MSc. Thesis

ALTINA BEKA

2024

MAGYAR AGRÁR- ÉS ÉLETTUDOMÁNYI EGYETEM

Hungarian University of Agriculture and Life Sciences
Institute of Food Science and Technology

Melting Characteristics of Frozen Desserts in Function of Temperature and Composition

MSc. THESIS

Altina Beka

Budapest, 2024

Hungarian University of Agriculture and Life Sciences

Specialization name: Food technology and product development

Place of thesis preparation: Department of Livestock and Food Preservation Technology

Student: Altina Beka

Thesis title: Melting characteristics of frozen desserts in function of temperature and composition.

Supervisor: Dr. Kenesei György

Date of issuing the thesis: 29.04.2024

Head of department	Supervisor
Dr. Friedrich László	Dr. Kenesei György

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Title of the thesis: Melting Characteristics of Frozen Desserts in Function of Temperature and Composition

Year of publication: 2024

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1. Introduction

At the molecular level, ice cream is a colloidal dispersion consisting of air cells, ice crystals, fat globules, and a continuous phase composed of water, sugars, proteins, and stabilizers/emulsifiers. The freezing process initiates the formation of ice crystals, which grow and interact with other components during storage, ultimately influencing the texture and stability of the final product. (Clarke, 2015). Additionally, the composition and structure of fat globules play a crucial role in determining the mouthfeel and sensory perception of ice cream, with factors such as fat content, crystalline structure, and emulsifier concentration affecting overrun and meltdown behavior (Alvarez, 2023).

Physicochemical interactions further modulate the melting characteristics of frozen desserts, with temperature fluctuations and storage conditions exerting significant effects on product stability and sensory attributes. Temperature variations impact the phase transitions of water molecules within the ice cream matrix, influencing the onset and rate of melting. Moreover, compositional variations, such as changes in sugar content, alter the freezing point depression and viscosity of the mix, thereby affecting the texture and meltdown behavior of the final product (Hagiwara et al., 1996; Buyck & Baer et al., 2011).

The significance of understanding the melting characteristics of frozen desserts extends beyond mere culinary curiosity, encompassing practical implications for both industry stakeholders and consumers. Manufacturers can leverage insights gleaned from this research to optimize formulation strategies, enhance product stability, and refine sensory attributes, thereby meeting consumer expectations for quality and palatability.

The focal point of this thesis revolves around the dynamic interplay between temperature fluctuations, sugar content variations, and storage conditions, and their collective impact on the melting characteristics of frozen desserts. Specifically, the analysis extends to elucidating how different sugar content levels within ice cream formulations influence weight loss, color parameters (L*, a*, and b*), texture, and the rate of fruit drop (melting rate) over a storage period spanning from days 1 to 9. Moreover, the investigation encompasses two distinct storage temperatures, -12°C and -25°C, providing insights into how varying storage conditions modulate the sensory attributes and stability of frozen desserts.

The overarching goal of this thesis is to contribute to the body of knowledge surrounding frozen dessert science by elucidating the influence of temperature, composition, and storage conditions on melting behavior. However, this endeavor is not without its challenges. The complex interplay between temperature fluctuations and sugar composition necessitates meticulous experimentation and analysis. Moreover, the study of storage impacts adds an additional layer of complexity, requiring careful consideration of environmental variables and their effects on product stability.

2. Aim of Thesis Work

This study aims to investigate how sugar composition and storage conditions affect the melting behavior and quality of frozen desserts, focusing on ice cream. By analyzing ice cream samples with different sugar ratios, we aim to uncover the relationship between sugar composition and the physical and sensory attributes of frozen desserts. Additionally, we will explore the impact of two storage temperatures (-12°C and -25°C), mimicking common commercial and domestic environments, on ice cream melting characteristics over 9 days. Through a comprehensive analysis of texture, first dripping point, color, and weight loss, we seek to deepen our understanding of the underlying mechanisms governing frozen dessert physics. Ultimately, our findings aim to optimize production processes and enhance product quality in the frozen dessert industry.

3. Literature Review

Ice cream, a beloved frozen treat savored as both a snack and dessert, is typically crafted from dairy staples like milk and cream, frequently embellished with fruits or additional ingredients to enrich its taste and visual appeal. The manufacturing method entails chilling ice cream blends until they reach the preferred texture and thickness (Deosarkar, et al., 2016).

Ice cream consists of a blend of components like milk, sugars, emulsifiers, stabilizers, fats, and flavorings. After blending these components, the ice cream mixture undergoes a freezing process to incorporate air and then undergoes blast freezing to solidify it, as highlighted by (Clarke, 2015). Within ice cream, there exists a mixture of solids from ice crystals and fat globules, liquids from the sugar solution, and gases from air bubbles. Recognizing the significance of flavors in food enjoyment, various endeavors have been made to exploit flavorful variations of ice cream, as noted by (Visser & Thomas, 1987).

Further (Marshall et al., 2003) elaborates that ice cream encompasses a diverse range of frozen products, including plain ice cream, reduced-fat options, fruit-infused variations, and others like puddings, custards, and frozen yogurts.

Commonly, sweeteners like sugar or sugar substitutes are included, along with stabilizers, emulsifiers, flavorings, and colorings to enhance the product's texture and appearance. To achieve the desired consistency and texture, the ice cream mixture is agitated to incorporate air and rapidly cooled below the freezing point of water, as described by (Kailasapathy & Sultana, 2003).

The nutritional and physico-chemical characteristics of dairy items play a crucial role in shaping consumer preferences. Traditionally, ice cream has been viewed more as an indulgence rather than a dietary staple. However, recent years have witnessed a significant increase in the value enhancement of dairy items, driven by growing consumer health awareness and disposable incomes. In today's market, there is a strong preference and support for fortifying ice cream with nutrients or other bioactive compounds (Anal & Singh, 2007).

As (Marshall et al., 2003) noted, ice cream holds widespread popularity with high consumption rates across various nations. Nevertheless, concerning health considerations, standard plain ice creams often contain elevated levels of fat (ranging from 10% to 18%) and sugar (ranging from 15% to 18%), while offering very low dietary fiber content.

Table 1. A typical ice cream formulation according to (*Clarke, 2015*).

Ingredients	Amount (% weight)
Fat	7-15%
Milk Proteins	4-5%
Lactose	5-7%
Other Sugars	12-16%
Stabilizers, Emulsifiers and Flavours	0.5%
Total solids	28-40%
Water	60-72%

The provided table illustrates the standard composition of ice cream, detailing the weight percentage of major ingredients. Fat, contributing to the creamy texture and flavor, falls within the range of 7-15%. Milk proteins, essential for structural integrity, comprise approximately 4-5%. Lactose, a natural milk sugar, contributes sweetness within the range of 5-7%, while additional sugars apart from lactose enhance sweetness, with a range of 12-16%. Stabilizers, emulsifiers, and flavors, collectively making up 0.5%, are additives crucial for texture, stability, and taste. The total solids encompass the sum of all solid components, varying from 28-40%, while water constitutes the remaining percentage, ranging from 60-72%. These percentages serve as a framework for ice cream formulation, with deviations within these ranges impacting the texture, taste, and overall quality of the ice cream (Clarke, 2015).

3.1 Structure of Frozen Desserts

Ice cream contains a phase known as serum, which remains liquid even under extremely cold conditions and encompasses dissolved sugars, salts, proteins, and stabilizers, forming a layer amidst various other components. Small ice crystals are crucial for texture, aiming for a smooth sensation in the mouth and rapid melting, typically varying from a few microns to more than 100 microns in size. The air phase constitutes a significant portion of ice cream's volume, with overrun values varying from 25% to as high as 150%, dispersed as small cells that contribute to its light texture. Initially, fat globules are present as tiny emulsion droplets. These droplets partially combine during the freezing process, forming clusters of varying sizes. This phenomenon impacts the ice cream's ability to maintain its shape and its melting properties. Finally, the protein and stabilizer structure, composed of caseins in micellar form and dissolved whey proteins, alongside stabilizers like proteins or gums, exhibit diverse structures impacting ice cream characteristics and potential phase separation (Goff, 2018).

3.2 Types of frozen desserts

Based in (Clarke, 2015) discussion of frozen desserts, several distinct types are highlighted. Ice cream, governed by strict regulations, requires a minimum of 10 percent butterfat in a dairy mix for legal classification. Its texture relies on a delicate balance of fat and air content. Gelato, an Italian variation, incorporates egg yolks and is churned slower and longer, resulting in a denser texture with lower butterfat levels. Sherbet, differing from sorbet, utilizes milk and/or egg whites for a lighter texture, with butterfat levels typically around 1 to 2 percent. Frozen yogurt, made without cream, employs bacteria cultures for a softer texture and a probiotic element, often using Greek yogurt as a base. Sorbet, essentially a flavored sugar syrup water solution, is fat-free but may have a slightly icy texture due to its high-water content. Non-dairy ice cream alternatives, though not legally classified as ice cream, use milk substitutes like soy or almond milk, offering sweetened and flavored options that can be equally high or higher in fat, posing concerns for those with nut allergies. Each type presents unique characteristics catering to diverse dietary preferences and needs.

Table 2. The approximate compositions of commercial ice creams *(Marshall et al., 2003).*

Ice Cream	Fat %	MSNF %	Sugars %	Stabilizers %	Total Solids %
Non-fat	<0.5	12-14	18-22	1.0	28-32
Low-fat	2-5	12-14	18-21	0.8	28-32
Light	5-7	11-12	18-20	0.5	30-35
Gelato	4-8	11-12	16-22	0.5	36-43
Reduced fat	7-9	10-12	18-19	0.4	32-36
Standard	10-12	9-10	14-17	0.2-0.4	36-38
Premium	12-14	8-10	13-16	0.2-0.4	38-40
Super premium	14-18	5-8	14-17	0-0.2	40-42
Frozen yogurt: regular	3-6	9-13	15-17	0.5	30-36
Frozen yogurt: nonfat	<0.5	9-14	15-17	0.6	28-32
Sherbet	1-2	1-3	22-28	0.4-0.5	28-34

The table presents various categories of frozen desserts with their corresponding composition percentages, as outlined by (Marshall et al., 2003). Each category is characterized by its fat percentage, milk solids not fat (MSNF) percentage, sugar percentage, stabilizers percentage, and total solids percentage. For instance, non-fat ice cream contains less than 0.5% fat, 12-14% MSNF, 18-22% sugars, 1.0% stabilizers, and 28-32% total solids. As the fat content increases, the MSNF percentage generally decreases, while the sugar content varies across different categories. Stabilizers are found in minimal quantities, with the least amount present in super-premium ice cream. The overall solids percentage typically rises as the fat content increases, reaching its maximum level in super-premium ice cream. These distinctions are vital for understanding the nutritional profiles and textural qualities of various frozen desserts, aiding consumers in making informed choices according to their dietary preferences and health goals.

3.3 Frozen desserts ingredients and their influence in them

3.3.1 Sugar Content

Sweeteners are integral to enhancing the taste and texture of ice cream, intensifying its sweetness, and enriching its creamy flavor. Balancing sweetness is crucial; too little can result in blandness, while excessive sweetness can overpower other flavors. Various sweeteners, including invert sugar, corn starch hydrolysate syrup (CSS), sucrose from cane or beet (commonly known as "sugar"), fructose or high fructose syrup, maltodextrin, dextrose, maple syrup or sugar, honey, brown sugar, and lactose, are utilized in ice cream production. These sweeteners, termed "nutritive" or "caloric," provide metabolizable energy to the diet. A popular combination involves blending sucrose (10–12%) with CSS (3-5%) (Marshall et al., 2003)

Sucrose is commonly used as a sweetener in ice cream, providing sweetness, altering texture, and affecting costs. Ice cream typically requires at least 15% sucrose for sweetness, but glucose syrup can be a cost-effective alternative. Glucose syrups improve texture and flavor, extending shelf life. People with diabetes can choose non-nutritive sweeteners like cyclamates, aspartame, saccharin, sucralose, and acesulfame-K, with even a small amount of aspartame achieving the sweetness of 15% sucrose (Deosarkar et al., 2016)

Natural and synthetic sweeteners are generally distinguished, with Stevia Rebaudiana (being a naturally occurring option, known for its potency, being 250–300 times sweeter than sucrose (Adari et al., 2016). Sugar, a key component, not only enhances flavor but also contributes to the ice cream's viscosity and body texture, while also lowering the mix's freezing point, facilitating a smoother freezing process, and resulting in a more indulgent texture during consumption (Arbuckle, 1986). Bulking agents, which are utilized in the creation of low-fat, low-calorie frozen treats while maintaining a desirable taste and texture, act as fillers. These components imitate the physical properties of sugar without replicating its sweetness or calorie count (Bray, 1991).

3.3.2 Water and Air

In the realm of ice cream production, both water and air are indispensable elements that significantly shape the characteristics of the final product. Water serves as a fundamental constituent, contributing to the continuous phase of ice cream, whether in solid or liquid form. While external water sources must undergo purification, water originating from dairy sources is generally expected to be pre-cleansed during its extraction from mammary glands. Its roles encompass acting as a solvent and providing a liquid medium. Conversely, air is intentionally introduced during the ice cream preparation to create overrun, enhancing volume and texture. The amount of air added during this procedure, known as "overrun," represents the percentage ratio between the volume of gas and the volume of the continuous phase (Rizzo, 2016)

The quality of ice cream directly hinges upon the amount and consistency of air infused, with freezer filters ensuring air quality. Emulsifiers, fats, and proteins work to stabilize the air and water interface by forming a thin film. Despite its beneficial impacts, excessive air incorporation can lead to defects such as reduced ice crystal size, lower melting point, and diminished hardness in the final product (Arbuckle, 2013; Marshall et al., 2003; Sofjan & Hartel, 2004).

Control over the amount of air added is crucial, with specific overrun percentages tailored to the mix's composition to achieve optimal body, texture, and palatability in high-quality ice cream (Arbuckle et al., 2013). Insufficient air incorporation can result in densely packed ice cream, compromising its scoop ability (Warren & Hartel, 2018).

3.3.3 Emulsifiers and Stabilizers

In the manufacturing process of ice cream, the mix serves as an emulsion of oil in water, requiring the use of emulsifiers to maintain stability and hinder the undesirable aggregation of fat globules. Frequently utilized emulsifiers include mono- and diglycerides, sucrose esters, and polysorbates (Miller, 2016). These emulsifiers are essential for enhancing the texture and shape retention of ice cream by facilitating the effective incorporation of air into the mixture (Deosarkar et al., 2016), resulting in a smooth and desirable consistency in the final product. Emulsifiers play a vital role in the complex process of ice cream formation by disrupting the natural milk protein film surrounding milk fat globules during churning. This disturbance facilitates partial coalescence of fat droplets and air bubbles, resulting in the formation of a network of partially merged fat that stabilizes the foam. Without this stabilization, air bubbles could blend, enlarge, and escape the structure. (Miller, 2016; Rizzo, 2016). Moreover, emulsifiers play a role in shaping ice cream attributes by shortening freezing duration, enhancing whipping properties, and yielding a texture that is dry, firm, and resistant to melting. These effects ensure the creation of a finely textured and consistent ice cream product (Miller, 2016).

The structural integrity of ice cream is greatly impacted by the inclusion of stabilizers, with polysaccharides like guar, locust bean gum, carboxymethylcellulose, and xanthan frequently employed for this objective. (Deosarkar et al., 2016). Research based on (Mahidan & Karazhian, 2013) and (Cakmakci & Dagdemir, 2013) indicates that enhanced amounts of stabilizers result in enhanced incorporation of air and a better distributed arrangement of air pockets within the ice cream, enhancing its texture and overall quality. Stabilizers play a vital role in ice cream manufacturing by capturing excess water within the ice cream mixture and converting it into "water of hydration." (Soad et al., 2014). This process, as discussed by (Bahramparvar & Mazaheri, 2011; Abbas, 2016; Shanmungam & Marimuthu, 2017) enhances mixed viscosity, overall mouthfeel, and provides a smoother body and texture. Stabilizers also stabilize proteins, prevent wheying-off, suspend liquid flavors, inhibit the growth of ice and lactose crystals during storage, and contribute to improved melting properties by efficiently absorbing and retaining significant amounts of bound water. Careful choice of emulsifiers and stabilizers allows for the creation of premium ice cream with a significant amount of overrun, enhancing its texture, stability, and sensory attractiveness. This combination guarantees that the ice cream meets the required quality benchmarks and provides a delightful experience for consumers (Shanmungam & Marimuthu, 2017).

3.3.4 Flavors

Taste is a fundamental element that profoundly impacts the overall desirability of ice cream. The selection of flavoring components is paramount in defining the excellence of the ice cream blend, as even a subtle deviation in taste can obscure the intended flavor. Local consumer preferences play a pivotal role in determining the types and intensities of flavors utilized. Ice cream manufacturers have a wide range of options available, including both natural and synthetic substances, to achieve desired flavor profiles. Additionally, the color of ice cream is integral to its appeal, with visually attractive colors often associated with specific flavors. Achieving these colors is typically accomplished using chemically derived colors, which are available in either liquid or powder form (Deosarkar et al., 2016).

3.3.5 Fat

Ice cream is a sophisticated blend comprising partially destabilized fat droplets, tiny air bubbles, suspended casein micelles, ice crystals, and a concentrated unfrozen aqueous solution (Goff & Hartel, 2013). Research conducted by (Goff et al., 1999) highlights the essential structural function of fat in stabilizing the air phase within ice cream, while also imbuing distinct sensory qualities to the frozen dessert. Additionally, research by (McClements, 2015) highlights that fat influences the release of hydrophobic flavor molecules, thereby enhancing the overall flavor profile of ice cream (Marshall & Arbuckle, 1996) specify that traditional serving sizes of ice cream typically contain a minimum of 10% fat and are aerated to achieve 40 to 50% air volume.

3.3.6 Proteins

Milk proteins play a crucial role in shaping the structure of ice cream, performing three key functions. Initially, during the homogenization phase, they act as emulsifying agents for the fat component, guaranteeing the stability of the emulsion within the blend. Subsequently, interactions between proteins and emulsifiers during aging lead to a reduction in adsorbed protein levels, promoting the formation of a desirable fat structure through partial coalescence in both whipped and ice cream. Thirdly, proteins found in the serum phase aid in establishing an interface for air bubbles during whipping, thus maintaining small and stable air bubbles. Additionally, proteins that remain unabsorbed contribute to heightened mixed viscosity, particularly in the unfrozen serum phase following cryo-concentration, resulting in improved body and texture of ice cream while mitigating rates of ice recrystallization. Given the variety of protein sources available, product developers must carefully choose protein ingredients that offer the necessary functional properties tailored to their specific ice cream formulations (Goff et al,. 1999).

3.4 Ice Cream Manufacture Process

The standard procedures for manufacturing ice cream, which focus on managing both dry and liquid ingredients, vary depending on the production scale. Dry components are typically measured by weight, while liquid constituents can be either weighed or proportioned using volumetric meters. In smaller facilities with restricted capacities, dry ingredients are manually weighed and incorporated into mix tanks designed for indirect heating and equipped with efficient agitators. Conversely, large-scale producers opt for customized automatic batching systems. The ingredients contained within these reservoirs are heated and combined to achieve a uniform mixture, which is then subjected to pasteurization and homogenization. In larger manufacturing facilities, it is customary to employ two blending tanks sized to match the hourly capacity of the pasteurizer, ensuring continuous production. Dry constituents, particularly milk powder, are commonly introduced via a mixing apparatus where water circulation facilitates their integration into the mixture. The amalgamation is subsequently reheated to 50 – 60°C before being reintegrated into the tank to aid in dissolution. Liquid ingredients such as milk, cream, and liquid sugar are metered into the mix tank alongside the dry ingredients (Bylund, 2003).

3.4.1 Pasteurization

Pasteurization in ice cream production serves a dual purpose as outlined by (Marshall & Arbuckle, 1996) it not only eliminates harmful microorganisms but also aids in the formation of a colloid by melting fat during homogenization. Additionally, a crucial objective is to deactivate lipase, an enzyme that remains active even at low temperatures, thus preventing the occurrence of bacterial lipases. Moreover, for hardened ice cream, subjecting the mix to significant heat treatment is vital to reduce susceptibility to autoxidation (Walstra et al., 2005). Ice cream mixes can undergo pasteurization through two alternative methods: ultra-high-temperature (UHT) pasteurization and batch pasteurization. UHT pasteurization is particularly effective for producing ice cream mixes intended for later freezing. In this process, temperatures exceeding 140°C are employed, often accompanied by prolonged processing times ranging from 2 to 12 seconds (Spreer, 1998).

3.4.2 Homogenization

The main goal of homogenization is to decrease the size of fat globules to below approximately 2μm, enhancing their stability during the aging process of the mixture. Moreover, it serves to minimize the likelihood of fat churning in the freezer, guaranteeing a smoother texture and higher quality in the finished ice cream product (Marshall & Arbuckle, 1996).

According to (Wang, 2015), the ice cream-making process involves homogenization of the mix, typically carried out at pressures ranging from 2500 to 3000 psi. This procedure is crucial for decreasing the size of milk fat globules, facilitating the formation of a finer emulsion, and ultimately enhancing the smoothness and creaminess of the ice cream.

3.4.3 Cooling

Following homogenization and pasteurization, the ice cream mix is rapidly cooled to a temperature of 7.3°C or lower. The primary objective is to achieve swift cooling and sustain this low temperature to inhibit the growth or proliferation of microorganisms (Fellows, 2000). Cooling serves multiple purposes, primarily centered on ensuring the safety of the food product. Additionally, it induces milk fat crystallization and facilitates water binding through interactions between polysaccharides and proteins (Marshall & Arbuckle, 1996).

3.4.4 Aging

The aging process takes place in an Ice Cream Aging Vat, where the mixture is maintained at a temperature of 5°C for a minimum of 4 hours or overnight. The aging process serves multiple functions: it cools down the mixture prior to freezing, encourages partial crystallization of milk fat, and enables protein stabilizers to hydrate, thereby improving the aerating properties of the mixture. During aging, emulsifiers like lecithin from egg yolks adhere to the surface of fat droplets, creating a less rigid membrane that facilitates partial fusion. This leads to the formation of clusters of fat globules that stabilize air cells and contribute to a creamy texture. Additionally, chilling the mixture promotes fat crystallization, further assisting in fat globule fusion during freezing. Inadequate aging of the mixture can lead to ice cream defects such as poor shape retention, fast melting, and difficulty in stabilizing air bubbles, resulting in a dense, chewy consistency. Therefore, ensuring proper aging is essential for achieving the desired texture and quality in ice cream production (Wang, 2015).

3.4.5 Freezing

In ice cream production, freezing the mixture is a crucial phase that significantly impacts the yield, quality, and flavor of the final product. Typically, freezing occurs in two stages. Initially, dynamic freezing involves rapidly freezing the mixture while agitating it to release air and reduce the size of ice crystals. This is followed by static freezing, where the partially frozen product is hardened at a specific low temperature without agitation, allowing for quick heat removal. While the primary concern revolves around ice crystal formation during freezing, other vital processes such as the dispersal of air bubbles and the restructuring of fat globules also impact the flavor of the ice cream (Marshall et al., 2003).

Ice cream is rapidly cooled to a holding temperature below -25°C, with specific cooling temperatures and durations depending on factors like freezer type, packet shape, material, and ambient temperature. The aim of rapid cooling is to promote the swift freezing of water, leading to the formation of small ice crystals. This accelerated cooling process contributes significantly to enhancing the overall quality of the ice cream (Patel et al., 2013).

In ice cream production, the choice between batch and continuous freezers depends on the scale of operation and specific production needs. Batch freezers are favored by smaller shops, where a set amount of ice cream mix is frozen while being agitated to achieve the desired texture and overrun. Variables such as mix composition and freezer type influence the freezing process, which ideally takes 8–10 minutes per batch. Continuous freezers, on the other hand, are preferred by larger manufacturing plants due to their higher capacities and ability for continuous operation. They offer advantages like streamlined ingredient addition, automated packaging, and the production of various ice cream shapes. Ice cream from continuous freezers tends to be smoother and creamier, with more consistent quality due to precise control over freezing parameters. Advanced technology allows for high overrun and low drawing temperatures, enhancing product texture and appeal (Kilara et al., 2007).

3.4.6 Packaging

Ice cream packaging is typically done before the hardening process, although in some cases, it may occur afterward Following extraction from the freezer, ice cream is typically transferred into containers to mold and adjust its size for effortless handling during the subsequent stages of hardening, storage, and distribution. Important aspects of ice cream packaging include preventing contamination, providing an attractive appearance, ensuring easy opening, and resealing, and facilitating convenient disposal. Additionally, ideal packaging should protect against moisture and insulate against temperature changes, all of which help maintain the quality and integrity of the ice cream product from production through consumption (Patel et al., 2013).

3.4.7 Hardening of Ice Cream

The primary objective of this hardening phase is to expedite the freezing process of ice cream, aiming to minimize the size of ice crystals and enhance foam stability (Marshall & Arbuckle, 1996). In the ice cream production process, the ultimate phase entails solidifying the product at approximately –20°C. When ice cream is made using extrusion lines or stick novelty freezers, the solidification process is frequently integrated into production. Yet, for items packed right after freezing, they need to be moved to a distinct solidifying tunnel. It's important to mention that faster solidifying results in enhanced texture. Following solidification, the ice cream products are moved to a refrigerated storage area, where they're positioned on shelves or pallet racks at a temperature of –25°C. The period for which ice cream can be stored hinges on various factors such as product type, packaging, and the consistent maintenance of a low temperature. Storage spans may vary from no time at all to up to nine months. (Bylund, 2003).

3.5 Melting of Ice Cream

According to (Marshall et al., 2003) its main structural elements of ice cream include air pockets, ice crystals, and fat particles, all suspended in an unfrozen solution (serum). The fat particles, partly fused together, act to encase, and stabilize the air pockets. These components collectively influence the texture and melting properties of ice cream, although the precise interactions between them are not fully understood.

When ice cream is placed on a wire-mesh screen at room temperature, the pace at which liquid collects beneath the screen can be used to determine how quickly the ice cream is melting. The heat from the warm air around the ice cream melts it and dissolves the ice crystals as it melts. The ice cream first melts its outer layer, which produces a localized cooling effect surrounding the melting ice. The water produced by the melting ice is then absorbed by the thick, unfrozen serum phase, creating a diluted solution that, with the help of gravity, flows through the screen beneath the ice cream. It is generally preferred for ice cream to have a slow melting rate and to retain its shape well (Muse & Hartel, 2004).

3.6 Storage of Ice Cream

Several factors influence the overall qualities of ice cream, including variables like the size of ice crystals, the amount of air incorporated (overrun), the temperature at which it initially freezes, and the temperature at which it is stored. Storage temperature is particularly important for ice cream producers and sellers because it greatly affects the texture and mouthfeel of the ice cream (Buyck et al., 2014).

The dimensions and structure of the ice crystals and air bubbles play a crucial role in determining the ultimate quality of the ice cream. They affect the smoothness of its texture and the sensation of coldness perceived by customers (Caillet et al., 2003). Generally speaking, −28.9°C is the industry norm for ice cream storage (Buyck et al., 2011). According to The International Dairy Foods Association (1997), ice cream products stored at temperatures higher than −28.9℃ have suffered heat-shock damage and should not be sold in retail establishments.

According to (Buyck et al., 2011), consumers prefer products with smaller ice crystals (less than 55 μm) because they feel that the texture is less frosty and granular. To provide a smooth texture and mouthfeel when consuming, it is essential to maintain a consistent dispersion of small ice crystals (Flores & Goff, 1999). Ice creams with small ice crystals experience minimal recrystallization during frozen storage (Choi & Shin, 2014).

Some ice crystals melt and freely recrystallize into larger crystals as a result of variations in storage temperature (Buyck et al., 2011). A light texture and optimal melt-down are facilitated by the appropriate air cell structure in ice cream (Park et al., 2006). The standard for high-quality ice cream is thought to have air cell diameters between 30 and 150 μm, with an average diameter of 40 μm (Hagiwara & Hartel, 1996). When storage temperatures surpass −25℃, air cells tend to merge into larger cells, which causes the foam structure to become coarser (Sofjan & Hartel, 2004).

4. Materials and Methods

4.1 Lemon-Flavored Ice Cream Formulation

The commencement of ice cream production at MATE University, Budapest, Hungary, aimed to develop five distinct types of lemon-flavored ice cream with varying sugar content while maintaining consistent proportions of other ingredients. The formulation of Recipe 3 served as the base, with adjustments leading to Recipes 1, 2, 4, and 5, showcasing ±10% variations in sugar content relative to the base recipe. The production process adhered rigorously to predetermined ingredient quantities, ensuring uniformity and precision at every step. From the meticulous weighing of ingredients to the thorough homogenization of mixtures, each stage was executed with precision to guarantee the quality and consistency of the final product.

Experimental assessment further enriched the study by exploring the effects of storage temperature (-12 ℃ and -25℃) on various properties of the ice cream samples. Through meticulous sample preparation and systematic analysis, the study facilitated a comprehensive understanding of how temperature influences the weight, texture, melting point, and color of ice cream over a nine-day period. By conducting assessments with three repetitions for each analysis and allocating 30 cups per recipe per day, the study ensured statistical robustness and facilitated a detailed investigation into temperature effects on ice cream properties during storage.

Overall, this study contributes to the advancement of ice cream production techniques but also provides valuable insights into optimizing storage conditions to maintain the quality and sensory attributes of lemon-flavored ice cream.

Table 3. Composition of the lemon-flavored ice cream of the samples.

Recipe	Juice (l)	Sucrose (kg)	Water (l)	Citric Acid (kg)	Emulsifier- JILK (kg)	Stabilizer- Locust Bean (kg)
Recipe 1	1	0.8	2	0.01	0.02	0.02
Recipe 2	1	0.9	2	0.01	0.02	0.02
Recipe 3	1	1	2	0.01	0.02	0.02
Recipe 4	1	1.1	2	0.01	0.02	0.02
Recipe 5	1	1.2	2	0.01	0.02	0.02

4.2 Lemon-Flavored Ice Cream Production

The process of ice cream production was conducted with meticulous attention to detail, adhering strictly to predetermined ingredient quantities. Each ingredient was meticulously weighed using an electric scale to ensure accuracy and consistency throughout the production process. Initially, the dry ingredients, including sucrose, citric acid, and stabilizer, were combined separately from the liquid components, such as lemon juice and water. This separation allowed for precise control over the formulation of the ice cream base. The stabilizer, JILK, was then added to the mixture to the liquid mixture to ensure uniform distribution and enhance texture stability.

Through thorough homogenization, the dry and liquid mixtures were carefully blended until a consistent texture was achieved, ensuring the desired quality of the final product. The resulting mixture was then transferred to an ice cream manufacturing machine, where precisely 1 liter was dispensed for processing. The mixture underwent a rigorous process of mixing and freezing for 15 minutes to facilitate ice cream formation, ensuring the development of a smooth and creamy texture in the ice cream making machinery *(CRM, GEL 5)*.

Figure 1. Ice cream making machine (CRM, GEL 5). **Figure 2**. Lemon flavored ice cream

Following the mixing and freezing process, the ice cream was dispensed into 0.01L (Figure 3) cups to standardize portion sizes for analysis and evaluation. These filled cups were then placed in a refrigeration unit to undergo freezing, allowing for further texture development and maturation. The samples were stored at -12℃ (Figure 5) and -25 (Figure 4). This meticulous approach to ice cream production not only ensured consistency in product quality but also provided a platform for comprehensive analysis and experimentation within the scope of my thesis work.

Figure 3. Placement of ice cream into 0.01L cups. **Figure 4**. Ice cream storage at - 12°C.

Figure 5. Ice cream storage at -25℃

4.3 Analytical Methods

The meticulous analysis of frozen desserts encompasses a multifaceted examination of their physical and sensory attributes, necessitating the application of analytical techniques to elucidate nuances in color, weight loss, texture, and melting behavior. This scientific introduction provides a framework for comprehensively understanding the methodologies employed in assessing these parameters, highlighting their significance in evaluating product quality and stability.

4.3.1 Color analysis

Color analysis of the ice cream samples was conducted using a Konica Minolta colorimeter CR-400 from Japan. Prior to analysis, the colorimeter was calibrated according to manufacturer specifications using standard white and black calibration tiles. Ice cream samples were prepared according to predetermined formulations, with variations in sugar content and storage conditions. For each sample, a representative portion was placed in a standardized container and allowed to equilibrate to room temperature. Using the colorimeter, color parameters including L* (lightness), a* (redness-greenness), and b* (yellowness-blueness) were measured in triplicate for each sample. The instrument was positioned above the ice cream surface, and readings were taken at multiple points to ensure representative measurement. Results were recorded and analyzed statistically to assess differences in color characteristics among samples and storage conditions (Wrolstad & Smith, 2017).

Figure 6. Konica Minolta colorimeter CR-400 (Japan).

4.3.2 Texture analysis

Texture analysis was performed using a TA.XT Plus device from Texture Technologies, headquartered in Scarsdale, NY. Ice cream samples were subjected to controlled compression at a constant rate using a cone probe, and texture parameters including hardness, viscosity, and elasticity were measured. Evaluations focused on characteristics of texture profile analysis (TPA), including hardness, springiness, cohesiveness, gumminess, and chewiness. Each sample underwent two repetitions of analysis, with the first analysis performed at 0, 5, and 10 minutes, respectively, timed using a stopwatch. The instrument was configured with a compression test mode, with pre-test and test speeds set at 2mm/sec. The target mode was a distance at 20mm of the probe, with a trigger force of 0.049N. Units utilized were distance in mm, force in N, and time in seconds.

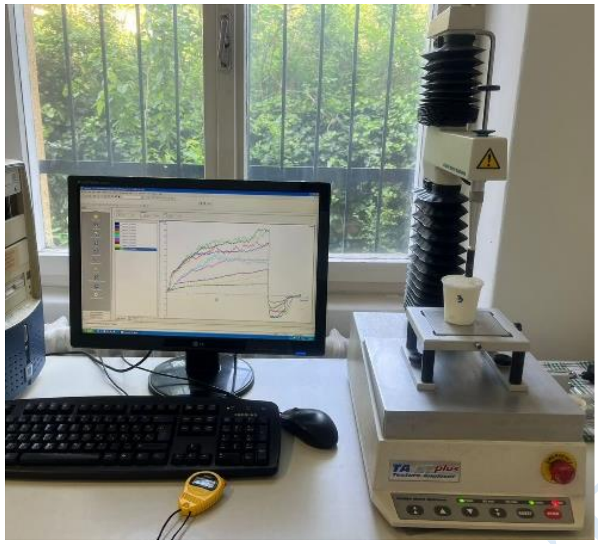


Figure 7. Texture Analyzer (TA.XT Plus, Texture Technologies, Scarsdale, NY).

4.3.3. Weight loss during storage time

Ice cream was systematically evaluated the weight changes of the ice cream samples over a nine-day storage period at two distinct temperatures: -12℃ and -25℃. These measurements were conducted using a Kern EMB 200-2 weight balance, featuring a 200g capacity and 0.01g divisions, ensuring precise and accurate readings. To analyze the collected data, we employed a rigorous statistical approach, utilizing multiple step-by-step regression analysis. This method allowed us to systematically examine the relationship between sugar, storage time, temperature, and weight loss of the ice cream samples.

Calculate Weight Loss: For each sample, subtract the weight on subsequent days from the initial weight to determine the weight loss at each time point. The formula for weight loss (WL) is:

Percentage Weight Loss = (WL / W1) x 100%

Where:

- WL is the weight loss.
- W1 is the initial weight on day 1.
- Wx is the weight on subsequent days (e.g., W3, W5, W7, or W9)

Figure 8. Kern EMB 200-2 weight.

4.3.4. Melting point – First drop analysis

Analyzing the melting point of ice cream can provide valuable insights into its quality and composition. The melting point is an important characteristic because it indicates the temperature at which the ice cream transitions from a solid to a liquid state, which can affect its texture, mouthfeel, and overall consumer experience (Muse at al., 2004).

Ice cream samples were analyzed for their melting points using a straightforward approach. Each sample was placed in a suitable spot for observation, and the time it took for the first drop of melting ice cream to appear was meticulously recorded with a stopwatch. This process was repeated for consistency across all samples. The aim was to understand how variations in sugar content and storage conditions might influence the timing of the first melting drop, providing insights into the ice cream's quality and stability.

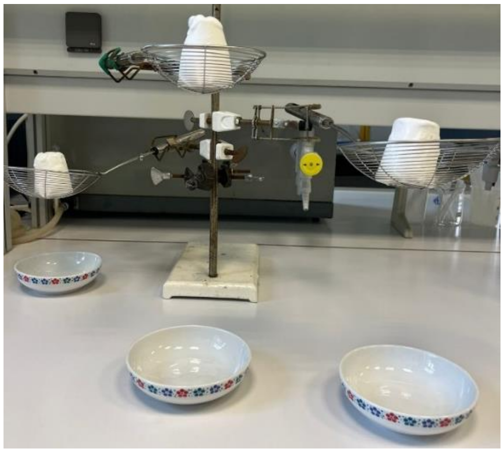


Figure 9. Improvisation where first drop of ice cream analysis was conducted.

5. Results and Discussions

In this chapter, we transition from theory to empirical findings, presenting a detailed analysis of the melting characteristics of frozen desserts. Through systematic experimentation and rigorous analysis, we explore the interplay between temperature variations, compositional profiles, and sensory attributes. By examining color, weight loss, texture, and frost drop behavior, we aim to uncover the underlying scientific mechanisms governing frozen dessert quality and stability.

5.1 Discriminant Analysis

Ice cream quality is influenced by various factors, including ingredients and storage conditions. To delve deeper into this relationship, a discriminant analysis was conducted to explore how different ice cream recipes and storage durations impact classification accuracy. This analysis aims to provide insights into which recipes are most closely associated with specific storage durations, shedding light on the factors contributing to ice cream quality over time.

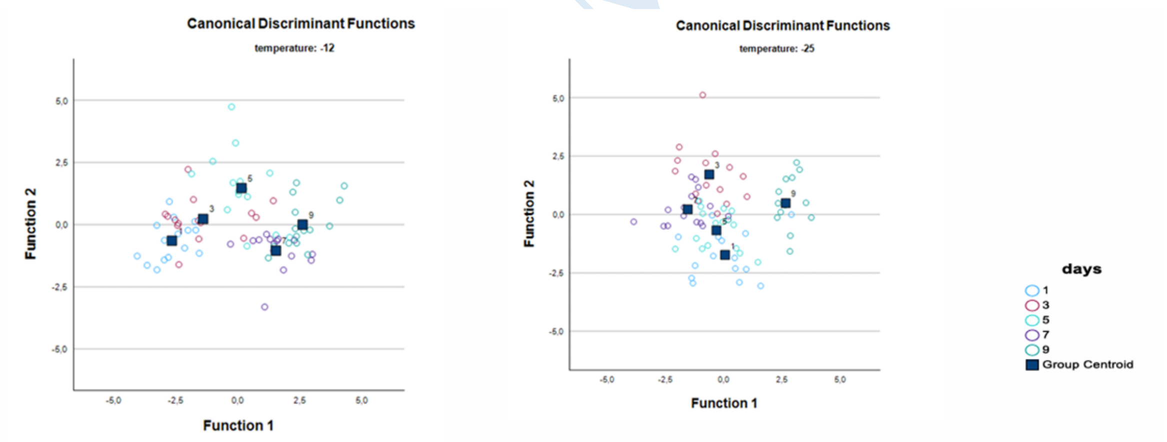


Figure 10. Canonical discriminant functions, in terms of storage temperature at -12°C & -25°C over 9 days of storage.

The discriminant analysis reveals that storage temperature (-12°C and -25°C) significantly affects how ice cream is classified based on storage days. The model performed well, accurately predicting storage conditions for over 80% of cases at both temperatures. However, when tested with cross-validation, its accuracy slightly declined to around 66.7%. This indicates that while storage temperature plays a crucial role in ice cream classification, the model's performance may vary with new data. Further refinement and validation are necessary to enhance its reliability and applicability. Overall, the analysis underscores the importance of considering storage conditions in ice cream quality assessment.

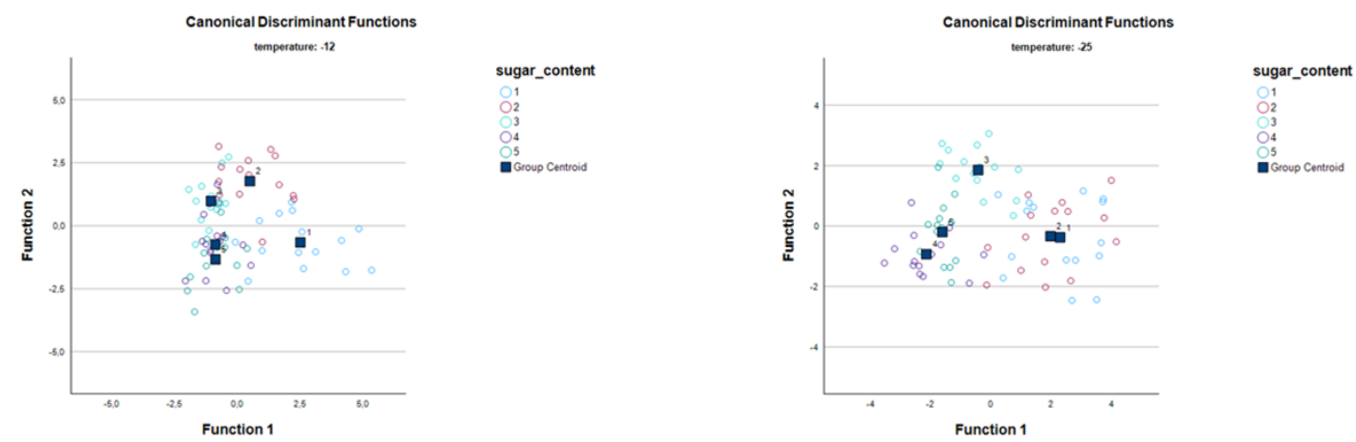


Figure 11. Canonical discriminant functions, in terms of storage temperature at -12℃ & -25℃ over 5 types of recipes.

The discriminant analysis underscores the pivotal role of storage temperature (-12°C and -25°C) and sugar content (recipe 1, 2, 3, 4, and 5) in determining ice cream classification. The analysis reveals that at -12°C storage temperature, the model achieved a moderate level of accuracy, correctly classifying 69.3% of the cases. Conversely, at -25°C storage temperature, the accuracy slightly improved, with 74.7% of cases correctly classified. However, when subjected to cross-validation, the model's performance exhibited a decrease in accuracy. Specifically, at -12°C storage temperature, the cross-validated accuracy dropped to 57.3%, while at -25°C storage temperature, it decreased further to 56.0%. These findings emphasize the necessity of refining the model to enhance its reliability and applicability in real-world scenarios, where variations in data are expected. Despite the insights gained from the discriminant analysis regarding the influential factors in ice cream classification, continuous efforts are warranted to ensure the model's effectiveness in practical applications.

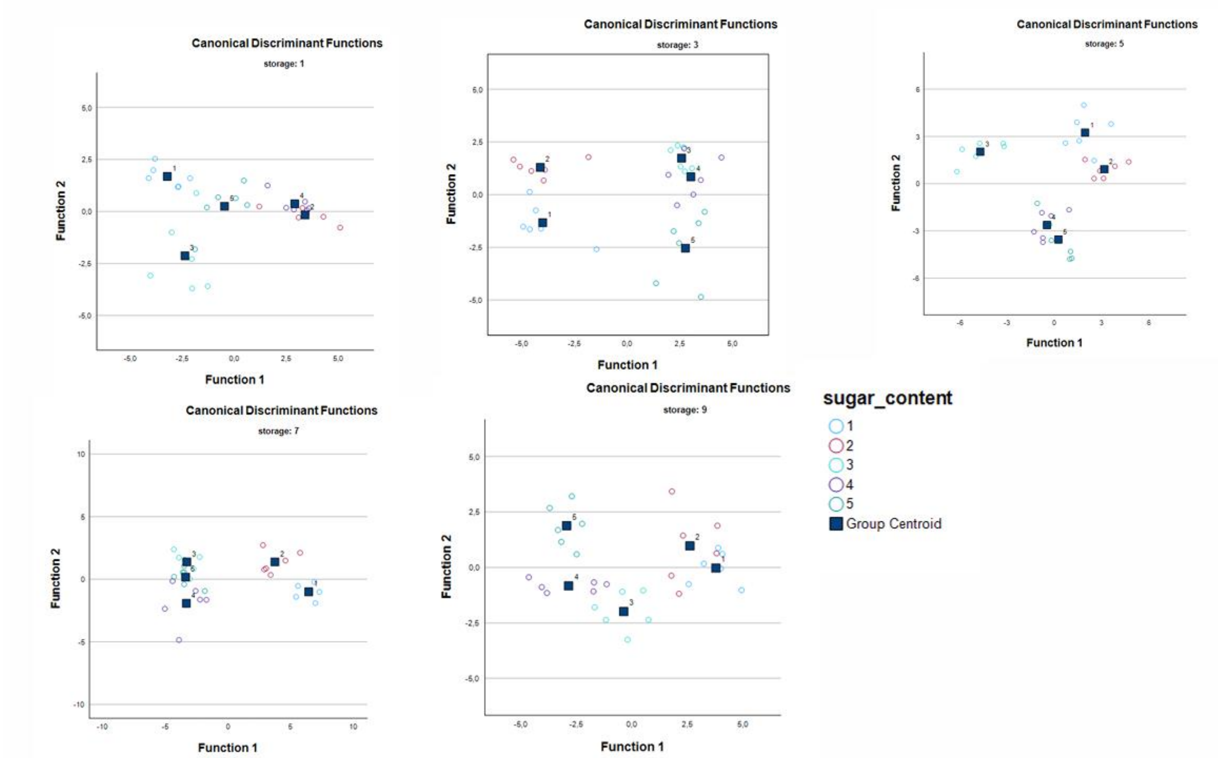


Figure 12. Canonical discriminant functions of storage day 1, day 3, day 5, day 7, day 9 and 5 recipes with different amounts of sugar.

The results of the discriminant analysis provide valuable insights into the interplay between storage duration and sugar content in ice cream classification. When examining ice cream stored for one day, the model achieved a high accuracy of 83.3% in correctly classifying cases based on sugar content. However, this accuracy decreased to 60.0% during cross-validation, indicating potential limitations in generalizability. At storage durations of three, five, and nine days, the model demonstrated consistently high original accuracy rates of 90.0%, suggesting a strong relationship between storage duration and sugar content. Nevertheless, cross-validated accuracy rates varied, ranging from 56.7% to 73.3%, underscoring potential challenges in model robustness when applied to new data. Ice cream stored for seven days exhibited the highest original accuracy of 96.7%, highlighting the significance of this storage duration in ice cream classification. However, even at this stage, cross-validated accuracy dropped to 70.0%. Overall, while the discriminant analysis illuminates the importance of storage duration and sugar content in ice cream classification, further refinement and validation are necessary to enhance the model's reliability and applicability across different storage durations.

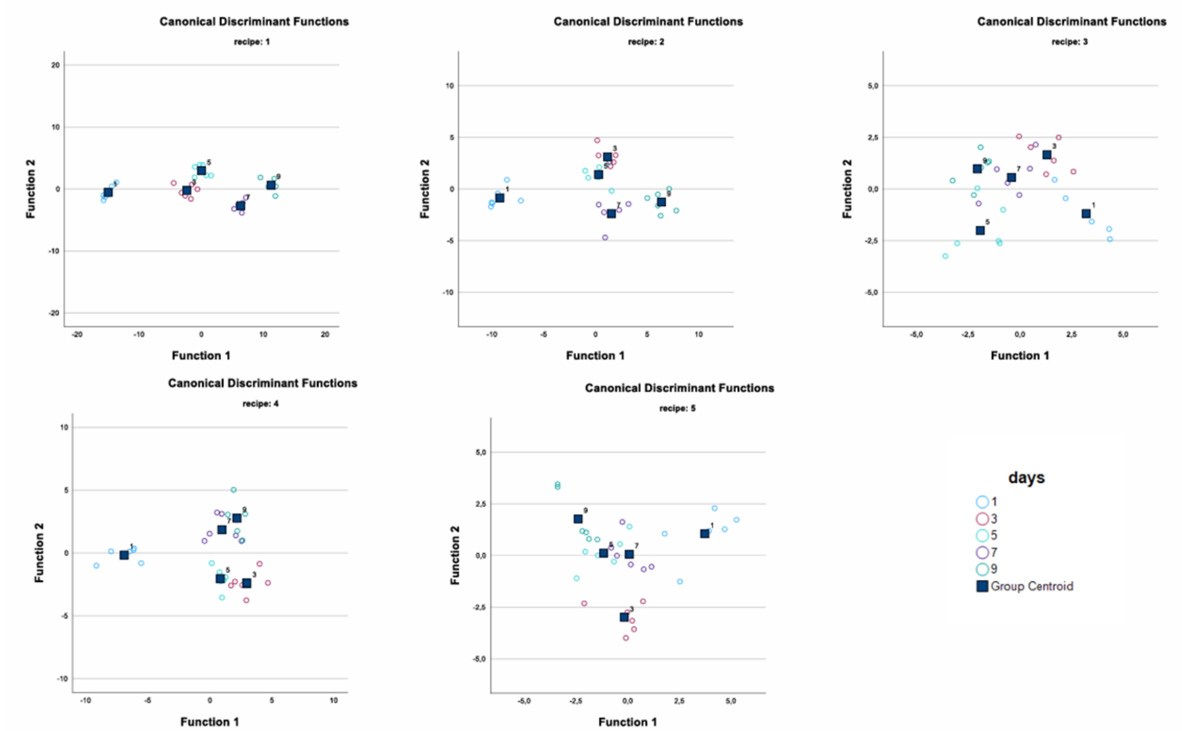


Figure 13. Canonical Discriminant Functions of Recipe 1,2,3,4,5 and storage days (1,3,5,7,9).

The discriminant analysis results offer valuable insights into the association between ice cream recipes (R1, R2, R3, R4, and R5) and storage durations (day 1, day 3, day 5, day 7, and day 9) in classification accuracy. Ice cream made with recipe R1 achieved perfect classification accuracy of 100.0%, demonstrating a strong relationship between this recipe and storage duration. Cross-validation upheld high accuracy at 93.3%, indicating robustness in generalizing to new data for recipe R1. Recipe R2 also exhibited high original accuracy at 93.3%, but cross-validation accuracy dropped to 70.0%, suggesting some limitations in generalizability. Ice cream made with recipe R3 achieved 90.0% accuracy in original classification, but cross-validation accuracy decreased substantially to 43.3%, indicating potential challenges in generalizability. Recipe R4 showed very high original accuracy at 96.7%, but cross-validated accuracy decreased to 63.3%, suggesting some limitations in generalizability. Similarly, ice cream made with recipe R5 demonstrated high original accuracy at 93.3%, but cross-validated accuracy dropped to 60.0%, indicating variability in model performance. Overall, while certain recipes exhibit strong associations with storage durations, cross-validation results suggest the need for further refinement to enhance model reliability and applicability across different recipes and storage durations.

5.2 Weight loss analysis

The results suggest that higher amounts of sugar positively influence the retention of ice cream weight (Drewnowski, 1987). For instance, at -25°C on day 3, ice cream with R1 (0.8kg sugar) experienced a weight loss of 0.08 ± 0.01%, whereas R5 (1.1kg sugar) exhibited a significantly lower weight loss of 0.02 ± 0.05%. This trend persisted across both -25°C and -12°C storage conditions.

The results highlight not only the influence of sugar content but also the impact of storage duration on ice cream weight retention (Aranya, 2008). For example, at -12°C, on day 3, ice cream with R1 (0.08kg sugar) exhibited a weight loss of 0.08 ± 0.058%, which increased to 0.17 ± 0.098% by day 9. This trend was consistent across both -12°C and -25°C storage conditions.

The comparison between storage temperatures reveals differences in weight loss trends. For instance, at -25°C, on day 3, ice cream with R5 (1.1kg sugar) experienced a weight loss of 0.02 ± 0.05%, while at -12°C, the weight loss was slightly lower at 0.009 ± 0.72%.

This suggests that ice cream stored at -25°C exhibited a slightly higher weight retention compared to those stored at -12°C during the same period. These findings highlight the importance of temperature control in minimizing weight loss and preserving the quality of ice cream products.

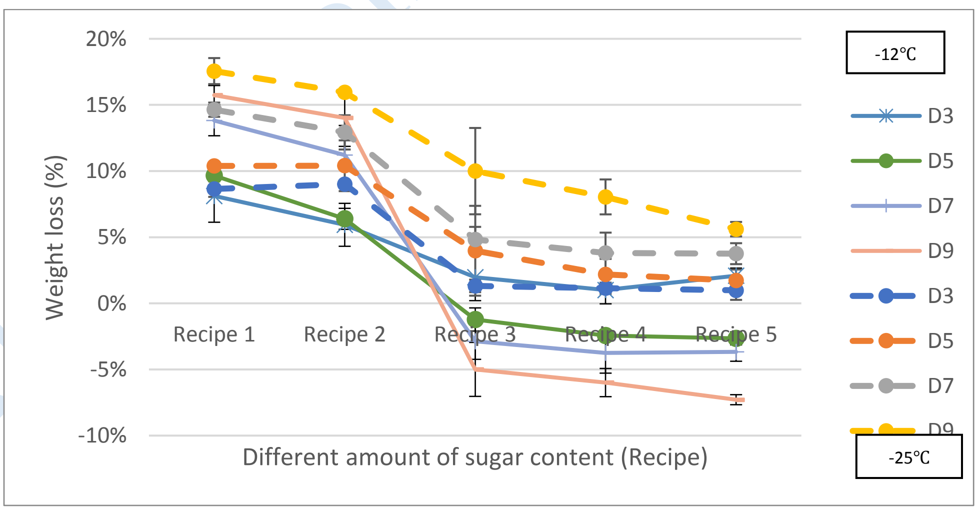


Figure 14. Weight Loss at -12°C & -25°C storage temperature over the 5 Recipes in different sugar contents and 9 days of storage.

[1] The full lines indicate storage at -25°C and dashed lines indicate storage at -12°C

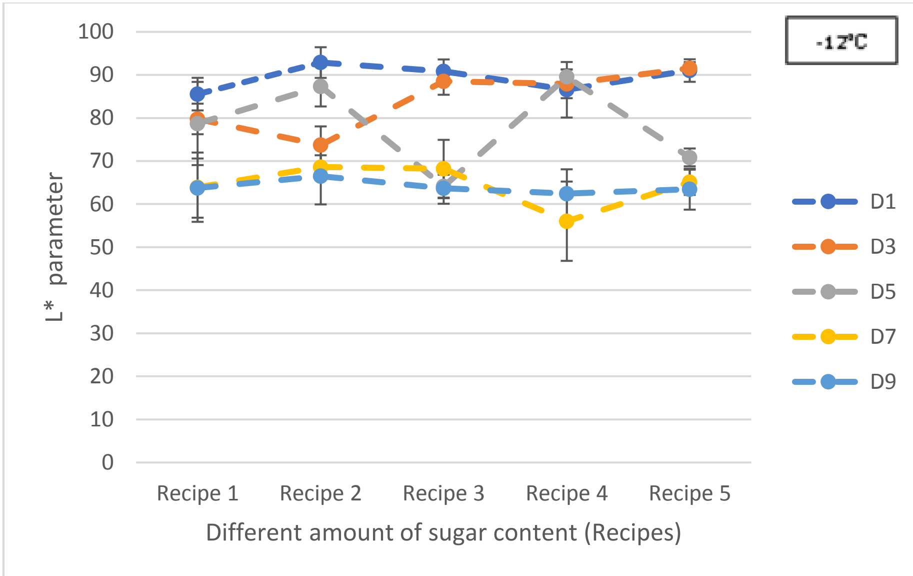
5.3 Color analysis

5.3.1 L* parameter

The observation is that samples with a higher content of sugar tended to have slightly higher L* values, indicating that they appeared lighter in color (Guinard J.-X. , 1997). This observation was particularly in samples R1 (0.8kg sugar) and R5 (1.2kg sugar). Specifically, on Day 9, sample R1 had a L* value of 78.26 with a standard deviation of 6.6, while sample R5 had a L* value of 90.87.

Difference in the L* parameter values between Day 1 and Day 9 of storage were noticed, regardless of the storage temperature. Specifically, for Recipe 2 containing 0.9kg of sugar and stored at -12°C, the L* parameter values were quite higher on Day 1 compared to Day 9. On Day 1, the L* value was measured at 92.87 with a standard deviation of 3.56, whereas by Day 9, it had decreased to 66.47 with a standard deviation of 5.55. This trend suggests a progressive darkening of the samples over the storage period, possibly influenced by chemical reactions, component degradation, or physical changes occurring within the samples during storage. This is in alignment with the study of (Sung Hee Park et al., 2015) that suggests lower temperatures like (-50℃) minimize color changes compared to higher temperatures (-18℃, -30℃). Optimal preservation is at -50℃.

This study further highlights the impact of storage temperature on the L* parameter values, with differences observed between temperatures. Specifically, at a storage temperature of -25°C, the L* parameter values were higher compared to those at -12°C. Take, for instance, Recipe 2 containing 0.9kg of sugar on Day 7: at -12°C, the L* parameter value measured 93.21 with a standard deviation of 1.33, while at -25°C, it was 68.00 with a standard deviation of 2.72. This suggests that lower storage temperatures, such as -25°C, tend to preserve higher L* parameter values compared to higher temperatures like -12°C.



1

Figure 15. L* of color at -12°C storage temperature over the 5 Recipes in different sugar contents and 9 days of storage.

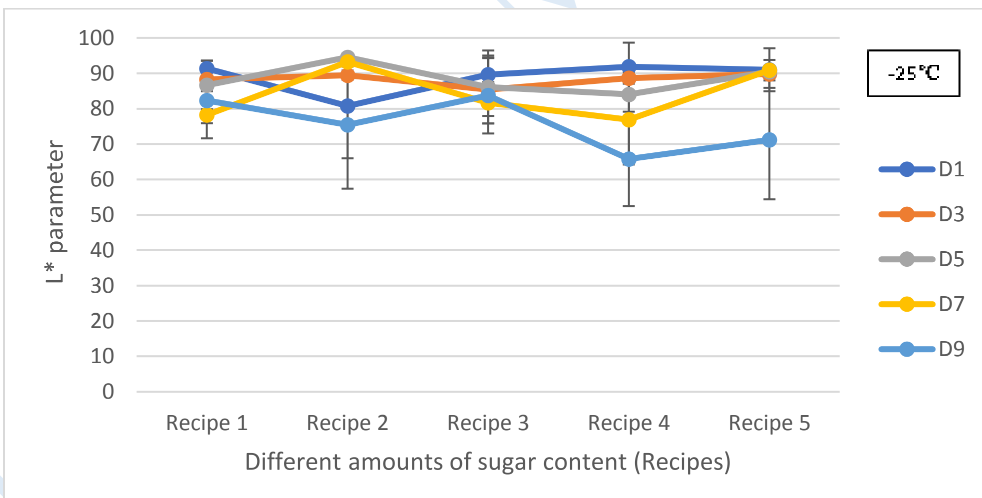
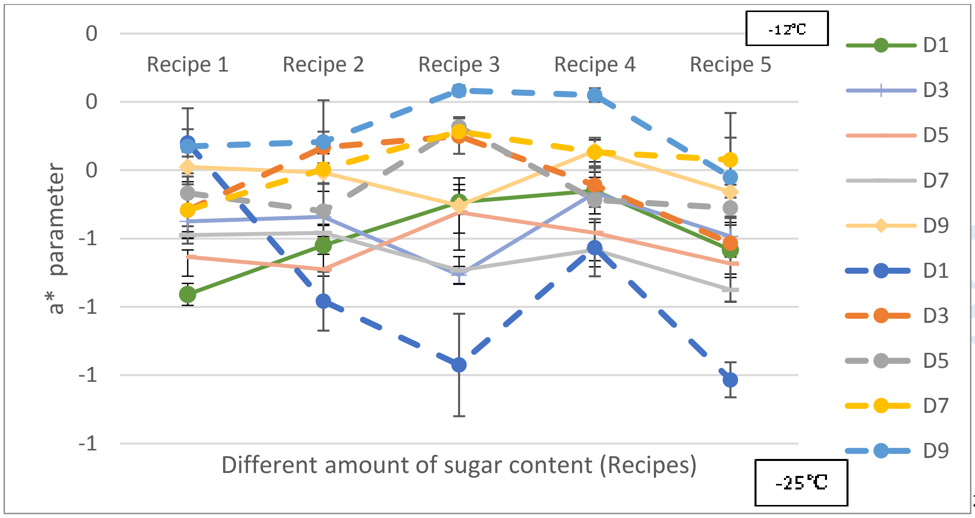


Figure 16. L* of color at -25°C storage temperature over the 5 Recipes in different sugar contents and 9 days of storage.

[1] [1] The full lines indicate storage at -25°C and dashed lines indicate storage at -12°C

5.3.2 a* parameter



2

Figure 17. a* of color at -12°C & -25°C storage temperature over the 5 Recipes in different sugar contents and 9 days of storage.

The results indicate that the parameter a* showed considerable fluctuations in response to changes in sugar content, with no clear trend observed. However, storage duration had a slight influence on the a* parameter in most cases, with higher values noted on day 1 compared to day 9 of storage.

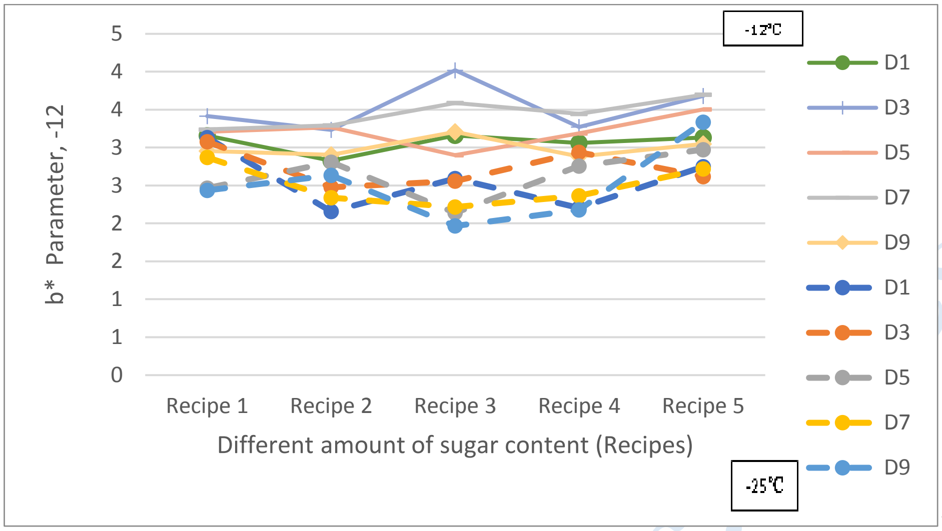
For instance, at -12°C, ice cream with R2 exhibited an a* value of -0.78 ± 0.09 on day 1, which decreased to -0.32 ± 0.12 by day 9. Similarly, at -25°C, the a* value was -0.62 ± 0.03 on day 1 and -0.41 ± 0.06 on day 9 for the same formulation (R2).

The comparison between storage temperatures reveals differences in the a* parameter for Recipe 4 on day 7. At -25°C, the ice cream exhibited an a* value of 0.63 ± 0.05, whereas at -12°C, the value was -0.35 ± 0.04.

This suggests that the storage temperature significantly influences the color characteristics of the ice cream. Ice cream stored at -25°C tends to have a more positive a* value, indicating a redder hue, while storage at -12°C results in a more negative a* value, indicating a greener hue.

[2] [2] [2] The full lines indicate storage at -25°C and dashed lines indicate storage at -12°C

5.3.3 b* parameter



[3]

Figure 18. b* of color at -12°C & -25°C storage temperature over the 5 Recipes in different sugar contents and 9 days of storage.

Comparing the results from ice cream samples stored at different temperatures (-12°C and -25°C) reveals intriguing nuances in the influence of sugar content and storage days on the b parameter, which denotes texture characteristics. At both temperatures, Recipe 3 consistently demonstrates higher b* parameter values across storage days, suggesting an optimal sugar content for texture maintenance. However, the patterns differ slightly between the two temperature conditions.

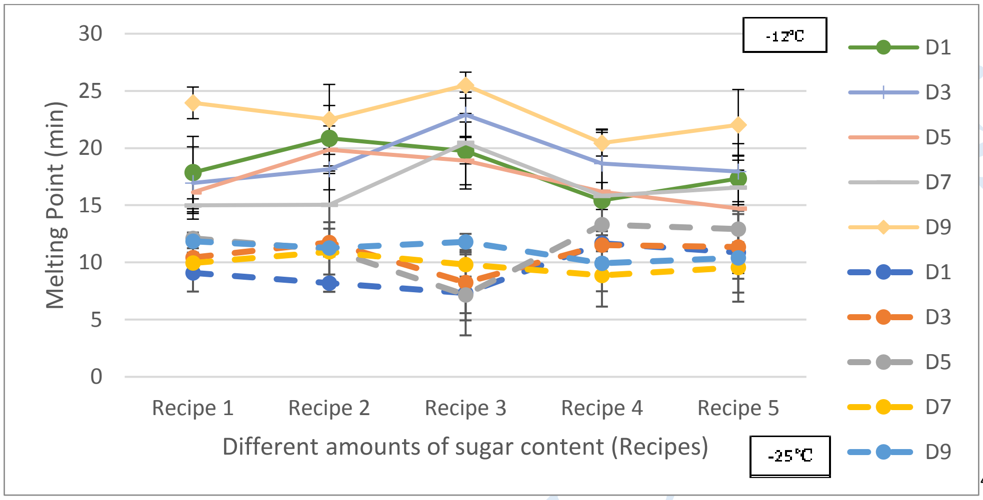
At -25°C, Recipe 5 exhibits the highest b* parameter value on day 7, indicating a potential positive effect of higher sugar content on texture preservation. Storage days impact each recipe uniquely, with some showing consistent decreases (e.g., Recipes 1 and 4) or fluctuations (e.g., Recipe 2) in the b* parameter over time. Recipe 3 shows fluctuations over the storage period, indicating a complex interplay between sugar content and storage duration.

Conversely, at -12°C, Recipe 5 consistently maintains higher b parameter values across storage days, suggesting an advantage in texture maintenance. However, the influence of sugar content becomes less clear over time, with Recipe 3 demonstrating the lowest b parameter values on multiple days, indicating potential challenges in texture preservation. Storage days impact each

[3] [3] The full lines indicate storage at -25°C and dashed lines indicate storage at -12°C

recipe differently, with some showing fluctuations (e.g., Recipes 2 and 4) or more consistent trends (e.g., Recipes 1 and 3) in the b parameter over time.

5.4 Melting Rate – First Drop of Melting



[4]

Figure 19. First drop point of melting at -12°C & -25°C storage temperature over the 5 Recipes in different sugar contents and 9 days of storage.

The results indicate that ice cream formulations with higher sugar content (R1, 1kg sugar) led to a delayed melting point at both -25°C and -12°C storage conditions. At -25°C on Day 3, the first drop of ice cream melted at 22.91 ± 1.98 minutes compared to other recipes which were faster. The same trend was noticed on Day 9 at -12°C, it melted at 11.80 ± 0.70 minutes which was higher than the other recipes. These findings highlight the significant influence of sugar content on ice cream stability, suggesting that the right amount of sugar can effectively regulate melting points under varying storage temperatures (Junior, 2011).

The results show that the duration of storage (1-9 days) affects ice cream melting, with longer storage times leading to a slower melting rate (Kozłowicz et al., 2019). This trend is consistent across both -25°C and -12°C storage temperatures. For example, at -25°C, day 1 ice cream with R3 (1kg sugar) took 15.43 ± 3.30 minutes to melt, increasing to 25.50 ± 1.14 minutes by day 9. Similarly, at -12°C, ice cream with R2 (0.9kg sugar) melted in 8.19 ± 0.79 minutes on day 1, and

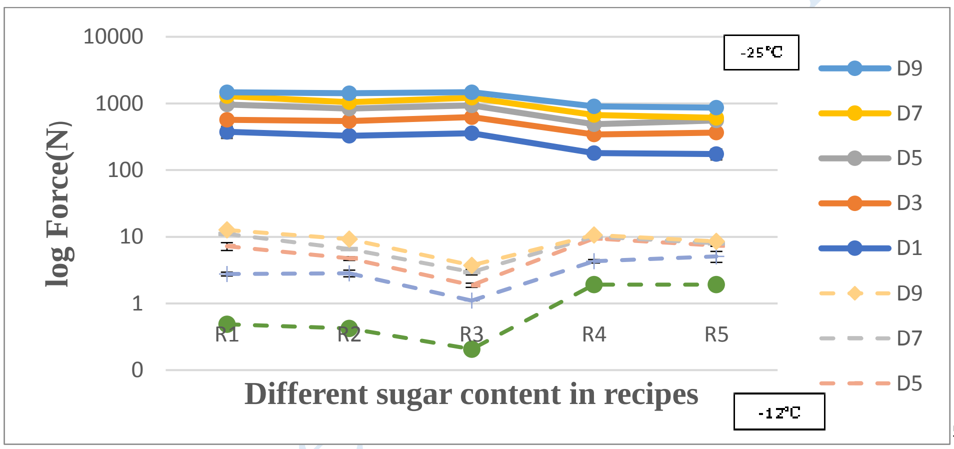
[4] [4] The full lines indicate storage at -25°C and dashed lines indicate storage at -12°C

in 11.28 ± 0.60 minutes on day 9. These findings highlight the importance of considering storage duration in assessing ice cream quality and stability.

The results indicate that samples stored at -12°C exhibited a higher melting rate compared to those stored at -25°C. For example, on day 1, ice cream with R5 (1.2kg sugar) melted at 17.34 ± 2.03 minutes at -25°C, whereas at -12°C, it melted faster, with a time of 10.87 ± 2.30 minutes. This suggests that lower storage temperatures contribute to higher melting rates, e emphasizing the importance of storage conditions in controlling ice cream stability.

5.5 Texture Analysis

5.5.1 Maximal Force (Fmax, N)



[5]

Figure 20. Texture (Fmax,N) at -12°C & -25°C storage temperature at 0min over the 5 Recipes in different sugar contents and 9 days of storage.

The texture analysis of ice cream presents clear distinctions between storage temperatures of -12°C and -25°C. At -12°C, Recipe 3, containing 1kg of sugar, showcases intermediate texture characteristics compared to other recipes.

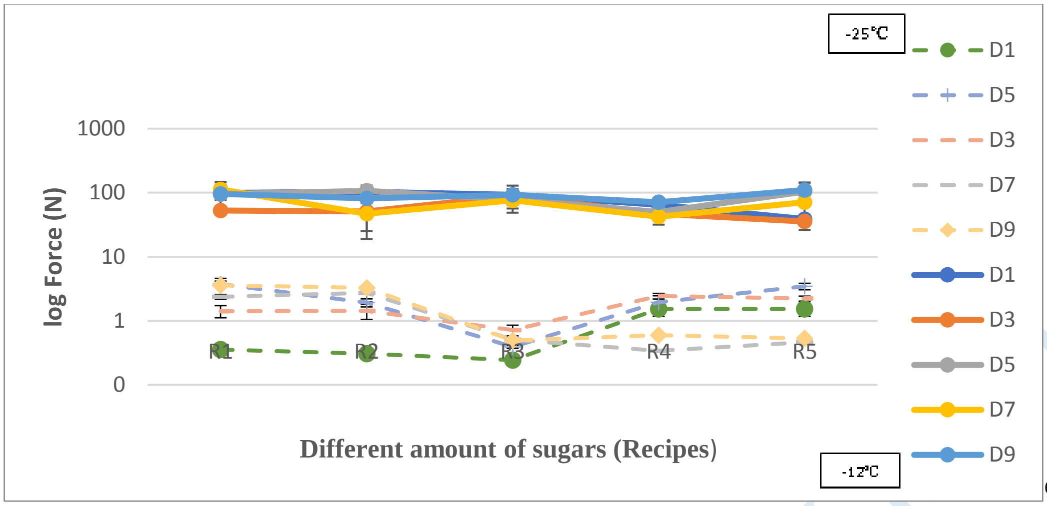
Recipes 1 and 2, with lower sugar content, display softer textures, while Recipes 4 and 5, with higher sugar content, exhibit increased hardness, indicating a probable influence of sugar on texture. Conversely, at -25°C, a different texture pattern emerges. Recipes 1, 2, and 3, with lower sugar content, demonstrate higher firmness compared to Recipes 4 and 5, despite having higher sugar content. This suggests that factors beyond sugar content may play a role in texture at this

[5] [5] The full lines indicate storage at -25°C and dashed lines indicate storage at -12°C

temperature. These findings underscore the temperature-dependent effects of sugar on ice cream texture, with softer textures observed at -12°C and unexpected texture variations at -25°C, highlighting the complexity of texture analysis in ice cream production.

Regarding storage duration, the texture analysis of ice cream stored at -12°C and -25°C reveals contrasting trends. At -12°C, there's a noticeable increase in hardness over the storage duration for Recipes 1, 2, and 3, whereas Recipes 4 and 5 exhibit a decrease in firmness over time. For example, Recipe 1 starts with a hardness of 0.49±0.04 on Day 1 and increases to 1.59±0.30 by Day 9, while Recipe 5 decreases from 1.93±0.23 on Day 1 to 0.54±0.05 by Day 9. Conversely, at -25°C, the trend reverses. Recipes 1 and 2 show a decrease in firmness over storage days, while Recipes 3, 4, and 5 demonstrate an increase in ice cream firmness. These observations suggest that storage temperature significantly influences texture changes over time, with differing effects on ice cream firmness observed between -12°C and -25°C storage conditions.

Comparing the same recipe stored at -25°C and -12°C reveals stark differences in texture. For instance, Recipe 1 exhibits significant contrast in firmness between the two storage temperatures. At -12°C, on Day 1, Recipe 1 has a firmness of 0.49±0.04, indicating a relatively soft texture. However, when stored at -25°C, the same Recipe 1 shows a much higher firmness of 363.04±74.50, suggesting a substantially firmer texture. So, storage temperature affects the hardness of ice cream. It is recommended to store ice cream at temperatures below minus 25°C to maintain quality (Sitnikova, & Tvorogova, 2019).



[6]

Figure 21. Texture (Fmax,N) at -12°C & -25°C storage temperature at 5min over the 5 Recipes in different sugar contents and 9 days of storage.

Examining the impact of sugar content and storage temperature on ice cream texture reveals distinct trends across varying conditions. At -12°C storage, the relationship between sugar content and texture is evident. Recipes with lower sugar content, such as R1 (0.8kg sugar) and R2 (0.9kg sugar), exhibit smaller firmness values, indicating a softer texture (Oli Legassa, 2020). Conversely, recipes with higher sugar content, like R4 (1.1kg sugar) and R5 (1.2kg sugar), present larger firmness values, suggesting a harder texture. This direct correlation underscores the influence of sugar content on texture at this temperature.

However, at -25°C storage, a contrasting trend emerges. Recipes with lower sugar content, R1, R2, and R3, demonstrate firmer textures, while those with higher sugar content, R4 and R5, exhibit softer textures (Guinard, et al., 1997).

These findings emphasize the complex interplay between sugar content and storage temperature, resulting in contrasting texture characteristics. Analyzing texture changes over the 9-day storage period at -12°C reveals consistent trends. Recipes with lower sugar content, such as Recipes 1, 2, and 3, experience increasing firmness over time, while Recipes 4 and 5 exhibit decreasing firmness.

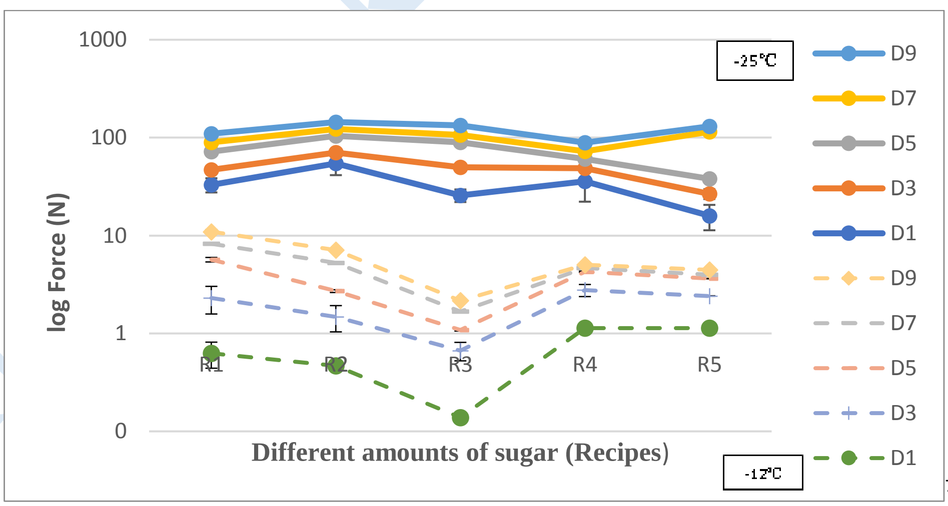
[6] [6] The full lines indicate storage at -25°C and dashed lines indicate storage at -12°C

For instance, Recipe 1 starts with a firmness of 0.35±0.02 on Day 1 and increases to 3.59±1.02 by Day 9, whereas Recipe 5 decreases from 1.53±0.01 on Day 1 to 0.54±0.05 by Day 9. This indicates that sugar content influences the evolution of texture during storage at this temperature. Conversely, at -25°C storage, a different pattern emerges. Recipes 1, 2, and 3 show softer textures over time, while Recipes 4 and 5 become firmer.

Recipe 5 demonstrates an increase in firmness from 38.37±0.56 on Day 1 to 110.40±33.64 on Day 9. This contrasting trend further emphasizes the temperature-dependent effects on ice cream texture.

Comparing the same recipe stored at -25°C and -12°C highlights significant differences in texture. For instance, Recipe 5 displays a contrast in firmness between the two storage temperatures. At -12°C on Day 1, Recipe 5 exhibits a relatively soft texture, with a firmness measurement of 1.53±0.36. However, when stored at -25°C, the same Recipe 5 demonstrates a significantly firmer texture, with a firmness measurement of 38.78±0.56.

These observations underscore the substantial influence of storage temperature on ice cream texture, with temperature variations leading to pronounced differences in texture characteristics for identical recipes



[7]

Figure 22. Texture (Fmax,N) at -12℃ & -25℃ storage temperature at 10min over the 5 Recipes in different sugar contents and 9 days of storage.

[7] [7] The full lines indicate storage at -25℃ and dashed lines indicate storage at -12℃

The texture analysis reveals intriguing trends in ice cream texture influenced by sugar content, recipe composition, and storage temperature. While lower sugar content generally results in softer textures, higher sugar content tends to yield harder textures, with Recipe 3 presenting an exception, consistently displaying the softest texture (Oli Legassa, 2020).

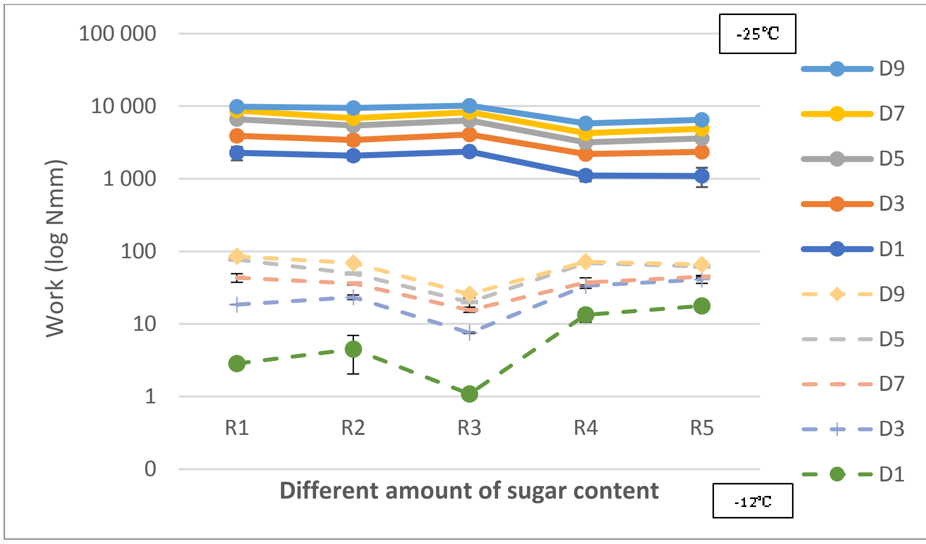
At -12°C storage, Recipe 1 had a firmness of 0.63 ± 0.19 on Day 1, while Recipe 3 exhibited a softer texture at 1.13 ± 0.04. Conversely, at -25°C, despite higher sugar content, Recipes 4 and 5 displayed softer textures compared to Recipes 1 and 2. For instance, Recipe 1 had a texture value of 22.07 ± 5.46 on Day 1, while Recipe 4 had a softer texture at 30.81 ± 13.69.

The analysis of texture changes over time at -12°C storage revealed contrasting trends between recipes. Recipes 1, 2, and 3 showed increasing firmness, while Recipes 4 and 5 became softer. For example, Recipe 1 started with a firmness of 0.63 ± 0.19 on Day 1, increasing to 2.71 ± 0.5 by Day 9, while Recipe 4 decreased from 1.13 ± 0.02 on Day 1 to 0.47 ± 0.18 by Day 9.

At -25°C storage, varying trends were observed, with no clear influence of sugar content on texture changes over time. Recipes 1 and 2 exhibited softer textures compared to Recipes 3 and 5. For instance, Recipe 2 had a texture value of 47.45 ± 13.12 on Day 1, decreasing to 21.66 ± 0.19 by Day 9. Meanwhile, Recipe 3 started with 23.63 ± 3.79 on Day 1, slightly increasing to 26.68 ± 1.11 by Day 9.

Comparing Recipe 5 stored at -25°C and -12°C highlighted significant differences in texture. At -12°C on Day 3, Recipe 5 had a soft texture at 1.28 ± 0.09, whereas at -25°C, the same recipe displayed a firmer texture at 10.73 ± 3.07. These findings emphasize the substantial impact of storage temperature on ice cream texture, with noticeable variations observed between different storage conditions for the same recipe (Robb, 2023).

5.1.2 Work (log Nmm)



[8]

Figure 23. Texture (Work, log Nmm) at -12°C & -25°C storage temperature at 0min over the 5 Recipes in different sugar contents and 9 days of storage.

The texture analysis conducted at -12°C provides valuable insights into the relationship between sugar content, storage duration, and the work required for texture analysis. Generally, there's a discernible correlation between sugar content and the work values, with higher sugar content recipes typically exhibiting lower work values, indicative of softer textures (Oli Legassa, 2020).

For instance, Recipe 5 consistently displays lower work values compared to Recipe 1, reflecting its higher sugar content of 1.2 kg versus 0.8 kg in Recipe 1. A specification is that on day 5 R1 demonstrated 33.71±5.87 and in R5 17.0±1.87.

Regarding storage duration, the effect varies across recipes. Recipe 1 and others as well demonstrates a fluctuating pattern in work values over the storage days, while Recipe 4 exhibits fluctuations, indicating a softening of texture over time. In day showed 13.34±2.79 and in day 9 it was 3.71±0.16.

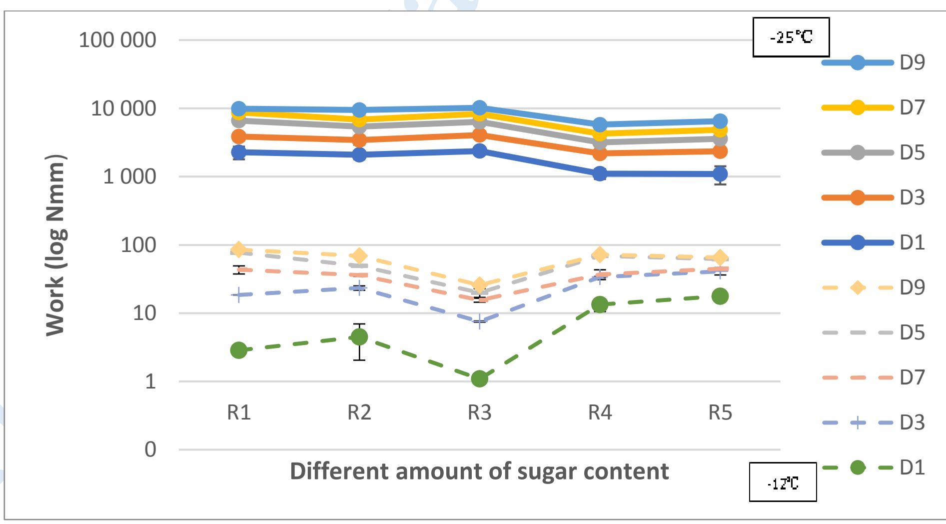
The texture analysis conducted at -25°C provides valuable insights into the relationship between sugar content, storage duration, and the work required for texture analysis. Higher sugar content generally corresponds to higher work values, suggesting firmer textures in ice cream formulations.

[8] [8] The full lines indicate storage at -25°C and dashed lines indicate storage at -12°C

For example, Recipe 1 consistently exhibits higher work values compared to Recipe 5, reflecting the differences in their sugar content. In day 5 we have R1 at 2719.55±131.98 and in R5 we had 1256.18±99.81.

Regarding storage duration, the effect varies across recipes, with different patterns of fluctuation in work values observed over the storage days. Recipe 1 shows a fluctuating trend, with work values decreasing on day 3, increasing on day 5, decreasing again on day 7, and finally decreasing further on day 9. The same fluctuations happened in other recipes as well. In contrast, Recipe 4 displays relatively stable work values over the storage period. In day 1 it shoed 1026.85±324.55 and in day 9 1608.57±62.48.

These findings underscore the complex interplay between sugar content and storage duration in shaping ice cream texture at -25°C, with higher sugar content generally associated with firmer textures and storage duration influencing the stability of texture characteristics throughout the storage period. Also, according to the study of (Akalin et al., 2008) storage temperature of -20°C improved the hardness of ice cream in the study.



[9]

Figure 24. Texture (Work, log Nmm) at -12°C & -25°C storage temperature at 5min over the 5 Recipes in different sugar contents and 9 days of storage.

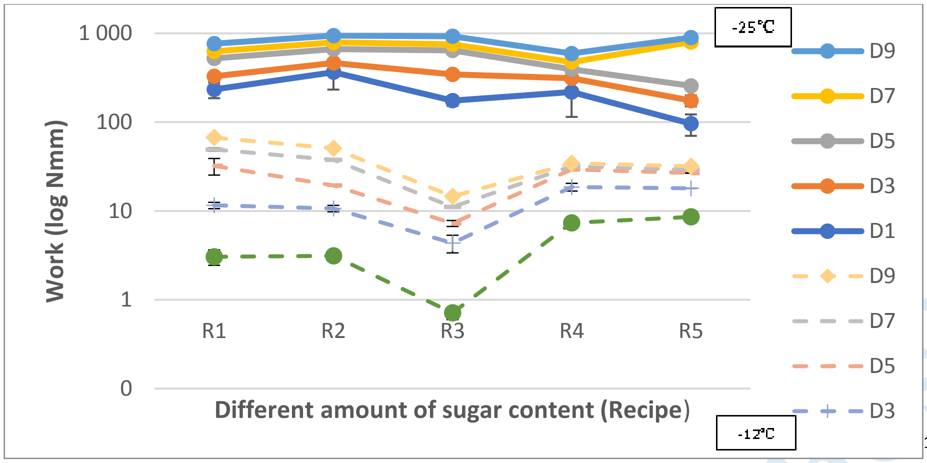
[9] [9] The full lines indicate storage at -25°C and dashed lines indicate storage at -12°C

The texture analysis reveals that higher sugar content in ice cream recipes generally corresponds to lower work values, indicating softer textures (Oli Legassa, 2020). For instance, Recipe 5, with the highest sugar content of 1.2 kg, consistently shows lower work values compared to Recipe 1, which has the lowest sugar content of 0.8 kg. In day 1, we have R1 with 2.05±0.08 and in R5 with 14.18±0.53.

However, the effect of storage duration on work values varies among recipes. Recipe 1 demonstrates a fluctuating pattern over the storage days, with work values increasing from day 1 to day 3, decreasing on day 5, increasing again on day 7, and dropping slightly on day 9. Similay happened to all others R2 and R3. Conversely, Recipe 4 initially exhibits a high work value on day 1 (10.09±2.49), which significantly decreases by day 9 (4.21±0.19), suggesting a softening of texture over time. The same trend was noticed in R5 as well. Overall, while there's no consistent trend across all recipes regarding the influence of storage days on work values, the higher sugar content generally correlates with softer textures.

The texture analysis conducted at -25°C reveals trends in the influence of sugar content and storage duration on work values, reflecting ice cream texture. Consistently, recipes with higher sugar content exhibit lower work values, indicating softer textures, mirroring observations at -12°C. For example, Recipe 2 and Recipe 3, with comparatively higher sugar contents, consistently display lower work values compared to Recipe 1, which has a lower sugar content.

However, the effect of storage duration on work values varies across recipes. Recipe 4 shows a decreasing trend in work values over the storage days, suggesting a softening of texture over time. Conversely, Recipe 5 demonstrates fluctuations in work values, with an increase on days 3 and 5 followed by a decrease on days 7 and 9. Overall, while there's no uniform trend across all recipes regarding the influence of storage days on work values at -25°C, the higher sugar content generally corresponds to softer textures, aligning with observations at -12°C (Oli Legassa, 2020).



[10]

Figure 25. Texture (Work, Nmm) at -12℃ & -25℃ storage temperature at 10min over the 5 Recipes in different sugar contents and 9 days of storage.

The texture analysis data at 10 minutes after removal from storage at -25°C provides insights into the influence of sugar content and storage duration on ice cream texture. Regarding sugar content, there is no clear trend indicating a consistent relationship between sugar content and work values across recipes. Work values vary across recipes regardless of sugar content.

However, regarding storage duration, there are distinct patterns of fluctuation in work values observed. For example, Recipe 1 shows an increasing trend in work values from day 1 to day 3, followed by relatively stable values on day 5 and day 7, with a slight increase on day 9. In contrast, Recipe 4 exhibits decreasing work values over the storage days, with a decrease from day 1 to day 5 before a slight increase on day 7 and day 9.

Overall, while sugar content may not consistently influence work values, storage duration significantly impacts texture characteristics, with varying patterns of fluctuation observed across different recipes over the storage period. A trendline analysis could further elucidate these trends by providing a clearer visualization of the overall direction of change in work values over time for each recipe.

[10] [10] The full lines indicate storage at -25°C and dashed lines indicate storage at -12°C

6. Conclusions

In this comprehensive thesis, an extensive investigation delved into the multifaceted dynamics of sugar content, storage conditions, and duration on various aspects of ice cream quality. The findings uncovered a robust positive correlation between higher sugar content and the retention of ice cream weight across different storage temperatures, elucidating the crucial role of sugar in preserving product integrity. Furthermore, the examination of parameters L*, a*, and b* revealed nuanced interactions, with higher sugar content generally leading to lighter coloration (higher L* values) and variations in color hue (a* parameter) and texture attributes (b* parameter) influenced by both sugar content and storage conditions.

Additionally, the study unveiled significant insights into ice cream stability and melting rates, with formulations boasting higher sugar content demonstrating delayed melting points and slower melting rates, particularly noticeable at lower storage temperatures. Moreover, the texture analysis elucidated complex interplays among sugar content, recipe composition, and storage temperature, showcasing differing texture characteristics influenced by these variables.

For instance, while lower sugar content generally yielded softer textures at -12°C, a different texture pattern emerged at -25°C, where formulations with higher sugar content exhibited softer textures despite expectations. Furthermore, the examination of texture changes over the storage period highlighted contrasting trends between -12°C and -25°C conditions, emphasizing the critical impact of storage temperature on ice cream texture.

In summary, this thesis provides comprehensive insights into the multifaceted dynamics of sugar content, storage conditions, and duration on various ice cream quality attributes, including weight retention, color, texture, stability, and melting rates. By offering valuable empirical data and insights, this research contributes to informed strategies for optimizing ice cream formulations and enhancing product quality and stability in the food industry. However, further research is warranted to deepen our understanding of these relationships and refine strategies for optimizing ice cream production and quality control practices, ensuring continued advancements in the field.

7. Summary

This study investigated the effects of sugar content and storage conditions on the physical characteristics of flavored lemonade ice cream during frozen storage at -25°C and -12°C, over a 9-day period. By systematically exploring temperature, composition, and sensory attributes, we aimed to understand their interactions and influence on frozen dessert quality. Our findings revealed that higher sugar content positively impacted weight retention, particularly over extended storage durations, while lower temperatures helped maintain color and weight. Moreover, sugar content influenced melting points, with higher levels resulting in delayed melting. Texture analysis indicated that higher sugar content generally led to softer textures, though this varied depending on storage conditions. These results highlight the intricate complexity of frozen dessert quality and emphasize the importance of considering factors such as sugar content, storage temperature, and duration for optimizing production processes. Further research is necessary to fully comprehend these mechanisms and enhance frozen dessert production practices.

8. Acknowledgements

I extend my deepest gratitude to my thesis advisor, Professor Dr, Kenesei Gyorgy, whose guidance, expertise, and unwavering support have been instrumental throughout this journey. Your mentorship has shaped not only the outcome of this thesis but also my growth as a researcher and scholar.

I am also thankful to MATE University and Institute of Food Science and Technology for providing the necessary resources and facilities for conducting this research. The scholarly environment fostered by the institution has been invaluable in shaping my academic pursuits.

I extend my heartfelt appreciation to my family and friends, particularly my parents, Burbuqe Rafuna Beka and Isa Beka, whose unwavering support has been the cornerstone of my academic journey. Their encouragement, guidance, and boundless love have fueled my determination and propelled me forward, shaping me into the person I am today. I owe an immeasurable debt of gratitude to them for their unwavering belief in me and for always being my biggest cheerleaders.

Lastly, I extend my heartfelt appreciation to all those who directly or indirectly contributed to this thesis. Your collective efforts have played a significant role in its completion, and I am sincerely thankful for your support!

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