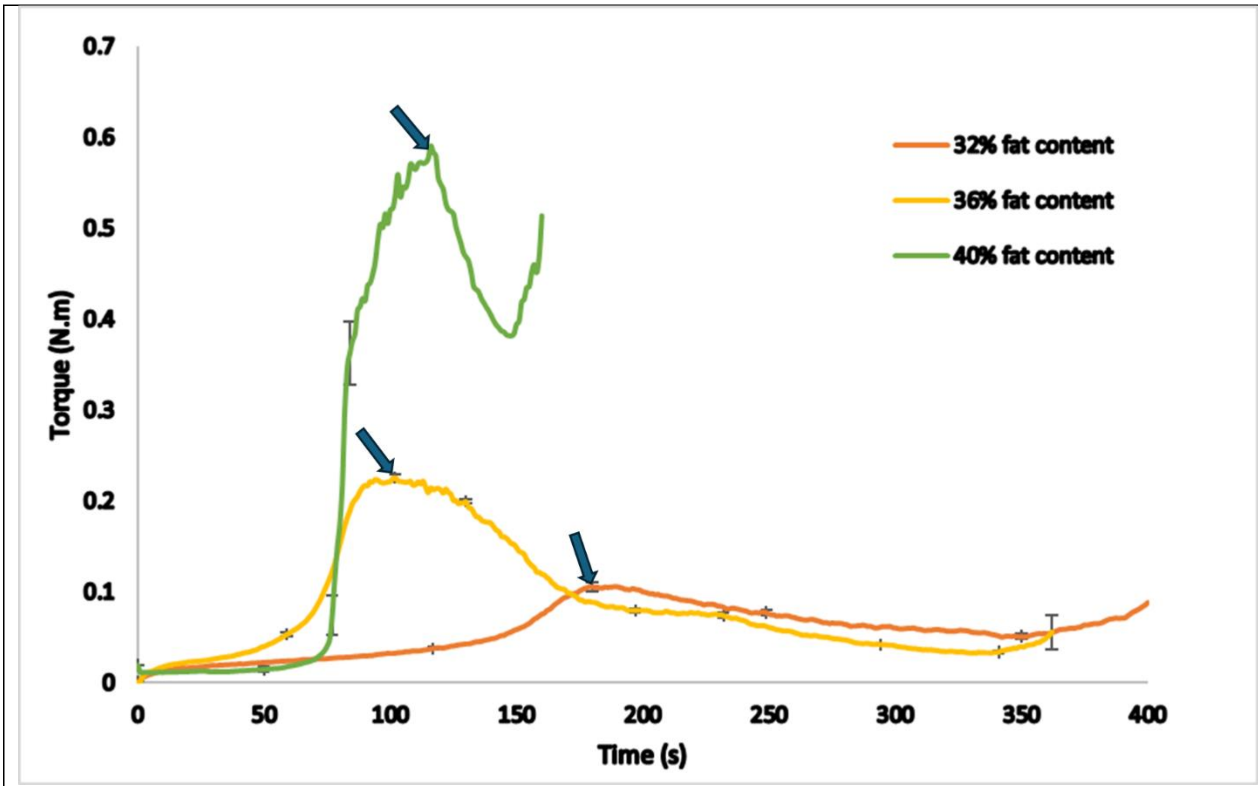
(b)

Figure 26: (a) Torque Vs Time developed during whipping cream with different fat content of 32%, 36% and 40%. The arrows indicate the exact point (ideally whipped stage) when the

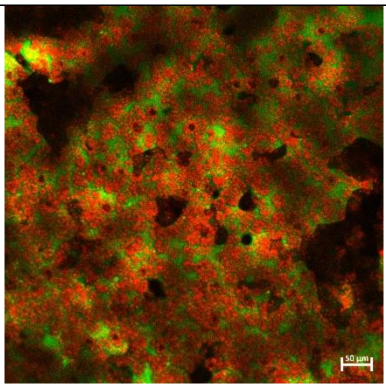
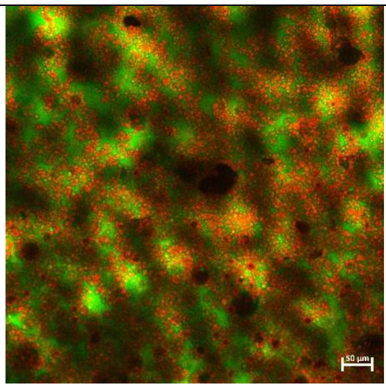
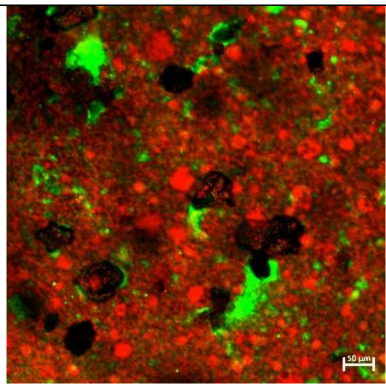
samples were collected to observe under microscope (b) CLSM foam micrographs observed at ideally whipped stage, for different fat content.

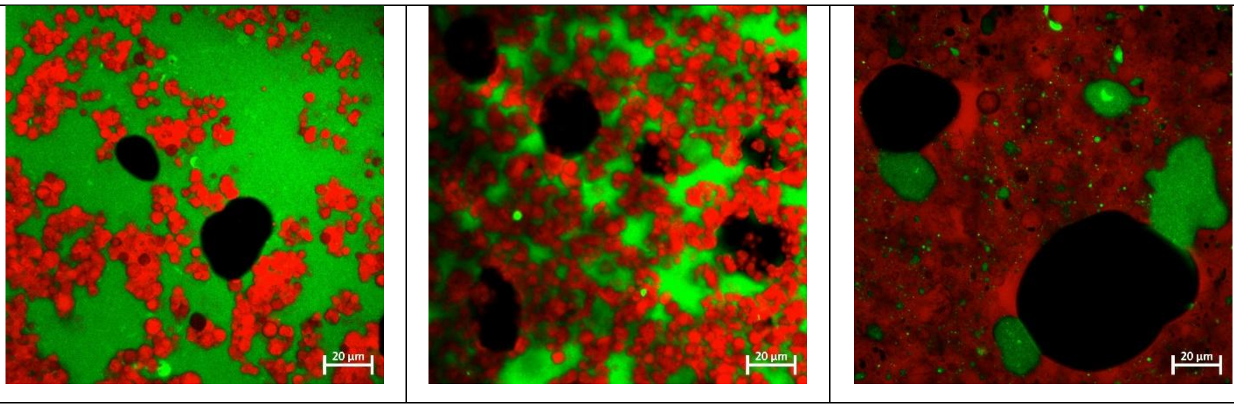
Figure 27 showing the foam microstructures at the maximum torque point, confirmed the presence of non-spherical gas bubbles, especially at 32% and 36% fat content. The air bubbles were linked to each other losing their round shape and forming channels especially at 32% fat. This linking of air cells is an important step that comes before the breakdown (breaking point) of the foam structure. The red fat globules were also merged having lost their spherical shaped, forming more of a connected network around the gas at 36% fat compared to 32%.

Clearly, at 40% fat cream, the foam structure exhibited the highest peak torque, with also the most significant structural changes as already observed at the early whipping times. The large, irregular black voids (air bubbles) had merged together. Additionally, the image clearly showed phase inversion: smaller and separate droplets of the green-stained aqueous phase (water droplets) were now trapped in a continuous matrix of the red-stained fat phase (butter structure). The fact that the 40% fat sample at peak torque already showed signs of phase inversion, and an aggregated fat matrix suggests it has moved into a butter-like state, or "breaking point," where the foam structure was replaced by a fat-continuous phase. This confirms that for high-fat creams, the mechanical peak torque occurs at the same time as or immediately after the transition to butter.



(a)

Observed under 10X		
32% fat content (190 sec)	36% fat content (70 sec)	40% fat content (116 sec)
		
Observed under 40X (oil immersion)		
32% fat content (190 sec)	36% fat content (70 sec)	40% fat content (116 sec)



(b)

Figure 27:(a) Torque Vs Time developed during whipping cream with different fat content of 32%, 36% and 40%. The arrows indicate the exact point (peak torque) when the samples were collected to observe under microscope (b) CLSM foam micrographs observed at peak torque (maximum torque) of whipping, for different fat content.

6.4 OVERALL DISCUSSION

The combined results from the torque vs. time analysis during whipping, and the foams attributes analysed (firmness, overrun, microstructure and visual appearance), lead to a clear conclusion about how fat content affects the whipping of fresh cream. Overall, the 36% fat cream stands out as the best option, achieving a good balance between whipping time and product quality. This is probably not a surprise, as this is the fat content found in commercial whipping cream.

As fat content increases, whipping becomes faster and peak torque rises. This is due to the quicker and more extensive formation of the fat globule network (Dhungana et al., 2020). The 36% cream demonstrated a significantly shorter optimum whipping time compared to the 32% cream (55 sec and 158 sec, respectively). It also reached a much higher peak torque (maximum torque), which indicates a stronger and more stable foam structure was created in less time. This conclusion is backed by the data from whipping cream characterization. The 36% cream displayed superior firmness at 0.4 N and a high overrun of 101.57%. This confirms that the quick formation of the fat network seen in the torque analysis resulted in a stable and well-aerated foam. The high visual score of 4 for the rosette further supports this, showing a strong and defined foam structure that can hold its shape well.

Although the 40% cream whipped nearly as quickly, at 60 seconds, and produced a much higher peak torque, this whipping speed negatively affected the quality of the final product. An important factor in the analysis is that the 40% fat cream was sensitive to fat globule damage during preparation. This pre-existing damage, probably due to the high-shear effect of the centrifugation and temperature variability of the water bath, may have resulted in a weakened fat globule membrane (MFGM). Recombined creams, where globules are coated with non-native interfacial layers instead of intact MFGM, show different and often faster partial coalescence behaviour and clump formation, consistent with reduced resistance to aggregation when the native membrane is absent or damaged (Andrade & Rousseau, 2021). This was probably the case here in the present study.

The impact of fat content on the whipping properties have been previously investigated in the 80's (Moor & Huyghebaert, 1982) and recently reviewed (Dabo et al., 2024). The earlier study reported that decreasing fat content from 42% to 38% increased whipping time, increased overrun, and reduced firmness of the whipped cream foam, directly demonstrating that lower fat levels impair the formation of firm, stable whips even within the high-fat range. The fact that we could not observe and improvement of the whipping properties when increasing the fat content in this study is the likely due to the interference of the presence of damaged fat.

6.5 CONCLUSIONS

The whipping behaviour was predicted quite successfully by the torque vs time analysis, and the characterization data validated the quality of the final product. This study highlights the fact that the rate of whipping can be increased by increasing the fat content in the cream, but that physical integrity of the fat globules, before whipping, is ultimately the most important factor in determining the quality of a high-superior whipped product.

High fat concentrations (e.g., 40% fat content) dramatically accelerated the phase change. The mechanical peak torque in these samples coincided with the loss of foam structure and the transition to a butter-like state via extensive fat aggregation and water-in-oil phase inversion. The cream with 36% fat content was able to create a stable, interconnected fat globule network that traps air effectively without turning into butter, so it will be the best option for whipping dairy cream.

Chapter 7: SUMMARY

7.1 CONCLUSIONS

The aim of this research was to systematically investigate the three most critical variables governing the emulsion to foam transformation: the initial volume of cream, the initial whipping temperature, and the different fat content. Furthermore, the study successfully validated a monitoring protocol combining rheological torque profiling and confocal laser scanning microscopy (CLSM) to visualise and study the microstructural evolution of the foam, varying different factors.

In Chapter 4, the effect of the initial cream volume on the whipping properties was studied. This provided crucial insights into how shear stress distribution influences foam microstructure. The comparison of 200 mL, 400 mL, and 600 mL cream volumes demonstrates that the effective shear environment substantially determines the rate and extent of fat-network development. Larger volumes exhibited more pronounced air bubble deformation, thicker fat networks, and earlier signs of structural stress.

- The 400 ml volume emerged as the optimal processing condition for the specific equipment used (Kenwood mixer). It achieved a balance between aeration and structure, yielding a firmness of 0.4 N and an overrun of 101.57%. This volume allowed for the formation of an evenly distributed air bubble matrix stabilised by a robust yet sufficiently aerated fat network. Hence, the 400ml of cream was used for further studies in this research.
- The 600 ml samples exhibited the highest peak torque (0.33 ± 0.005 N.m) and firmness (0.44 ± 0.04 N) but the lowest overrun (89.46%). As the volume increases, the probability of collision between fat globules rises under shear, creating a robust structural scaffold. However, this density comes at the cost of aeration; the stiff fat network resists the incorporation of air, resulting in a heavier product with a lower volume yield.
- the 200 ml samples achieved the highest overrun (123.97%) but produced the softest foam (0.29 N). While the low volume allowed for efficient air incorporation, the resulting fat network was too sparsely distributed to maintain structural integrity.

Microstructural analysis confirmed that at peak torque, the 600 ml samples displayed highly distorted, non-spherical air bubbles and the formation of interconnected channels. This deformation indicates that the mechanical stress exerted by the dense fat network exceeded the Laplace pressure attempting to keep the bubbles spherical, placing the foam in a state of high stress near the point of rheological failure.

In Chapter 5, the effect of the initial cream temperature on the whipping properties was studied. The comparison between 7°C, 10°C, and 13°C revealed that maintaining a low temperature is essential for stability.

- At 7°C, the high SFC provided the fat globules with sufficient rigidity to resist premature coalescence. This condition produced the most stable foam with the highest overrun (101.57%) and maximal firmness (0.4 N). The CLSM micrographs at 7°C showed fine, evenly distributed air bubbles surrounded by a cohesive fat network.
- Increasing the temperature to 13°C had catastrophic effects on foam quality. The reduction in solid fat rendered the globules softer and more susceptible to shear-induced damage. While the whipping process was accelerated, reaching peak torque in just 71 seconds compared to 102 seconds at 7°C, the resulting structure was severely compromised. The overrun plummeted to 73.25%, and the firmness dropped to 0.29 N.

The CLSM imaging provided the definitive explanation for this failure: the 13°C samples exhibited "phase inversion" at peak torque. The CLSM micrographs from the ideally whipped stage further confirmed these relationships: lower temperatures produced finer, densely distributed air bubbles with a strong, cohesive fat network that imposed non-spherical bubble geometry. Higher temperatures generated fewer, larger bubbles and a looser fat matrix, which correlates with lower overrun and reduced foam stability. The presence of pronounced phase separation and visible syneresis at peak torque in the 13 °C sample clearly indicates that the structural framework was no longer able to retain the aqueous phase, marking an early transition toward churning.

In Chapter 6, the effect of different fat content in the whipping properties of dairy cream was studied. The comparison between 32%, 36%, and 40% fat content highlighted that while fat is necessary for structure, increasing its concentration does not linearly improve quality due to the kinetics of aggregation.

- The 36% fat cream proved to be the ideal formulation, achieving the highest firmness (0.4 N) and overrun (101.57%) with a superior visual score of 4. This concentration provided enough fat globules to coat air bubbles efficiently and form a continuous network without overcrowding the continuous phase. The microstructural analysis showed a balanced distribution of fat and serum, creating a two-network system that effectively trapped air.

- At 40% fat cream, despite reaching the highest peak torque (0.590 N.m), the foam exhibited the lowest overrun (42.85%) and a poor visual score of 1. The CLSM imaging revealed that the high fat globule concentration led to immediate and uncontrolled coalescence. The globules appeared as large, dense clusters rather than a fine network. This suggests that the high collision frequency in the 40% cream caused the system to bypass the stable foam stage and move directly to a churned, butter-like state. This was likely exacerbated by damage to the MFGM during the concentration process (centrifugation). The CLSM micrographs showed clear evidence of phase inversion, with a continuous fat matrix enclosing aqueous droplets, structural characteristics of butter formation.
- The 32% cream was functional but suboptimal. It whipped significantly slower (158 seconds to reach the ideally whipped stage) and produced a much softer foam (0.15 N). The lower concentration of fat globules resulted in a less dense network, evidenced by serum pooling in the CLSM images.

Comparing the results across all chapters reveals that the optimum conditions for whipping dairy cream rely on a specific synergy of formulation and processing parameters. The ideal product profile was consistently achieved under the following conditions:

- Fat Content: 36% (balances network strength with aeration efficiency).
- Temperature: 7°C (ensures high SFC for rigid, stable globules and a wide processing window).
- Volume: 400 ml (optimized to the vessel capacity to ensure efficient shear without over-processing).

In conclusion, this thesis establishes that the physical properties of whipped cream texture, stability, and appearance are direct macroscopic manifestations of the microscopic state of the milk fat globule network. By strictly controlling the temperature to maintain solid fat content, optimizing the fat concentration to 36%, and standardizing the batch volume, manufacturers can consistently produce high-quality whipped cream that balances the competing demands of aeration and structural rigidity. The use of torque profiling offers a valid, real-time method to detect the onset of phase inversion, preventing the costly defect of over-whipping in industrial production. Deviations from optimal conditions—too much fat, excessive heat, or excessive shear—accelerate structural breakdown and promote early churning. These findings reinforce established theories of whipped-cream formation while providing detailed microstructural evidence that clarifies how small changes in process parameters can dramatically alter foam behaviour.

7.2 RECOMMENDATIONS FOR FUTURE WORK

Throughout this research, key recommendations for future work were identified:

- It is recommended to investigate the impact of different whipping blade designs and mixer geometries to determine their specific effects on shear distribution and the whipping process.
- It is recommended to employ instant freezing techniques using liquid nitrogen (cryo-fixation) to better preserve the delicate foam architecture for microstructural analysis.
- It is recommended to use more controlled cream that have not undergone damage by centrifugation or similar separation processes to ensure the milk fat globule membrane (MFGM) remains intact and undamaged prior to experimentation.
- It is recommended to create model emulsion systems where specific components such as fat types, protein sources, and emulsifiers can be systematically varied to isolate their individual contributions to foam stability and derive conclusions on whipping process.
- It is recommended to apply the UHT treatment to the model emulsion systems, to study the effects of Ultra-High Temperature (UHT) treatment on whipping properties.

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APPENDIX

Figure 28: Nutritional label and packaging of the fresh cream (Pams, New Zealand) utilized throughout the study.

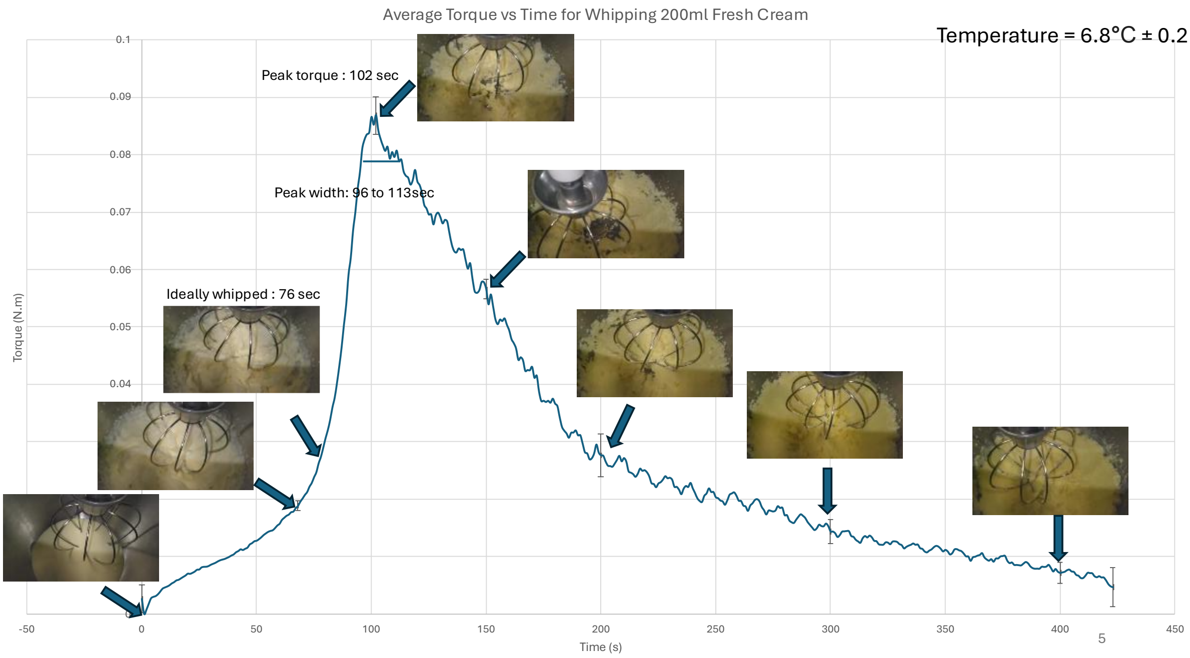


Figure 29: Average Torque vs Time for Whipping 200ml Fresh Cream

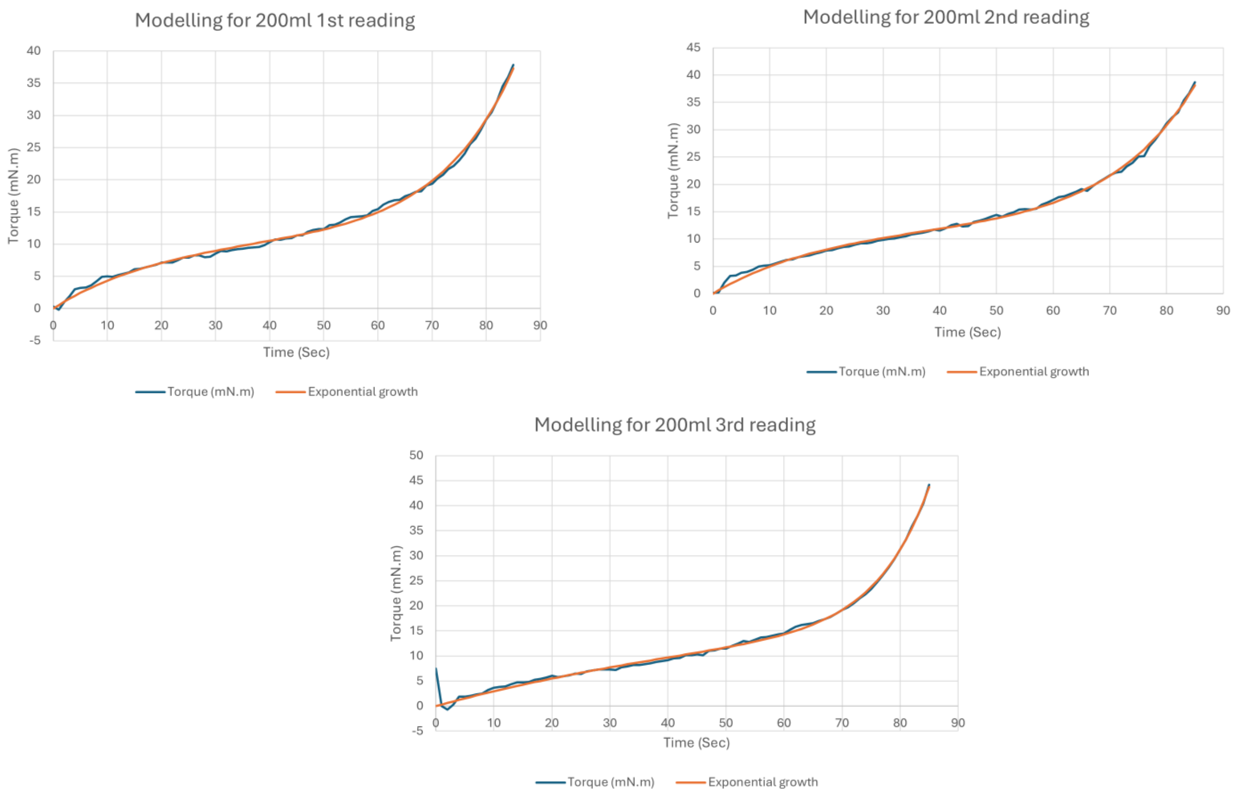


Figure 30: Mathematical modelling of torque evolution during the whipping of 200ml fresh cream.

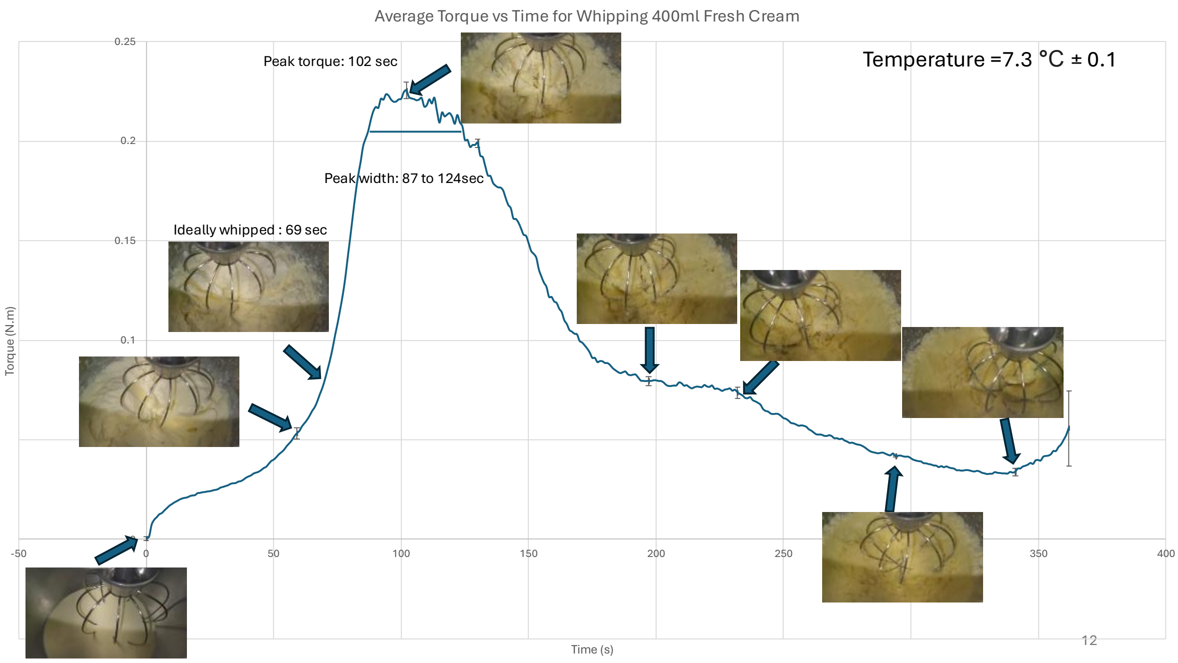


Figure 31: Average Torque vs Time for Whipping 400ml Fresh Cream

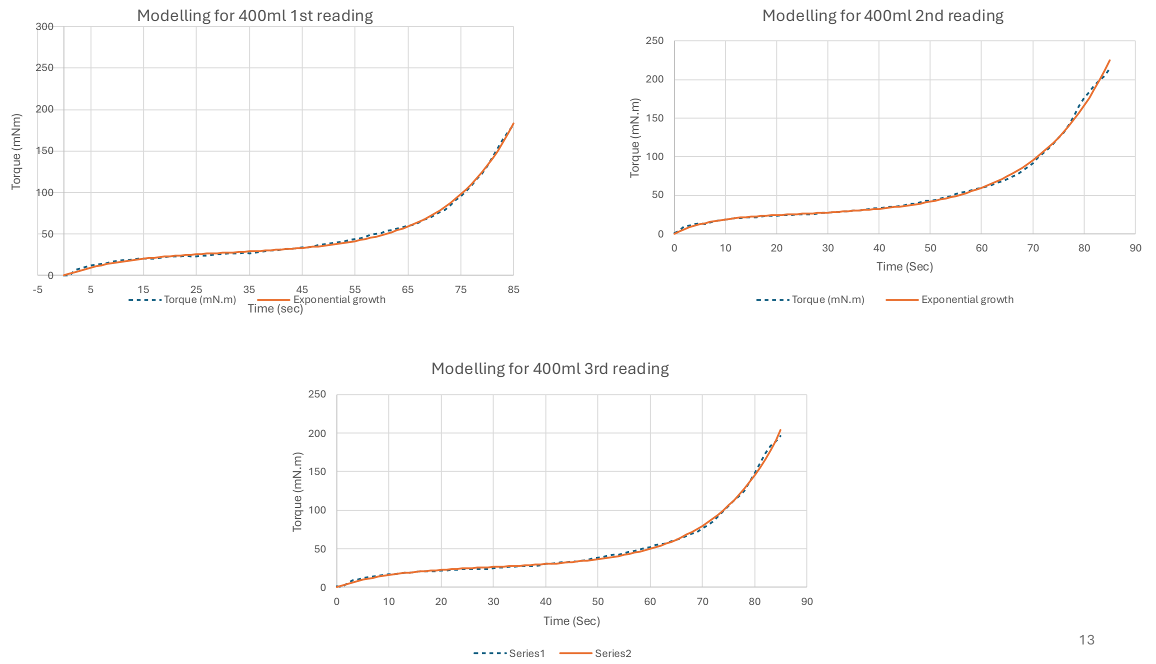


Figure 32: Mathematical modelling of torque evolution during the whipping of 400ml fresh cream.

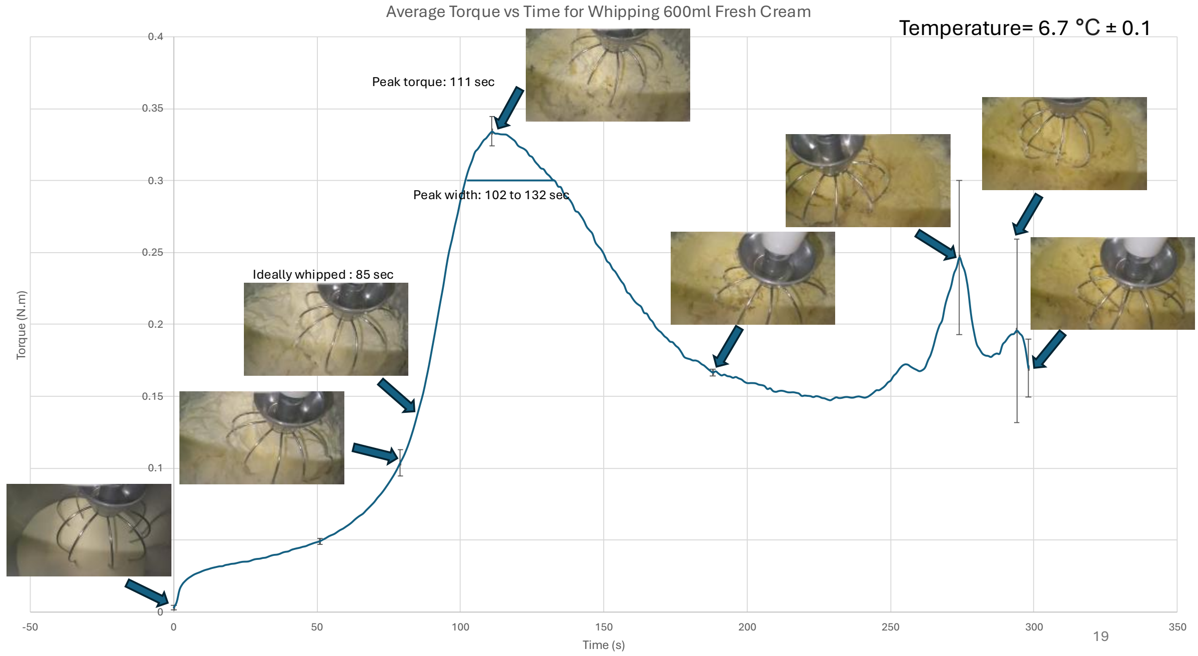


Figure 33: Average Torque vs Time for Whipping 600ml Fresh Cream

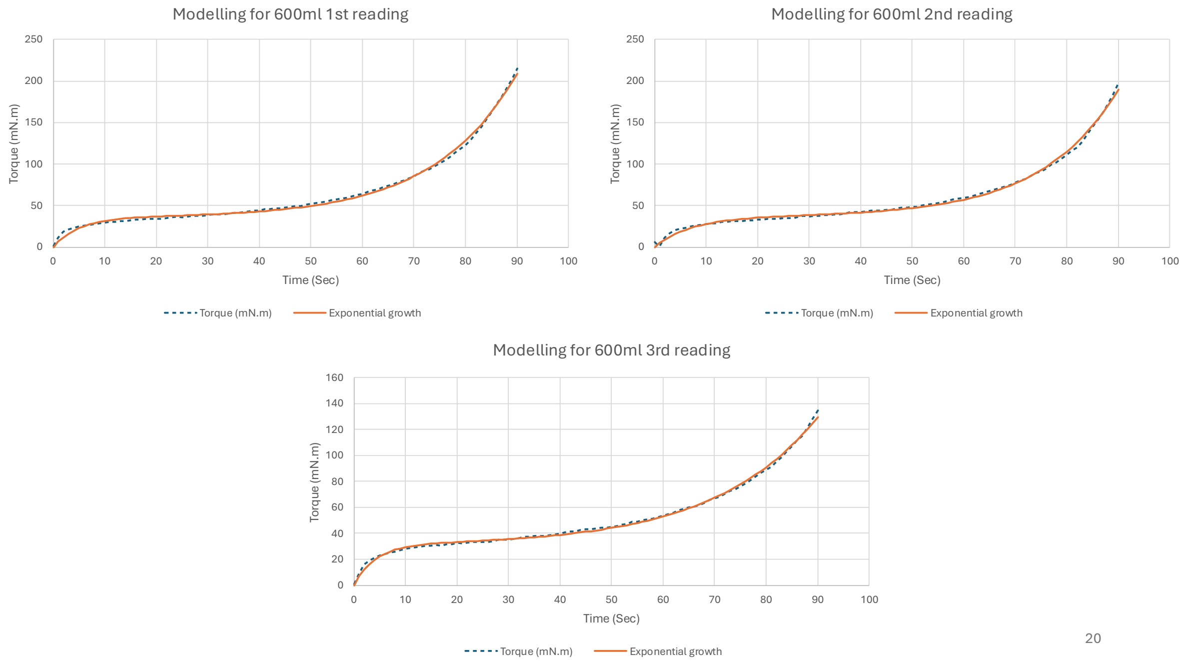


Figure 34: Mathematical modelling of torque evolution during the whipping of 600ml fresh cream.

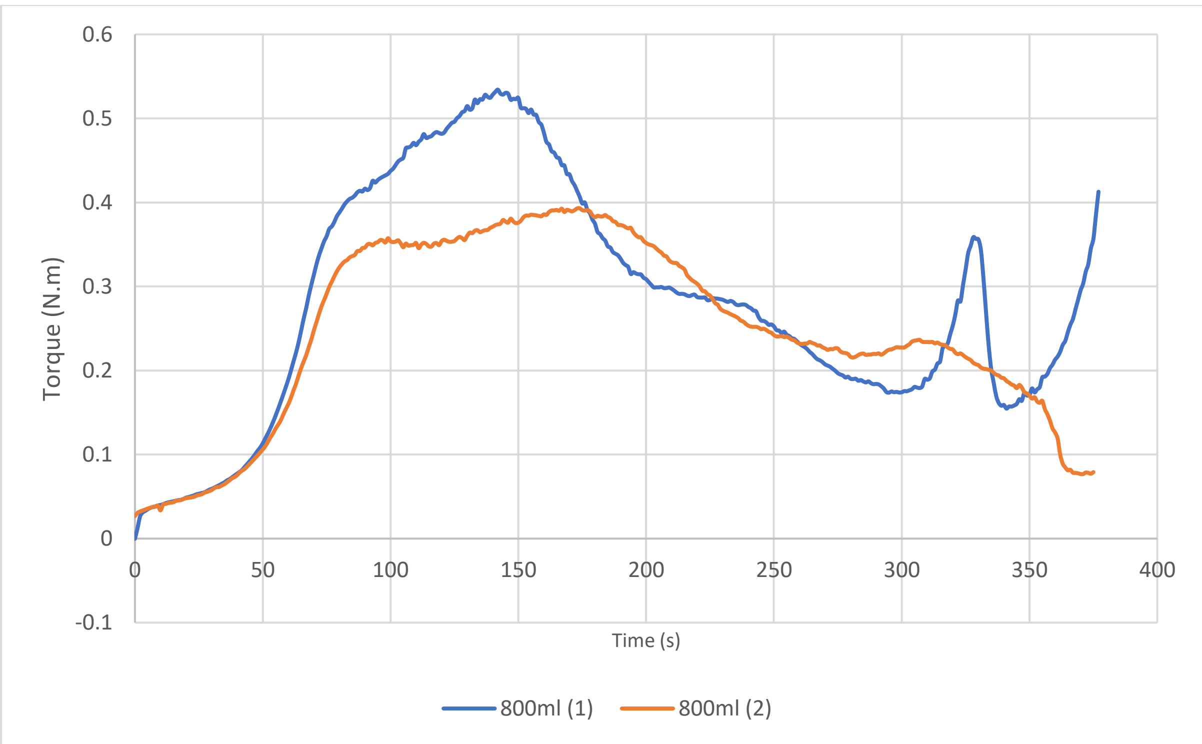


Figure 35: Torque vs Time for Whipping 800ml Fresh Cream: Comparative Analysis of replicates

Table 11: Experimental data showing the temperature before and after whipping the replicates for effect of initial cream volume and time required to reach butter formation.

Trial No.	*Initial Volume (mL)*	*Temperature (°C) before whipping*	*Temperature (°C) After whipping*	*Time to Butter (min)*
1	200ml (Reading 1)	7°C	13°C	7 min
2	200ml (Reading 2)	6.4°C	12.2°C	7 min
3	200ml (Reading 3)	7°C	13°C	7 min
4	400ml (Reading 1)	7°C	12.2°C	6 min
5	400ml (Reading 2)	7.5°C	12°C	6 min
6	400ml (Reading 3)	7.4°C	12.6°C	6 min
7	600ml (Reading 1)	6.7°C	11.3°C	5 min
8	600ml (Reading 2)	6.8°C	11.2°C	5 min
9	600ml (Reading 3)	6.7°C	11.2°C	5 min
10	800ml (Reading 1)	6.4°C	12.2°C	6 min
11	800ml (Reading 2)	6.5°C	12.2°C	6 min

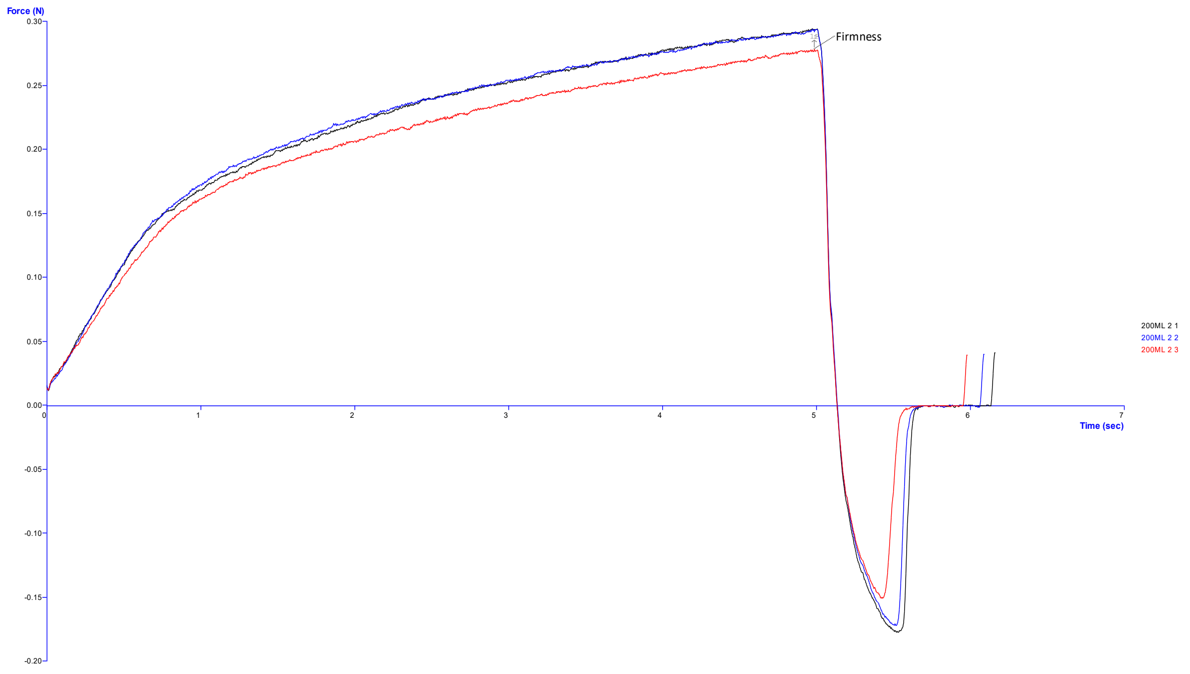


Figure 36: Texture Analyzer graph for 200ml

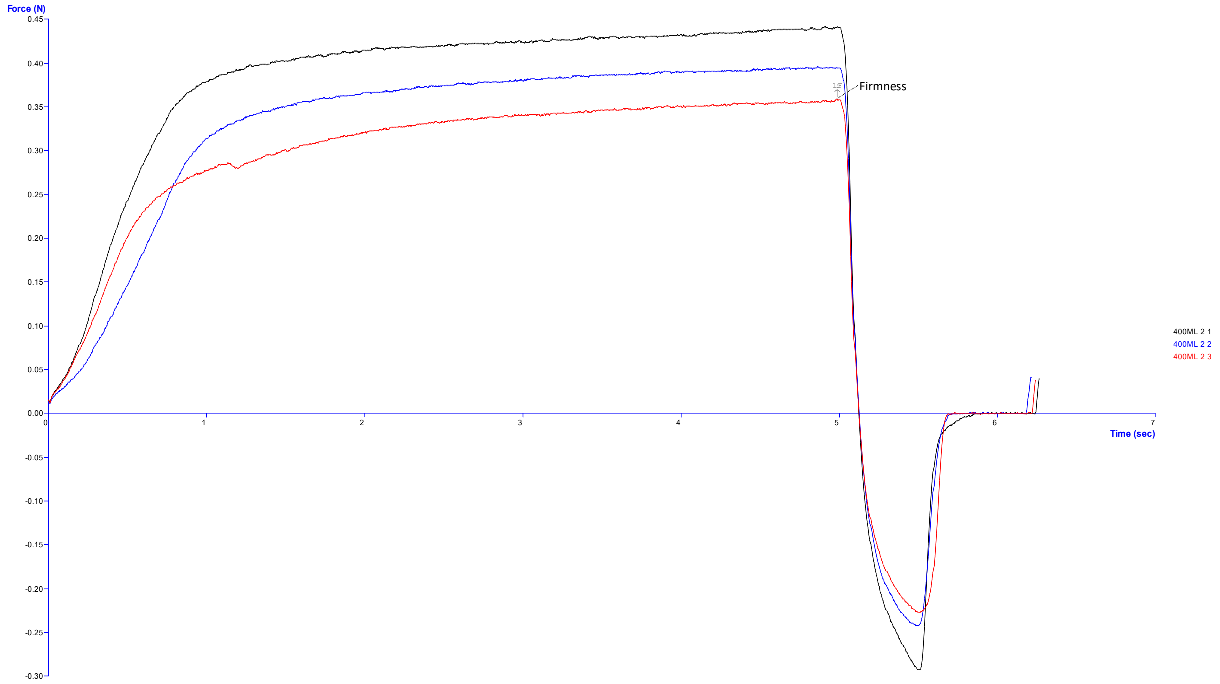


Figure 37: Texture Analyzer graph for 400ml

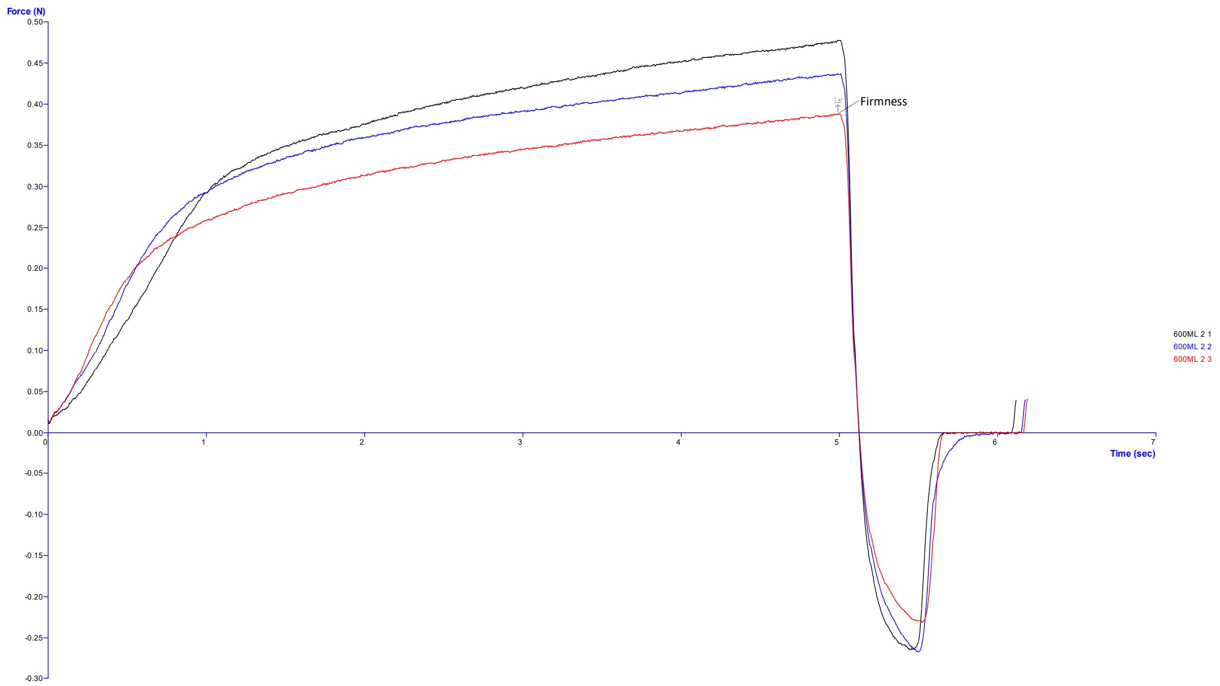


Figure 38: Texture Analyzer graph for 600ml

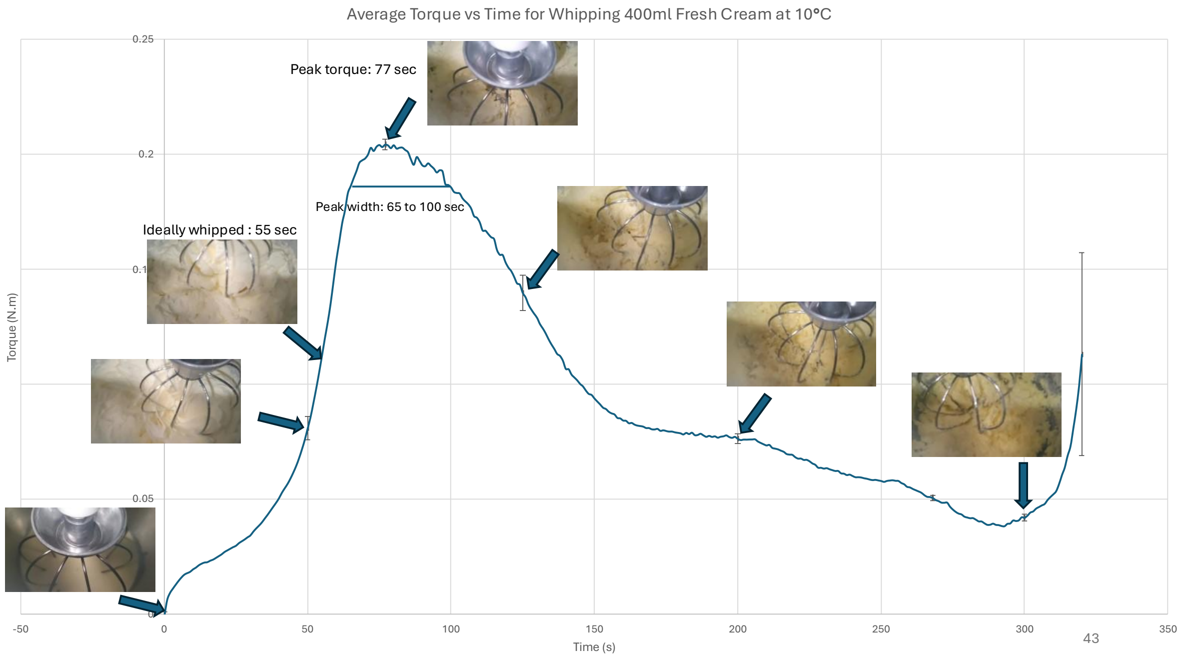


Figure 39: Average Torque vs Time for Whipping 400ml Fresh Cream at 10°C

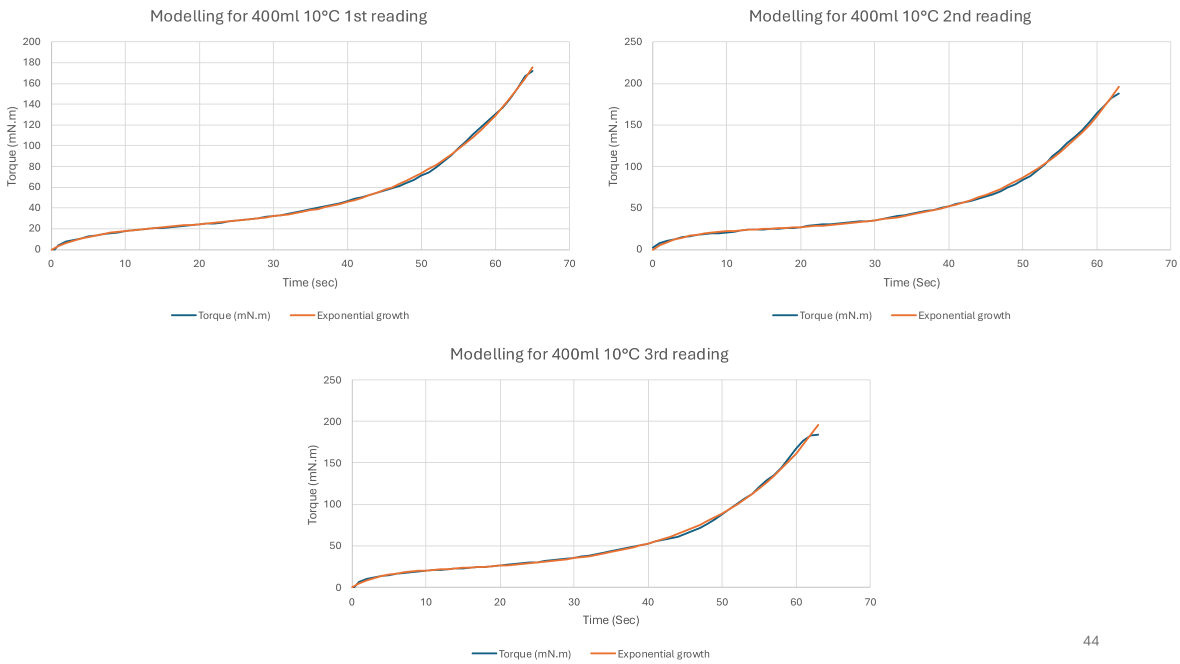


Figure 40: Mathematical modelling of torque evolution during the whipping of 400ml fresh cream at 10°C.

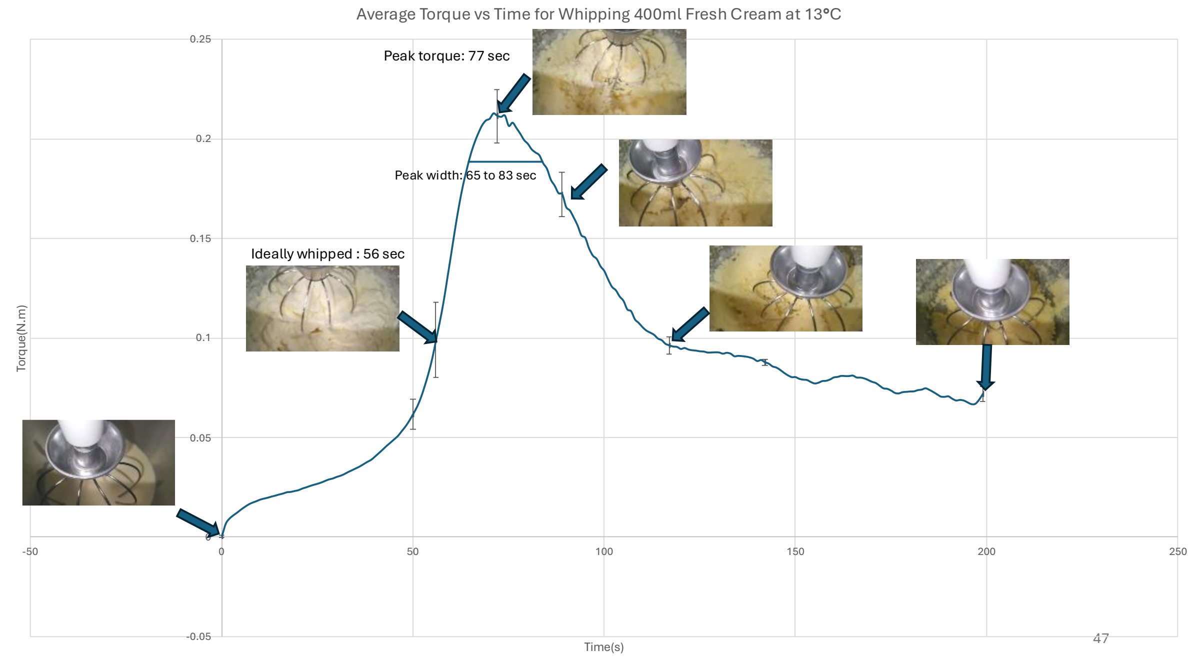


Figure 41: Average Torque vs Time for Whipping 400ml Fresh Cream at 13°C

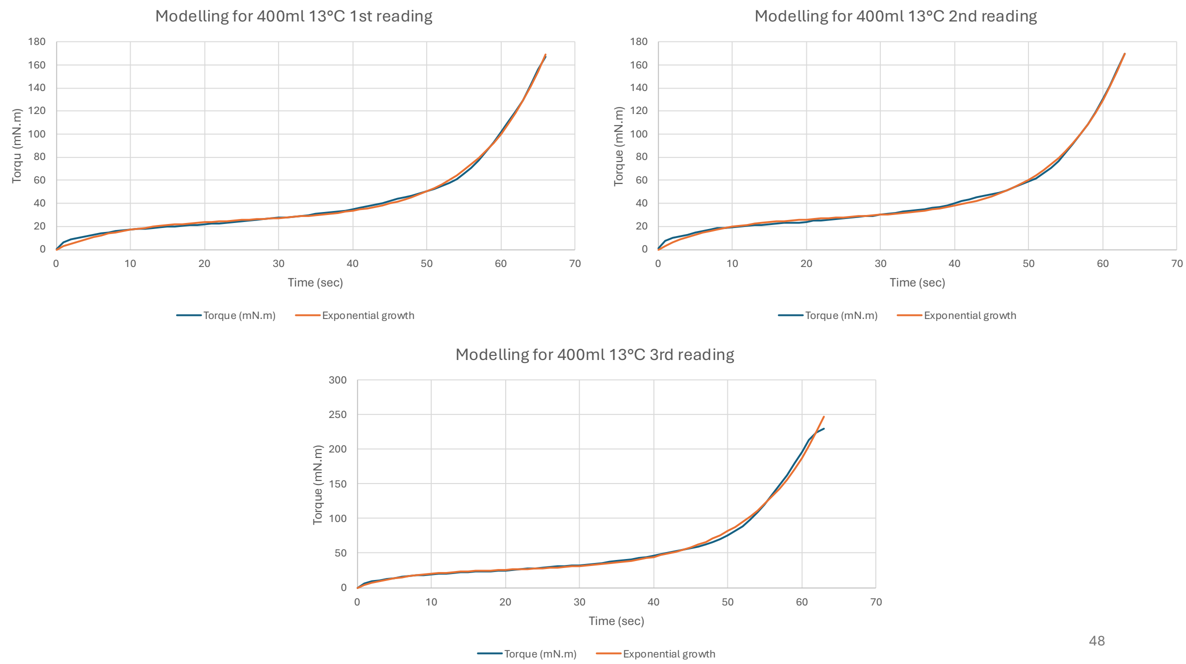


Figure 42: Mathematical modelling of torque evolution during the whipping of 400ml fresh cream at 13°C.

Table 12: Experimental data showing the temperature before and after whipping the replicates for effect of different initial temperature and time required to reach butter formation.

Trial No.	*Initial Volume (mL)*	*Temperature (°C) before whipping*	*Temperature (°C) After whipping*	*Time to Butter (min)*
1	400ml (Reading 1)	7°C	12.2°C	6 mins
2	400ml (Reading 2)	7.5°C	12°C	6 mins
3	400ml (Reading 3)	7.4°C	12.6°C	6 mins
4	400ml (Reading 1)	10°C	14.2°C	6 mins
5	400ml (Reading 2)	10°C	14.4°C	6 mins
6	400ml (Reading 3)	10°C	14°C	6 mins
7	400ml (Reading 1)	13°C	14.8°C	4 mins
8	400ml (Reading 2)	13°C	15.1°C	4 mins
9	400ml (Reading 3)	13°C	15.1°C	4 mins

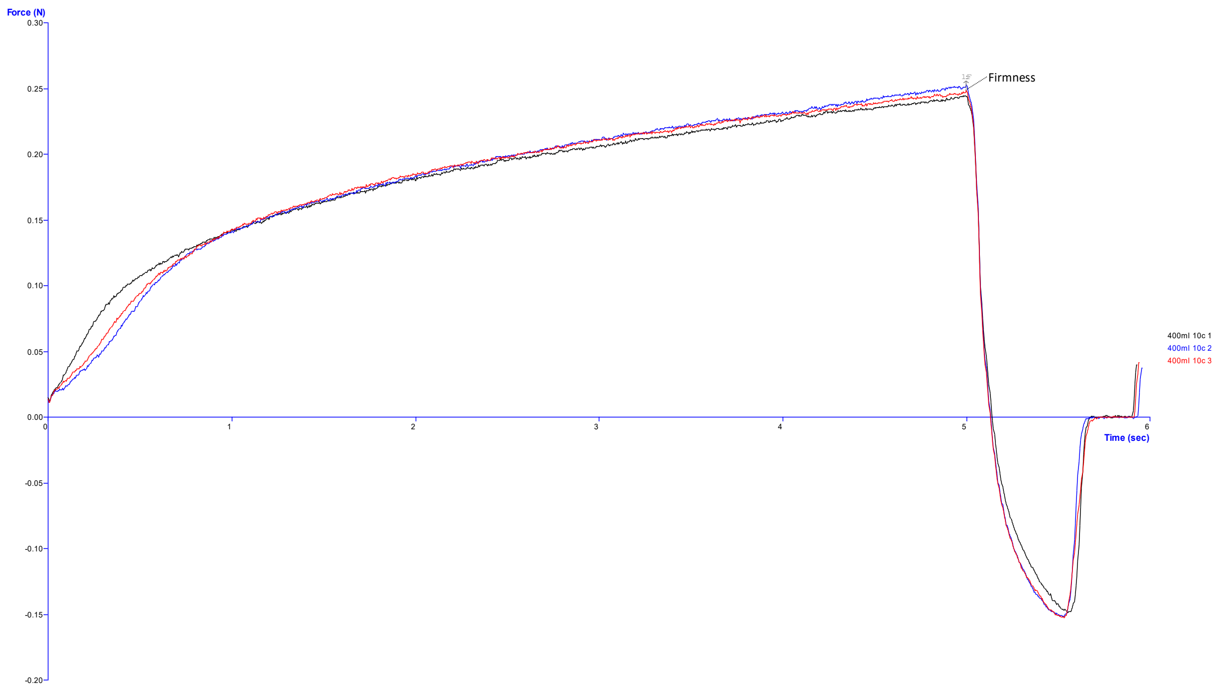


Figure 43: Texture Analyzer graph for 400ml (10°C)

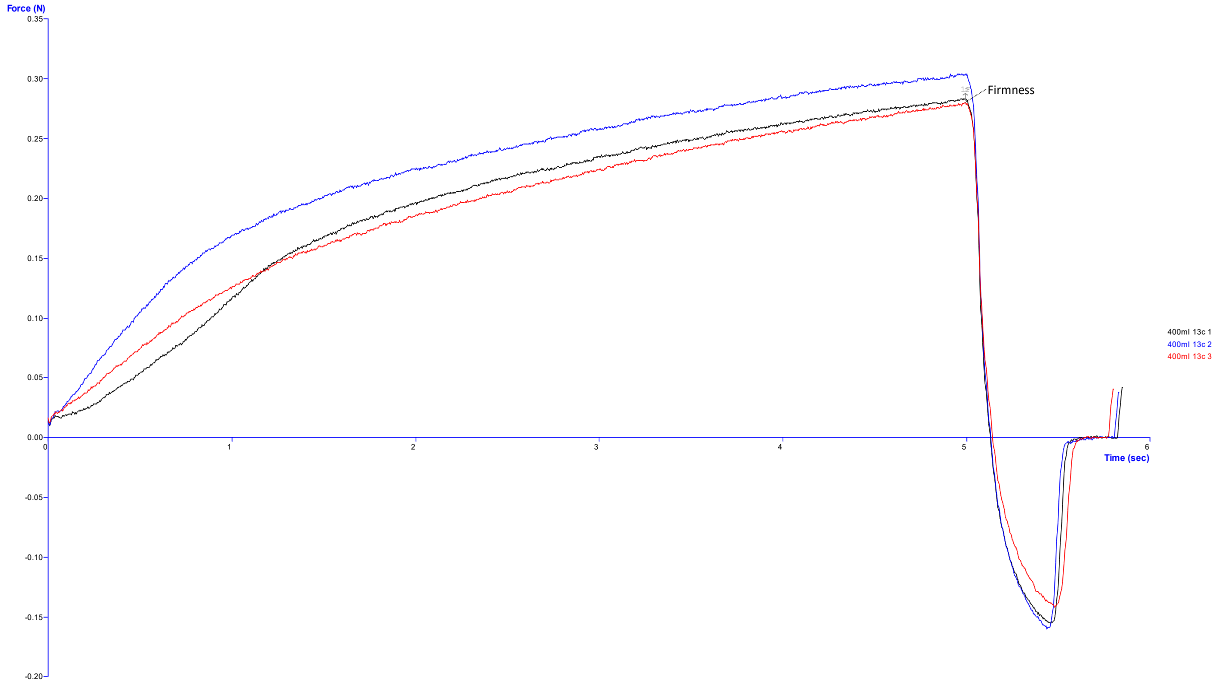


Figure 44: Texture Analyzer graph for 400ml (13°C)

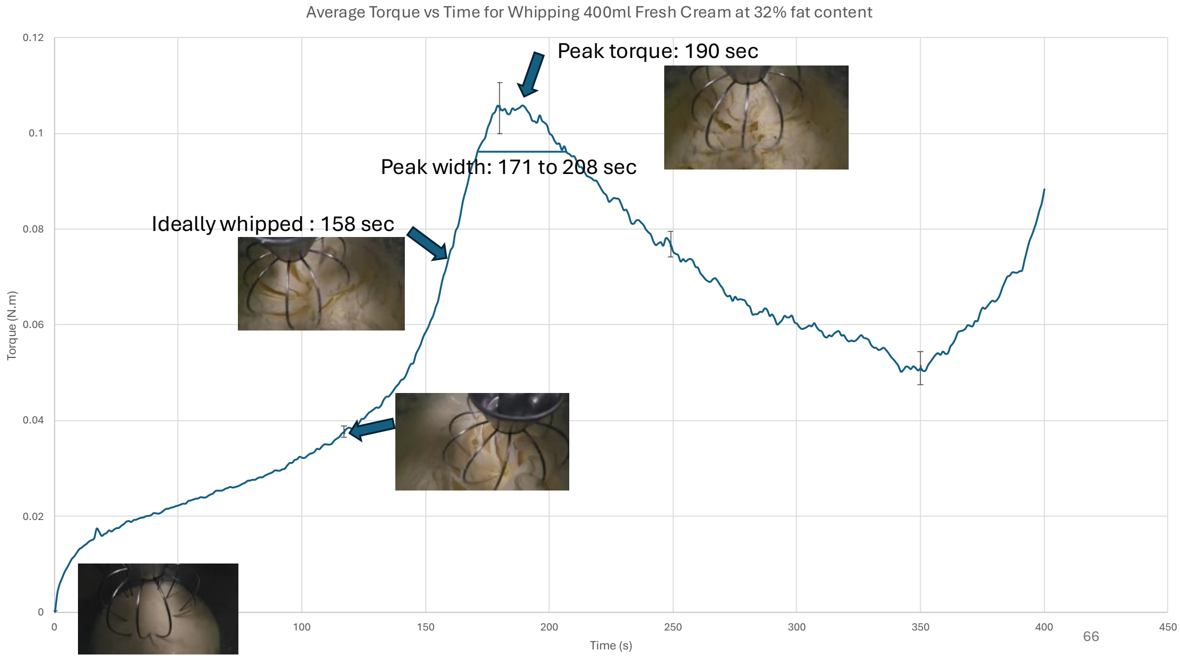
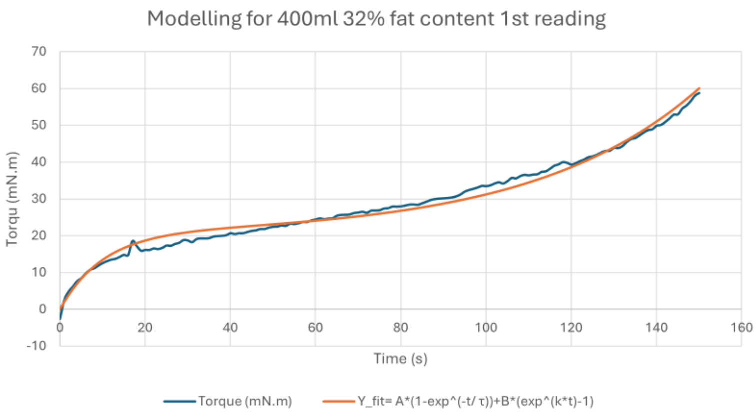


Figure 45: Average Torque vs Time for Whipping 400ml Fresh Cream at 32% fat content



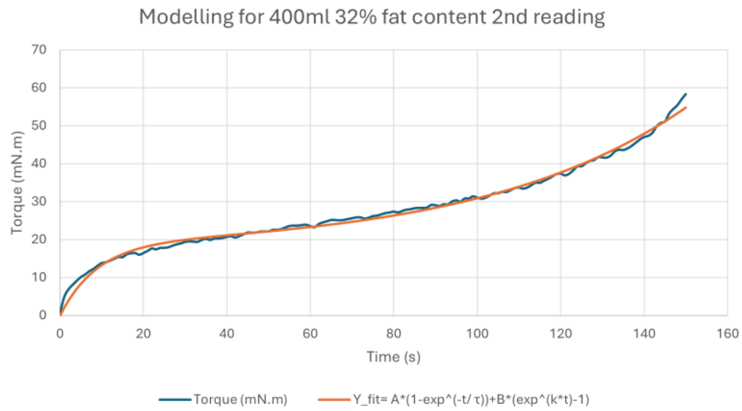


Figure 46Mathematical modelling of torque evolution during the whipping of 400ml fresh cream with 32% fat content.

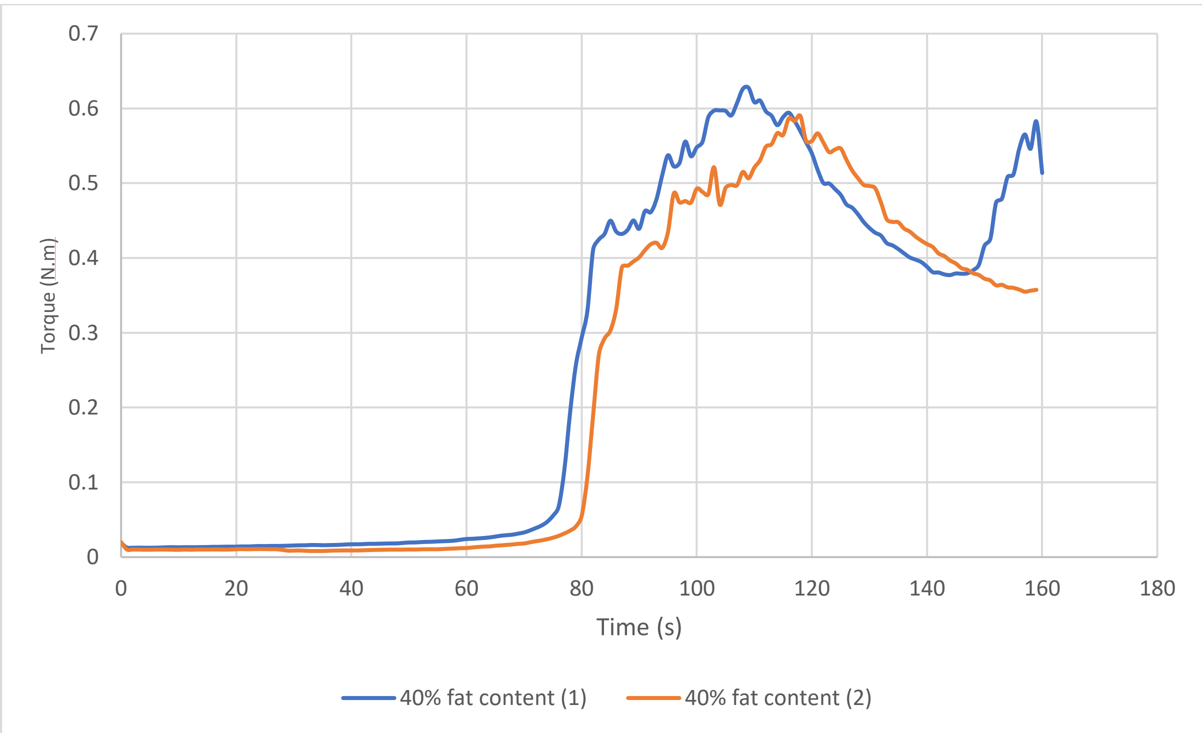


Figure 47: Torque vs Time for Whipping 400ml Fresh Cream at 40% fat content : Comparative Analysis of two readings

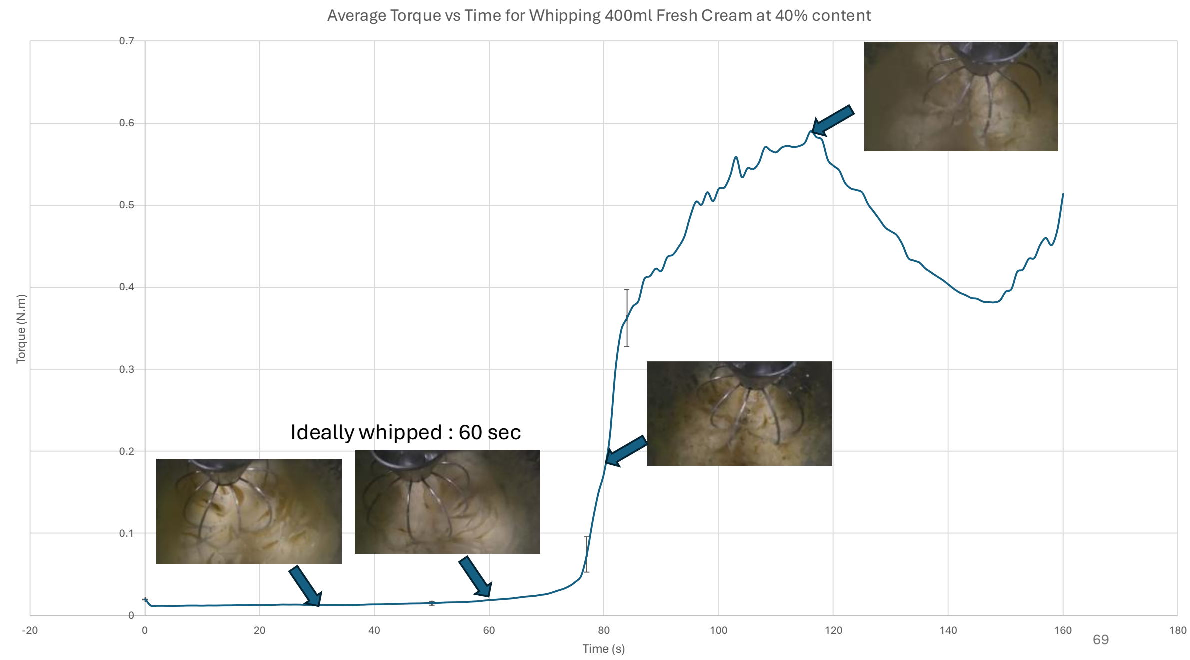


Figure 48: Average Torque vs Time for Whipping 400ml Fresh Cream at 40% content

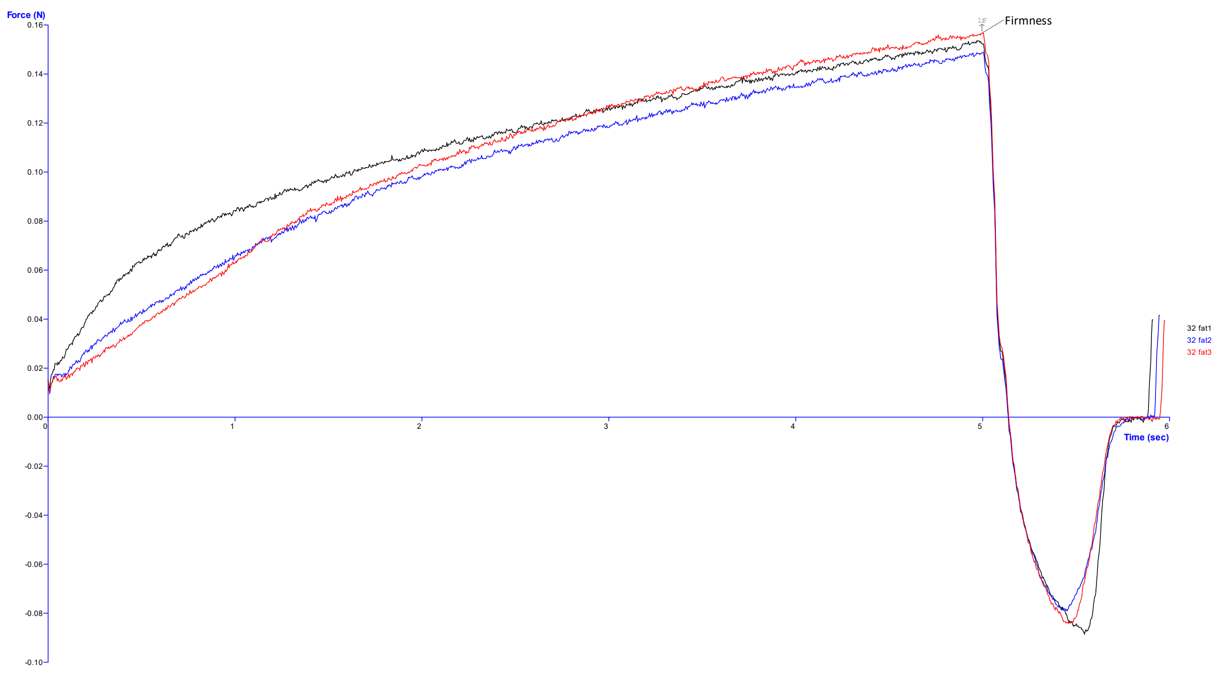


Figure 49: Texture Analyzer graph for 400ml (32% fat content)

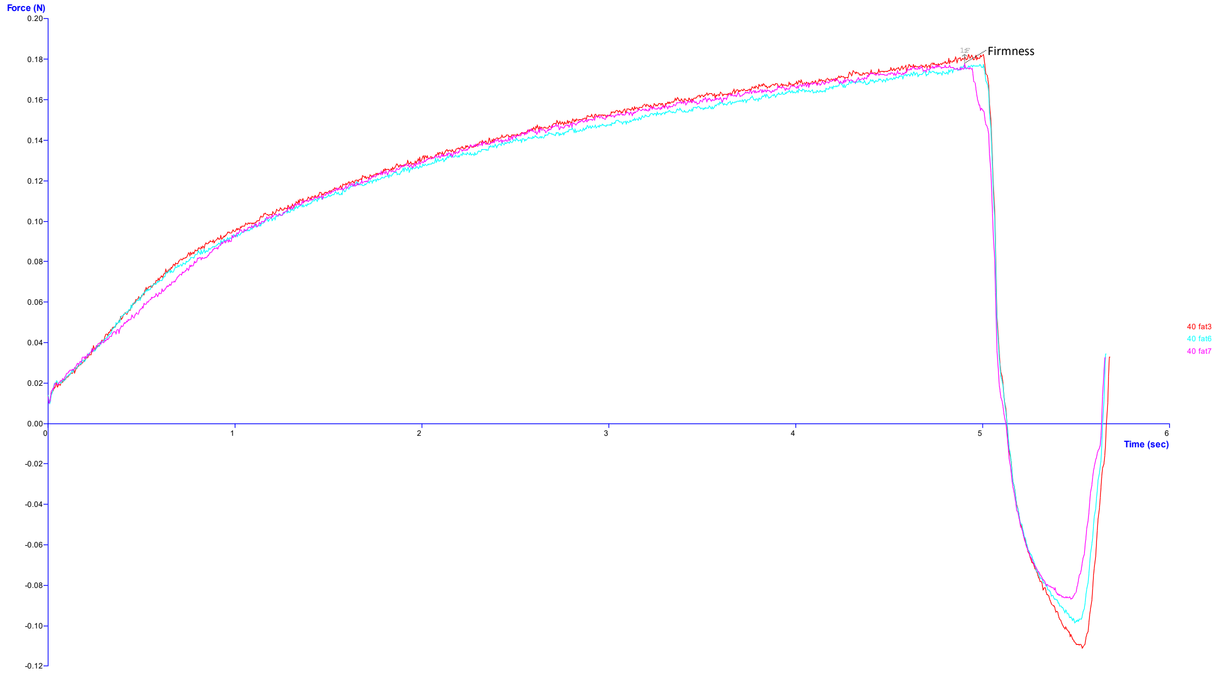


Figure 50: Texture Analyzer graph for 400ml (40% fat content)