FACTORS AFFECTING THE QUALITY OF PLANT-BASED FROZEN DESSERT

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ABSTRACT

In this study, the effects of changing formulation and processing conditions on the quality of plant-based, frozen dessert were investigated. A total of 26 formulations were compared, including one commercial dairy ice cream sample and one commercial plant-based frozen dessert sample which were used as reference points to gauge consumer acceptability. Physicochemical properties (e.g. pH, total soluble solids as degree Brix, overrun, color components, particle size) of the mixes before and after scaling up were measured, and these findings were used to inform product development decisions. Results suggested that vanilla frozen dessert quality showed most potential with the following attributes: pH 6, total soluble solids value of 36% as degree Brix, overrun of 100%, L* color value above 80, smooth and bimodal particle size distribution with average particle size D [4,3] of 4.1 μm, composition of: 14.75% fat, 37.1% solids, with gum or blends as stabilizers made of gum acacia, locust bean gum, and guar gum.

BIOGRAPHICAL SKETCH

Ning Xuan Yip is a graduate student at Cornell University pursuing a Master's in Food Science. Prior to Cornell, she earned a Bachelor of Science degree in Chemical Engineering from Purdue University in 2017, where she focused on food and biopharma applications. During her undergraduate studies, Ning developed metabolic models to convert biomass in photosynthetic bacteria to commercially valuable chemical and energy sources, and worked in R&D and engineering internships, which sparked off her interest in creating innovative and sustainable solutions. After graduating, Ning worked for about 3 years at FrieslandCampina and Abbott Nutrition, where she developed dairy products and infant and adult nutraceuticals. When the pandemic hit, Ning realized that the food system needed saving and wanted to deepen her knowledge in sustainable food solutions. She started working part-time as a Good Food Institute Research Fellow to advance research in alternative proteins, while pursuing credentials in plant-based nutrition, biomanufacturing and biotechnology so she could deepen her knowledge in the field. In 2020, Ning finally decided to focus fully on understanding sustainable food solutions by enrolling in Cornell's Food Science graduate program. Since then, she's worked in a variety of sustainability-focused projects with companies like Turtletree Labs and Siena Development, started the Alternative Protein Project at Cornell and completed projects in plant-based protein isolates, biodegradable packaging, and better-for-you, upcycled plant-based snacks. Beyond academics, Ning volunteers as a speaker in public workshops, United Nations and IFT to expand her leadership skills. She also was a TA for a viticulture and enology course and was awarded with the Women in Agribusiness Scholarship. After graduation, Ning plans to pursue her dream of developing sustainable food solutions as a Food Scientist-Engineer.

To Hon Mun and Abhishek,

for inspiring me to take the leap and pursue my dreams.

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1.1 Introduction

Definition. In this study, the term “plant-based frozen dessert” will be used to describe the non-dairy frozen dessert formulation developed with an aim to give a similar organoleptic experience derived from consuming conventional dairy ice cream. “Plant-based frozen dessert” has no official regulatory definition, but it generally refers to a product that excludes dairy, eggs, and other animal-based ingredients.

Regulation. According to the FDA (USDA, 2022), a product qualifies as “ice cream” if the product contains at least 10% dairy milkfat and has no more than 100% overrun and weighs no less than 4.5 lb/gal. Ice cream is heavily regulated in detail under the 21CFR135.110 guideline by the FDA. Thus, because plant-based frozen dessert formulations do not meet most of the FDA criteria, these dessert formulations cannot be labeled as “ice cream” in the US, giving rise to the birth of names like “dairy-free sorbetto layers”, “non-dairy frozen dessert” and “vegan frozen dessert”.

Figure 1. Examples of various naming conventions for plant-based frozen desserts

History vs. global trends. The world's earliest known recipes (Shurtleff & Aoyagi, 2013) for plant-based frozen dessert is in 1899 by Almeda Lambert, who published the vegetarian cookbook “Guide for Nut Cookery”. Her dairy-free, nut-based frozen dessert formulations were based on either peanut milk or almond milk and the recipes involved cooking together a mix of nut cream, sugar and vanilla, and then freezing it. In 1934, the world’s first commercial soy ice cream was introduced by Jethro Kloss in Washington, D.C., who also founded the company, Scientific Food & Benevolent Association to produce in bigger quantities. Globally, in countries such as China, U.K., South America and Japan, soy ice cream and other nut-based, dairy-free frozen desserts were also being developed and sold, but only on a small scale.

Shifting our focus to the present day, the plant-based frozen dessert market is estimated at USD 1.89B in 2020 and is expected to grow by a CAGR of 9.10% through 2027 (Market Data Forecast ltd, 2022). The demographic of consumers wanting allergy-free, healthier, animal-free and clean label products are growing significantly, fueling the demand and incentivizing more companies to include non-dairy, plant-based frozen desserts in their portfolio. Multinational conglomerates such as Unilever (Brands: Ben & Jerry’s, Talenti, Breyers, Magnum), General Mills (Brand: Häagen-Dazs) and Danone (Brand: So Delicious) have taken up the challenge of developing and commercializing these treats at a global scale. Even local, small-sized ice cream shops joined the trend; it is not as much of a surprise now than perhaps, ten years ago, to see vegan and allergy-friendly ice cream options on the menu.

Figure 2. Examples of the vegan ice cream options in small, local businesses

Challenges of developing plant-based frozen dessert. Plant-based frozen desserts contain a variety of sugars, fats, protein and minerals that can influence functional ingredient properties. Key functional properties such as freezing point depression (which affects the shelf-life, freeze-thaw stability and texture), emulsification performance (which affects the texture and stability) and protein-fatty acid composition (which affects stability and texturizing considerations) will be harder to predict due to their variable composition and processing. Plant-based ingredients also have more flavor-variability relative to dairy, and many ingredients have off-notes that must be masked or complemented. There is no “gold” standard of plant-based frozen dessert formulation, as the composition in each formulation is unique since it depends on how the rest of the ingredients interact with each other. In addition, literature on 100% plant-based frozen dessert formulations is limited, with most articles focusing on a specific characteristic or technology. Without a standard of identity and sufficient references, plant-based frozen dessert formulation options seem unlimited, and parameters can be difficult to define. Section 1.4 will discuss more in detail.

Goal of the study. The aim of this study is to analyze the factors that affect the quality of a plant-based frozen dessert developed on a bench scale and after scaling up for commercial production.

1.2 Plant-based frozen dessert market assessment

Market assessment of plant-based ice cream. According to Mintel (Kamp, 2021), plant-based frozen desserts have the potential to be a long-term driving force in the the plant-based category and the segment is becoming increasingly competitive, with dairy-free claims growing 8.8% from 2019 to 2020. The COVID-19 pandemic (Rosenstock, 2021) has sparked off an even larger growth in the proportion of consumers who opt for animal-free, sustainable and better-for-you indulgence. In a study done by the International Food Information Council's 2020 Food & Health Survey (*2020 Food & Health Survey*, 2022), 54% of consumers said that they care more about the health effects of their food and beverage choices in 2020 than they did in 2010, and a 2018 study by DuPoint Nutrition & Health (Siegner, 2018) showed that 52% of consumers felt that eating plant-based foods made them healthier.

Consumer perception. Despite the significant increase in demand for plant-based frozen desserts, companies have been having a hard time retaining customers who repeat purchases. The most pressing issue for plant-based formulators remains nailing an appetizing taste profile (Decker, 2019). Besides the challenging profile and texture of plant bases, processing conditions too, can contribute to an overall negative organoleptic experience, if not optimized well. For example, rice protein has a naturally gritty texture that may not be as appealing as the creamy texture of whey, possibly presenting some formulation challenges. In addition, high-temperature processing can exacerbate textural and stability problems.

1.3 Current formulations of plant-based frozen dessert

Despite not having a standard of identity, the compositions of commercially available plant-based frozen desserts were compared, and these ranges were found.

Protein. About 50-60% of the plant-based frozen dessert comprises of nuts, seeds, grains, legumes and fruit (e.g. Soy, Peanut, Rice, Oat, Flax, Sunflower, Coconut, Avocado). Protein influences the emulsifying abilities of the ice cream mix by preventing water and fat from separating. Plant-based proteins contribute to these three important functional roles: emulsification, aeration and solution behavior. Proteins stabilize the fat emulsion formed in the ice cream mix. Instability of the proteins in the mix will lead to issues such as curdling of the mix during freezing, which causes separation of the fat and thin serum (Goff & Hartel, 2013).

Fat. Fat comprises of about 8-10% (Goff & Hartel, 2013) of the product. Depending on the step at which the fat is added and the rest of its composition, either solid or liquid fat will be used. A few common fat sources are: coconut cream, sunflower oil and canola oil.

Solids non-fat. Typically 36% is (Goff & Hartel, 2013) the low-average used in formulations. The amount of plant solids non-fat can bring a great number of different sugars and minerals which affect the freezing point in unpredictable ways, and may require the need for additional gums to maintain a creamy texture.

Stabilizers/ Emulsifiers. The amount of stabilizers and emulsifiers would vary, depending on the quantity of solids or protein content. Usually, it is about 0.1-0.8% (Goff & Hartel, 2013) of the product.

Stabilizers help stabilize the emulsion through preventing the creaming of fat, aiding in the suspension of liquid flavors and disrupting serum separation that occurs because of the incompatibility between milk proteins and polysaccharides. Common stabilizers include carrageenan, guar and locust bean gum.

Emulsifiers are added to the ice cream mix to reduce the stability of the fat emulsion and to encourage its partial coalescence. Partial coalescence of the fat molecules allows for fat destabilization which enhances the final product’s smooth and creamy texture. For the food industry, small molecular surfactants (e.g. synthetic emulsifiers like polysorbate 80, monoglycerides and diglycerides, natural emulsifiers like egg yolk and sweet cream buttermilk) are usually used as emulsifiers as they are able to displace proteins from the surface of fat globules, allowing them to be more susceptible to partial coalescence (Brady, 2013).

Other additives. Secondary ingredients such as flavors and sweeteners may be added to differentiate the product, enhance the desired flavor and complement off-notes present from other bases. An example would be to use nut butters to complement the earthiness of a pea protein-based frozen dessert. Figure 3 gives a summary of the relationship between each ingredient in ice cream and its key microstructural components.

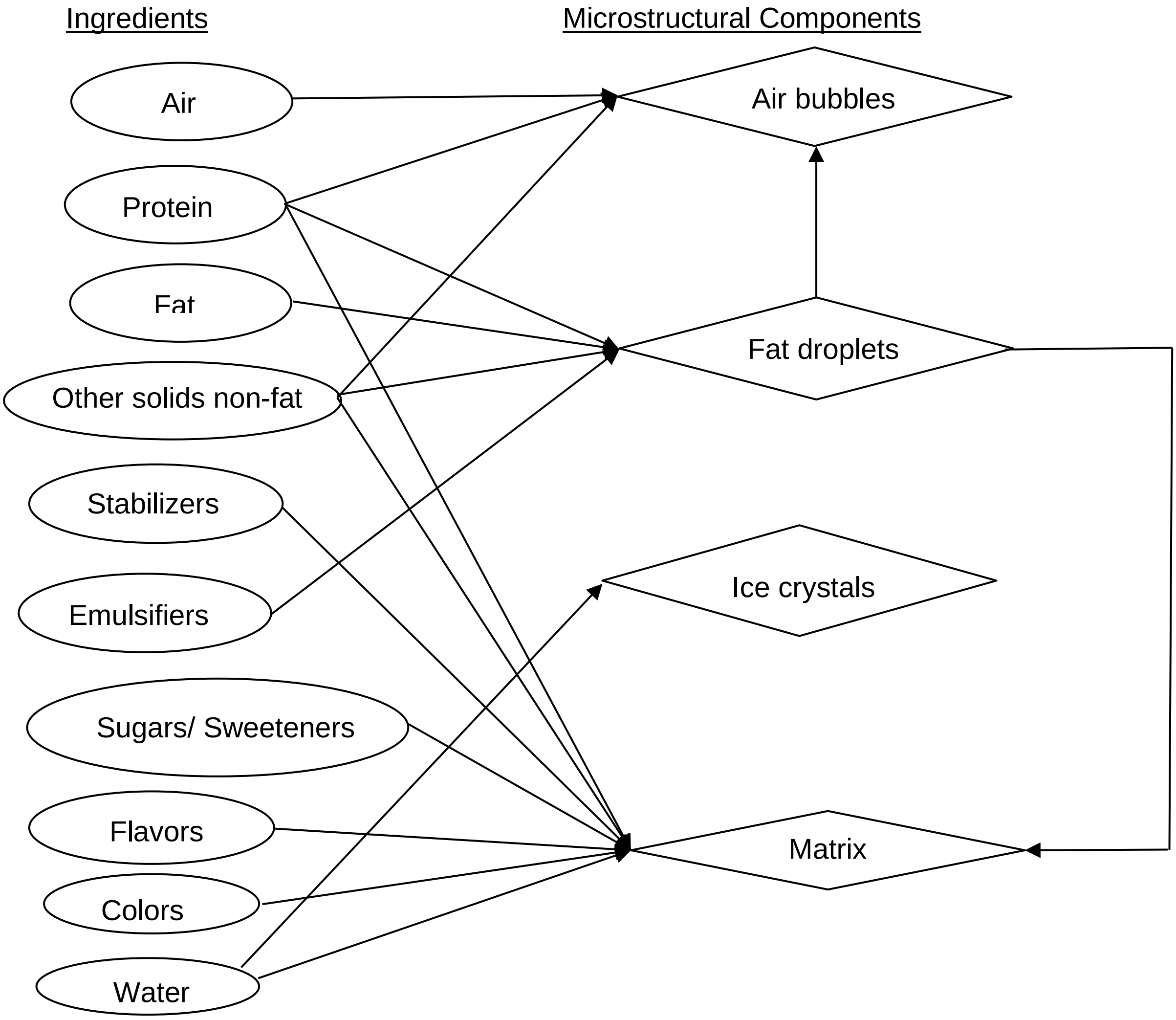


Figure 3. Relationship between ingredients and microstructural components of ice cream or plant-based frozen dessert. Figure adapted from book (Clarke, 2015).

Air, protein and other solids non-fat coat the surface of the air bubbles. The fat droplets are made of protein, fat, emulsifiers, and the ice crystals are formed from water. Matrix refers to the solution of sugars, stabilizers, milk proteins and other additives like flavors and colors in which some of the fat is suspended. Since each ingredient will affect more than one structural component of the final product, careful calibration of all parameters is required to achieve the ideal quality. Table 1 gives a guide on the typical volume percentages of the microstructural components for different types of frozen dessert (The Culinary Institute of America (CIA) & Migoya, 2008).

Table 1. Typical volume percentages of microstructural components for different types of frozen dessert. Values for plant-based frozen dessert were determined based on commercially available products.

Microstructural components	Standard Ice Cream (%)	Premium Ice Cream (%)	Low Fat Ice Cream (%)	Soft serve (%)	Frozen Yogurt (%)	Sorbet (%)	Plant-based frozen dessert (%)*
Air	50	35	48	52	60	0	37.8
Ice	30	35	31	23	68.65	64	61
Matrix	15	20	20	21	29.35	34.5	TBD
Fat	5	10	1	4	2	1.5	7.95

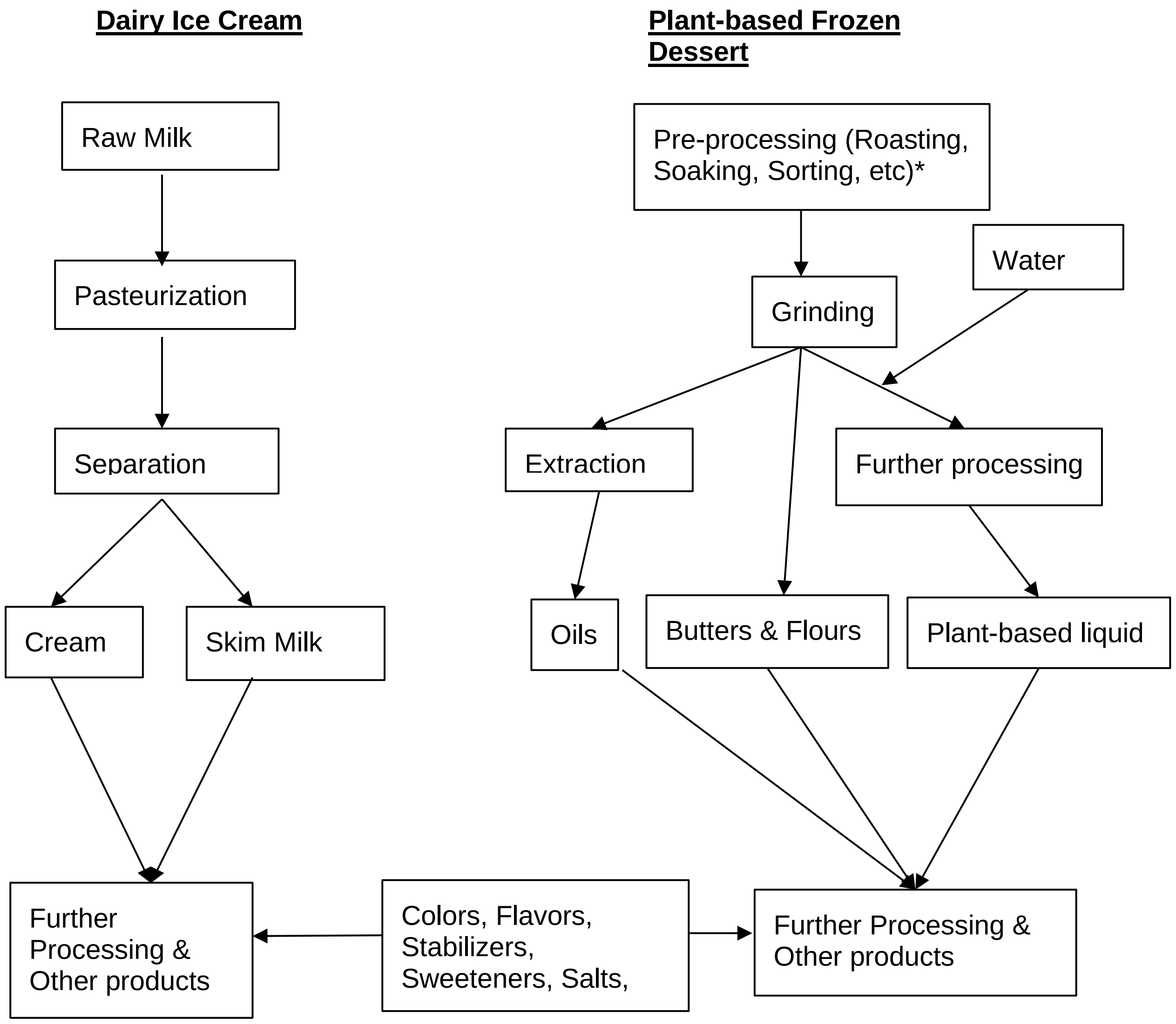
*Products used in the calculations for plant-based frozen dessert can be found in Table 2.
**Percentages adapted from* (The Culinary Institute of America (CIA) & Migoya, 2008)

Table 2. Average values of overrun for plant-based frozen desserts from a variety of sources. Note: Percentage of air was based on percentage overrun.

Type of Plant-based Frozen Dessert	Air (%)	Fat (%)
Low-fat pea protein vegan frozen dessert with prebiotic properties (supplemented by inulin) (Narala et al., 2022)	32.6	2
Frozen dessert produced from fresh walnut milk (Bekiroglu et al., 2022)	47.31	18.88
Vegan frozen dessert made of sugar or stevia and chia seeds (Velotto et al., 2021)	39.9	3.17
Lactose-free frozen dessert made of soy or rice protein with sucrose (de Medeiros et al., 2019)	41	7
Imitated ice dairy products made of sesame or peanut (Elsabie & Aboel Einen, 2017)	42.2	6.8
Vegan ice cream made of potato protein (Lomolino et al., 2020)	24.3	10
Average values	37.8	7.95

1.4 Plant-based frozen dessert production

Dairy ice cream vs. plant-based frozen dessert production process. Unlike dairy ice cream processing, when nut milks are processed, there are often some portions of the original nonfat solids that are separated out. This creates two product streams; for instance, in the case of soymilk processing, a second product stream called Okara (i.e. soybean pulp) is created (Liu et al., 2018). This changes the composition of the nonfat-nonprotein solids used to make frozen desserts, subsequently affecting the ice crystal formation, melting rate perception and mouthfeel (Stampanoni Koeferli et al., 1996). Figure 4 shows a generic overview of other differences in processing dairy-based ice cream and plant-based frozen dessert.



**Sources of plant-based frozen dessert can be nut, legume, fruit, grain. In this example, we focus on nut.*

Figure 4. Comparison between dairy ice cream and plant-based frozen dessert production process.

Plant-based frozen dessert production - Product Development. As mentioned earlier, as of current knowledge, there is no standard of identity for plant-based frozen dessert production. However, there are some general strategies we can adopt. Since the quality of ice cream is usually judged by factors like hardness, meltdown or melting rate, flavor, color and packaging, the strategies suggested below will focus on the optimization of these characteristics.

Strategies - Controlling Hardness. The hardness of ice cream is known as the resistance of the ice cream to deformation when an external force is applied (Muse & Hartel, 2004). It is affected by a variety of factors such as the overrun, ice crystal size, ice phase volume and most importantly, the extent of fat destabilization or partial coalescence.

Overrun. Overrun is defined as the percentage of the expansion of ice cream achieved from the air incorporated into the product during the freezing process. The presence of air (i.e. high percentage overrun) decreases the hardness of ice cream, as found in a 1998 study (Tharp et al., 1998). More specifically, increasing the overrun from creams. This phenomenon is caused by two different mechanisms that change air cells - coalescence and disproportionation (i.e. Ostwald ripening). Analyzing the factors that affect these mechanisms will help adjust the final texture of the ice cream through adjusting overrun. Coalescence happens when two air bubbles come into contact and the film between them ruptures. Disproportionation occurs because the pressure inside one bubble is larger than the pressure outside it. The difference in pressure (i.e. the Laplace pressure), is related to the difference in size and the interfacial tension (Chang & Hartel, 2002). In order to inhibit disproportionation, the viscosity of the fluid phase should be increased as increased viscosity of the fluid phase decreases the diffusion rate of gas between bubbles, retarding disproportionation. One method to achieve this is through adding proteins that can be adsorbed at the air bubble surface. When proteins are adsorbed at the air bubble surface, surface tension is lowered, reducing the driving force for disproportionation and slowing it down. Adsorbed proteins also cause steric stabilization, which reduces coalescence. Another method to reduce disproportionation is to encourage fat droplets at the air bubble surface. With sufficient fat for the whole surface of the air bubble to be covered, the ratio of fat to protein is higher, allowing the fat droplets to partially coalesce and form a three-dimensional structure that stabilizes the air bubbles, linking them to form a foam (Clarke, 2015). This would not happen if the fat were liquid, because if so, the fat droplets would form large spherical fat globules instead when they coalesce. Thus, prior to whipping the ingredients, cream should be chilled. If the fat source gets too warm, the solid fat melts and the partially coalesced fat structure cannot be formed (Clarke, 2015). Since there is no cream in the formulation of plant-based frozen desserts, we postulate that a similar trend will be seen when using plant-based fat sources like plant oils and thus recommend a similar approach.

Ice crystal size. Ice creams with larger ice crystals are generally harder than ice creams with fewer large ice crystals. Ice crystal size is closely related to the air cell size, which is associated with freezing point depression. Increasing the ice crystal size increases the hardness of ice cream. This could be due to a low freezing point because of a lack of solids to cause the freezing point depression effect. Equations x, y, z (Goff, 1996) illustrate one method to calculate the freezing point of a given mix.

$$SE = (NMS\ x\ 0.545) + (WS\ x\ 0.765) + S + (10DE\ CSS\ x\ 0.2) + (36DE\ CSS\ x 0.6) + (42DE\ CSS\ x\ 0.8) + (62DE\ CSS\ x\ 1.2) + (HFCS\ x\ 1.8) + (F\ x\ 1.9)$$

Equation x. Equation to calculate the Sucrose Equivalence (SE) in a g/ 100g of ice cream mix. NMS = nonfat milk solids, 0.545 is the percentage of lactose typical of NMS. ; WS = whey solids (from dry or condensed whey), 0.765 is the percentage of lactose typically found in whey solids; S = sucrose or other disaccharides such as lactose or maltose added directly; DE = dextrose equivalence of the CSS (corn syrup solids); HFCS = high fructose corn syrup; F = pure fructose or other pure monosaccharides such as dextrose; all in g/100g mix (or %).

$$FPD_{SE}\ [g\ sucrose/\ 100g\ water] = SE * \frac{100}{W}$$

Equation y. Equation to get the equivalent concentration of sucrose in water (g/ 100g water). W is the water content (i.e. 100% - total solids %).

$$FPD_{SA} = \frac{(NMS + WS) * 2.37}{W}$$

$$FPD_{Total} = FPD_{SE} + FPD_{SA}$$

Equation z. Equations to calculate FPD_{Total} which will be compared to a table of equivalence (Table 3) that gives the freezing point depression. FPD_{SA} refers to the freezing point depression for salts (°C) contained in NMS and WS, and the constant 2.37 is based on the average molecular weight and concentration of the salts present in milk.

Table 3. Table of values for freezing point depression(°C) below 0°C of sucrose solutions (g/100g water), adapted from *Ice Cream* (Goff & Hartel, 2013).

g Sucrose / 100 g water	FPD (°C)
3	0.18
12	0.72
21	1.29
30	1.86
39	2.4
48	2.99

57	3.63
66	4.33
75	5
84	5.77
93	6.5
102	7.32
111	8.04
120	8.92
129	9.71
138	10.47
147	11.19
156	11.88
165	12.67
174	13.28

Using these steps as a guide, amounts of each ingredient can be altered such that the ideal freezing point depression can be achieved.

Ice phase volume. The ice phase volume is affected by the freezing point of the mixture and is closely related to the ice crystal size. Based on the 2004 study done by Muse and Hartel (2004), the greater the amount of monosaccharides a mix has, the higher the freezing point and the higher the ice content. Thus, increasing the amount of monosaccharides like fructose and glucose can reduce the freezing point, making the ice cream softer and easier to scoop, compared to that if using disaccharides like sucrose.

Extent of fat destabilization. The hardness of ice cream increases as the level of destabilized fat increases (Goff & Hartel, 2013). A study by Tharp et. al. (1998) found that increasing the levels of destabilized fat through increasing the concentration of the emulsifier, polysorbate 80, from levels 0.02% and above, greatly decreased the hardness of ice cream (Goff & Hartel, 2013).

Freezing point depression. As freezing point depression (FPD) (Mullan, 2021) affects the extent of fat destabilization, it is one of the important factors that affects the hardness of ice cream. In general, the lower the freezing point depression, the softer the ice cream and less energy is needed for it to melt, which also affects the texture and mouthfeel. Thus, controlling the FPD is one of the key steps to achieving the desired final quality of ice cream. In order to calculate FPD, sucrose equivalence (SE) caused by each particular ingredient is calculated. By analyzing the composition of the plant-based ice cream, using Equations x-z, the resulting SE can be used to adjust the freezing point of the plant-based frozen dessert.

Strategies - Controlling Meltdown or Melting rate. The melting rate of the ice cream is usually quantified by measuring the mass that drips from the hardened ice cream through a mesh screen as a function of time (Goff & Hartel, 2013). It is affected by a variety of factors such as the extent of fat network formed during freezing and destabilization, nature of ice crystals and overrun.

Extent of fat network formed during freezing and destabilization. The extent of fat destabilization significantly affects the melting rate of ice cream. Destabilized fat in ice cream, in the form of clumps of fat globules, coats and supports the air cells and forms chains to build a fat network in the ice cream (Marshall et. al., 2003). A study by Tharp et. al. (1998) found that increasing the levels of destabilized fat through increasing the levels of the emulsifier, polysorbate 80 (Tharp et al., 1998) greatly increased the hardness of ice cream. As explained earlier in Section 1.3, emulsifiers (Muse & Hartel, 2004) it is important to grow the fat network formed during freezing and encourage the partial coalescence of fat molecules, allowing for more fat destabilization. A greater extent of destabilized fat increases the resistance to flow of the unfrozen phase as ice melts, which leads to slower melting rates (Muse & Hartel, 2004). Thus, the amount of emulsifiers can be adjusted to increase the ice cream's resistance to meltdown during consumption. This is a common way to troubleshoot texture problems in the finished product.

Ice crystal size. The nature of the ice crystals and network of fat globules formed during freezing also affects the melting rate of ice cream.increases. This can be explained through the flow path of melted ice cream (Muse & Hartel, 2004). With many small ice crystals, the flow path of the unfrozen phase as the ice melts takes more time since fluid must travel around more surface area. Thus, with many smaller ice crystals, the rate of drip loss, and thus, melting rate, is reduced. Smaller ice crystals and air cells leads to a reduced rate of heat transfer, since the trapped air functions as thermal resistance layers (Sakurai et al., 1996). This causes the desirable quality of gradual melting. The homogeneity of ice crystals and air cells also affects the meltdown. In general, a more homogenous distribution would mean that the small and dispersed air cells can produce a stable foam (Eisner et al., 2005) and creamier mouthfeel. With a more homogenous distribution, the air cells can coalesce (Chang & Hartel, 2002), leading to the loss of two small bubbles and the formation of a single large bubble, which causes an increase in air cell size. Smaller air cells with a narrow size distribution improves the rheological properties of ice cream and improves the creaminess and mouthfeel as the melting ice cream is being consumed (Hanselmann & Windhab, 1998).

Overrun. The higher the overrun in ice cream, the slower its meltdown (Sofjan & Hartel, 2004). This is because an ice cream with higher overrun has more air, which is a good insulator of heat. More air will slow down the rate of heat transfer into the ice cream and lower its melting rate. Another reason for slower meltdowns (i.e. higher melting rates) in ice creams with high overrun is the greater fat destabilization achieved due to the higher shear stress (Sofjan & Hartel, 2004) when processing ice creams with high overrun. Greater fat destabilization promotes minimal collapse of the fat-coalesced air cell and more resistance to meltdown.

Strategies – Flavor. Flavor refers to the sensory impression of the ice cream and is determined mainly by the chemical senses of taste and smell. Defects or adjustments in flavor can make significant changes to the overall quality and acceptability of the ice cream. In ice cream scorecards, flavor is often ranked as one of the top few criteria to determine the quality of ice cream. Specifically, flavor is listed as the first and most important quality, bearing 45 points, followed by body and texture at 30 points (Marshall & Arbuckle, 2000). An ice cream with flavor scored at 45 points would be very close to the ideal flavor, which is the carefully balanced blend of flavor from dairy products and the added flavoring material. This ideal standard may be a little different, depending on the type of frozen dessert in question; for instance, good sorbets, are expected to have a flavor (Falkowitz, 2014) that is rich in fruity and tart notes, does not feel too dilute and not excessively sweet. As non-dairy frozen desserts aim to closely substitute traditional dairy ice cream, non-dairy frozen desserts should have a flavor profile similar to that of traditional dairy ice cream (i.e. rich, creamy and delicate).

Formulation considerations. Recipes should start off with using good quality ingredients. This refers to ingredients that are stored within the recommended storage time and temperature (e.g. to prevent an overcooked flavor, unnatural flavor, oxidized flavor etc.) prepared in the right form (e.g. not using over-concentrated or overheated ingredients) and added in optimal proportions (e.g. not too little to avoid the problem of a lack of flavor, not added too much of one ingredient like salt or milk-solids-non-fat which will give an excessively salty flavor or adding too little sugar, flavoring or milk solids which causes a flat flavor).

Processing considerations. Prompt, efficient cooling of the mix after pasteurization and homogenization should be done to avoid the excessive generation of acids produced by degraded proteins (Goff & Hartel, 2013). During the aging process, storage of the mix at optimally low temperatures should be maintained. These steps will reduce the possibility of having acid or bitter flavors. In particular, storing the mix at optimally low temperatures for a recommended period of time will prevent certain types of bacteria from producing bitter off-flavors. During the pasteurization step, carefully maintain the temperature and time to prevent overheating the mix, which will prevent the product from having cooked off-flavors. Controlling the pasteurization step will also prevent the presence of tallowy or cardboard-like off-flavors, which indicates oxidation of the product. Specifically, the oxidized flavor is caused by pasteurizing the mix at excessive high temperatures (e.g. 170 °F). In every stage of the process, ensure that stainless steel equipment is used, especially avoiding the use of copper as copper contaminated mixes can give a strong metallic flavor. Using stainless steel equipment also prevents the chance of oxidation from occurring, reducing the risk of oxidized off-flavors. Flavor defects can be prevented by adapting rigorous Good Manufacturing Practice (GMP) and Hazard Analysis Critical Control Point (HACCP) procedures,

Strategies – Color. Preferences for the color of ice cream have evolved across the years, as with any other quality in the product, together with consumer preferences. As preferences in color are closely correlated with the body and texture of ice cream, many of the recommendations to control color are connected with the initial formulation and processing stages. For instance, some grades of corn sugar used in the ice cream mix were liked by consumers and imparted a yellow color, which resulted in consumers visually preferring the same yellow color (Lucas, 1941) in ice cream. Conversely, heating sucrose in the inversion process to make sweeteners longer than 35 minutes darkened it, imparting an unappealing taste to the ice cream (Lucas, 1941), which caused consumers to associate darkened colors with unappetizing products. To prevent unpleasant gray colors in ice cream, follow legal guidelines. For instance, in California, follow the California Code of

Regulations, Title 3 § 443 (*California code of regulations*, 1992) on neutralization of ice cream mix (i.e. not using the neutralizer for the adjustment of ice cream mix when the milk and/or cream used exceeds 0.2 % acidity or when the acidity of the entire mix exceeds 0.25 % acidity). Neutralization is an extra step that manufacturers may take when the ice cream gets too acidic. Unfortunately, as it also adds unappealing gray colors to the final product, manufacturers may need to add extra steps to troubleshoot. Following the Cal. Code Regs. Tit. 3, § 443 guidelines and strict process and quality control steps will help the manufacturer determine the best way to troubleshoot and prepare against any color defects. In the case of chocolate-flavored ice cream, slightly alkalized cocoa is preferred because it gives a deeper color and stronger flavor (Goff & Hartel, 2013). For fruit-flavored ice cream, using ingredients that are pre-colored would help save processing time. When using colors as additives, both in liquid and powder form, colors must be kept fresh since they can be easily contaminated. In general, ice cream should have a delicate, attractive color that suggests or is closely associated with its flavor. Ice cream of good quality is evidenced by delicate, appropriate and uniform colors, which enhance the layers and clearness of product outlines in its packaging.

Strategies – Packaging. Ice cream packaging must provide the desired form, size and appearance for convenient handling, efficient hardening, consumer appeal and consumer information (Karaman et al., 2015). Most commonly, ice cream is bulk packaged for sale as individual cones or consumer packaged for direct retail sale. Bulk frozen desserts are packaged in single-serve containers, some of which are reusable plastics. Parts of the packaging (e.g. bottoms, rings, overlapping tops) are shipped separately to the ice cream plant, then put together in their respective shapes (e.g. rectangular, cylindrical, conical) and sizes (e.g. 89 ml to 7.6 L). In order to minimize cost during transport, containers are recommended to be conical since they are shipped preformed and nested within each other. Conical containers also have a higher ease-of-use compared to rectangular or round ones since the product is more easily scooped out.

Packaging and storage conditions are closely associated; a correctly chosen package will not be able to maintain the integrity and quality of the product should the storage temperature be outside the acceptable range for a prolonged period of time (Ahvenainen & Mälkki, 2007). Choosing tight closed plastic packages, instead of conventional hot melt-coated cardboard packages can help extend the shelf life of ice cream by at least 1.5 times. Using aluminum foil to externally laminate the package will result in a longer ice cream shelf life, compared to using an LDPE-coated package. The package should also be sealed tightly such that no air can enter the package, preventing issues like rancidity and microbial growth. Commercial methods of sealing include heat sealing (i.e. applying a membrane directly to the cup as part of the filling process), adding a shrink band (i.e. a separate component applied after filling), or adding a “click-top” (carton with an interlocking front that keeps the lid in place and provides extra protection against freezer burn (Karaman et al., 2015)). Sealing tightly will always reduce the chance of freezer burns, allow ice cream packages to be opened more easily and reclosed in a manner that retains freshness.

Challenges - Contradictory trends in literature. Because ice cream is a complex mix of ingredients which interact uniquely based on different conditions, the trends observed before, particularly for meltdown and overrun, might not apply to all formulations. There are studies that contradict the trends stated earlier. For instance, in a 1996 study by Sakurai, ice creams with lower overruns had faster melting rates (Sakurai et al., 1996), in contrast to the 2004 study by Muse & Hartel which found that overrun had no significant effect on the melting rate of ice cream (Muse & Hartel, 2004). Possible reasons for this include the fact that Muse & Hartel used a batch freezer, instead of a continuous scraped-surface freezer, which contributed to the low range of overruns. A wider range of overruns is needed to allow for a significant effect on the melting rate. According to Sofjan & Hartel (2004), the melting rate and hardness of ice cream are most likely due to the differences in secondary effects like ice crystal formation. They found that it is the stability of the air cells that slows down the meltdown rate of ice cream, not the extent of fat destabilization. Researchers Campbell and Pelan also showed that meltdown resistance increased as draw temperature from the freezer decreased due to increased overrun and fat destabilization (Campbell & Pelan, 1998). They also acknowledge that ice crystal formation may have influenced the meltdown rate.

Challenges - Shelf-life and stability issues. Plant-based frozen dessert mixes, pre-homogenization, exist as a colloidal system made of large-sized dispersed particles (e.g. proteins, fats, starch granules, solids from raw materials) (Sethi et al., 2016). Without specialized processing methods, it is difficult to develop a stable final product that has a long shelf-life since problems such as a chalky mouthfeel (due to the settling of solid particles) and lack of creaminess (due to the low-fat content) can appear. Adding stabilizers like hydrocolloids and applying homogenization to stabilize and decrease the particle size distribution may help extend the shelf-life in most plant-based mixes. However, in some cases like a blend of almond and hazelnut mixes, after homogenization, the resulting emulsion was not stable. High temperatures and pressures during homogenization had caused protein denaturation and insolubility, which led to phase separation (Sethi et al., 2016). Thus, depending on the blend, the addition of stabilizers and processing methods should be carefully adjusted.

Plant-based frozen dessert production – Processing. Similar to plant-based frozen dessert product development, there is no standard sequence of processing steps for plant-based frozen dessert production. However, there are some general guidelines we see from literature.

Strategies – Maintaining a certain range for parameters in key processing steps. Figure 4 shared earlier shows a recommended way of pre-treating the plant-based mix before further processing into the frozen dessert. After pre-treatment, the mix should be homogenized, pasteurized, cooled and aged (4 – 5 °C, between 1 and 4 hours), freeze-churned (-18°C, at least 20 minutes until thickened), packaged, labelled, frozen and stored (-18°C, at least 2 hours) before conducting quality testing. Depending on the composition of the mix, these parameters will need to be adjusted. For instance, a mix with fat sources from coconut oil might need the addition of a liquid oil like sunflower oil in order to obtain the optimum amount of solid fat such that partial coalescence of fat can be achieved during homogenization.

However, a mix using palm oil may not have to add another fat source since it already has sufficient solid fat (Ruben, 2020).

Challenges – Conventional processing methods may not be as effective for plant-based frozen desserts. Dairy ice cream involves thermal treatment in the form of homogenization and pasteurization to the mix. Applying similar processes to plant-based frozen dessert mixes will destroy heat-sensitive vitamins and denature proteins, depending on the temperature and exposure time. Also, since most plant-based frozen dessert mixes involves decanting (i.e., soaking or bleaching) the raw material prior to its production, the final concentration of the micronutrients in the product will be influenced since water-soluble vitamins may be lost. In most cases, plant-based frozen desserts are made using a blend of plant sources to match the nutritional content of dairy ice cream. Because of the infinite number of combinations of blends, current literature does not provide enough material to determine which processing method is the best.

1.5 Sensory acceptability of plant-based frozen dessert

Importance of sensory acceptability. As mentioned earlier in Section 1.2, nailing an appetizing taste profile continues to be the most pressing issue for plant-based formulators (Decker, 2019) In addition, competition between plant-based frozen dessert companies to gain market share have been escalating. Sensory evaluation is essential in food product development to ensure that product developers drive consumers to make repeat purchases and gain space on grocery store shelves. Sensory acceptability also ensures that the quality of product is maintained post-scaling up, inferior products are not released in the market and shelf-life is maximized through assessing microbial quality.

Natural sensory characteristics of plant-based ingredients. Products using plant-based ingredients tend to be described as “grassy, beany, earthy, bitter and chalky” (Gelski, 2018) with unconventional off-colors. For instance, in certain formulations, foods containing soy derivatives were found to be not well accepted by consumers (Osman & Michael, 2017) because of the unpleasant flavor present in the grain formed during processing. Dairy alternatives that use rice protein are known to have a naturally gritty or sandy texture (Juliano & Hicks, 1996), as opposite to the creamy texture of whey in dairy proteins, which negatively affects the consumers’ organoleptic experience. Products made with pea protein are known to have issues with astringency, bitterness (Gelski, 2018) and show excessive darkness (Guler-Akin et al., 2021) and redness not seen in dairy ice cream.

Considerations when using plant-based ingredients in non-dairy frozen dessert. Dairy ice cream comprises of milk solids, cream, sugar and water. As mentioned in Section 1.4, the extent of fat destabilization and agglomeration and ice crystallization greatly affect the creaminess of ice cream. Thus, when making plant-based frozen dessert, substitutions for these dairy-based ingredients should contain similar structural components to preserve the texture and mouthfeel. Some ways to cover these include: taste masking (e.g. taste inhibition of odor-active molecules in pea protein isolate (Trindler et al., 2021)), off-taste reduction (e.g. fermentation to reduce the concentration of unwanted aroma molecules in soybean fiber (Wang et al., 2022)) and volatilization of off-flavors (e.g. designing preconditioning and atmospheric venting devices in the extrusion system that assists in the volatilization of off-flavors (Rokey & Kearns, 2013)).

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CHAPTER 2
SELECT FORMULATION AND PROCESSING FACTORS AFFECTING THE QUALITY OF PLANT-BASED FROZEN DESSERTS

2.1 Introduction

Many formulation and processing factors affect the quality of plant-based frozen desserts which can be measured by a variety of indicators.

For instance, changing the formulation of the frozen dessert mix through adjusting the total solids content (e.g. by increasing the amount of emulsifiers) affects the extent of fat destabilization. Measurements like pH, Brix and particle size can be taken to quantify the changes due to modifications in individual components. The extent of the fat destabilization consequently affects the melting rate of ice cream and its freezing point depression.

Changing processing conditions such as time, temperature and pressure in the homogenization stages can also affect final characteristics like mouthfeel, color and overrun. In this case, particle size analysis is key in quantifying the effects of homogenization on the final mix.

The objectives of this study were to explore the effect of formulation and processing on indicators such as pH, Brix, overrun, color and particle size. These results will help us better understand the frozen dessert's characteristics such as melting rate, hardness and flavor, which will inform decisions involving packaging, shelf-life and quality.

2.2 Materials & Methods

Ingredients. Most ingredients were purchased from Wegmans' Food Market, while the others were bought from a specific manufacturer. Table 4 gives more details on each ingredient and its source.

Table 4. Brand and Manufacturer of Ingredients Used in Formulation of Plant-based Frozen Desserts (final few iterations).

Ingredient	Brand	Manufacturer	State/Country of Origin
Water	Poland Spring	Blue Triton Brands	Connecticut, USA
Rice milk powder	Shafi Gluco Chem	Shafi Gluco Chem (Pvt.) Ltd.	Balochistan, Pakistan
Oat base	SunOpta	SunOpta Inc.	Brampton, Canada
Inulin	Ciranda	Ciranda, Inc.	Wisconsin, U.S.A.
Coconut oil	Ciranda	Ciranda, Inc.	Wisconsin, U.S.A.
High oleic sunflower oil	Ciranda	Ciranda, Inc.	Wisconsin, U.S.A.
White sugar	Domino	Domino Foods Inc.	New York, U.S.A.
Agave	Ciranda	Ciranda, Inc.	Wisconsin, U.S.A.
Vanilla essence	Nielsen-Massey	Nielsen-Massey Vanillas	Illinois, U.S.A.
Salt	Morton Salt	Stone Canyon Industries Holdings, Inc.	California, U.S.A.

Chemicals and reagents. There were a few chemicals and reagents used in the formulation and analytical testing of plant-based frozen desserts. These are described in Table 5.

Table 5. Type/ Form and Manufacturer of Chemicals and Reagents Used in Formulation of Plant-based Frozen Desserts (final few iterations).

Ingredient	Type/ Form	Manufacturer	State/Country of Origin
Gum blend	Powdered blend of Gum acacia, Guar gum and Locust bean	TIC Gums/ Ingredion	Illinois, U.S.A.

	gum		
Sunflower lecithin	Finely powdered non-GMO sunflower lecithin	Ciranda/ Ciranda, Inc.	Wisconsin, U.S.A.

Preparation of plant-based frozen dessert

Process Flowchart

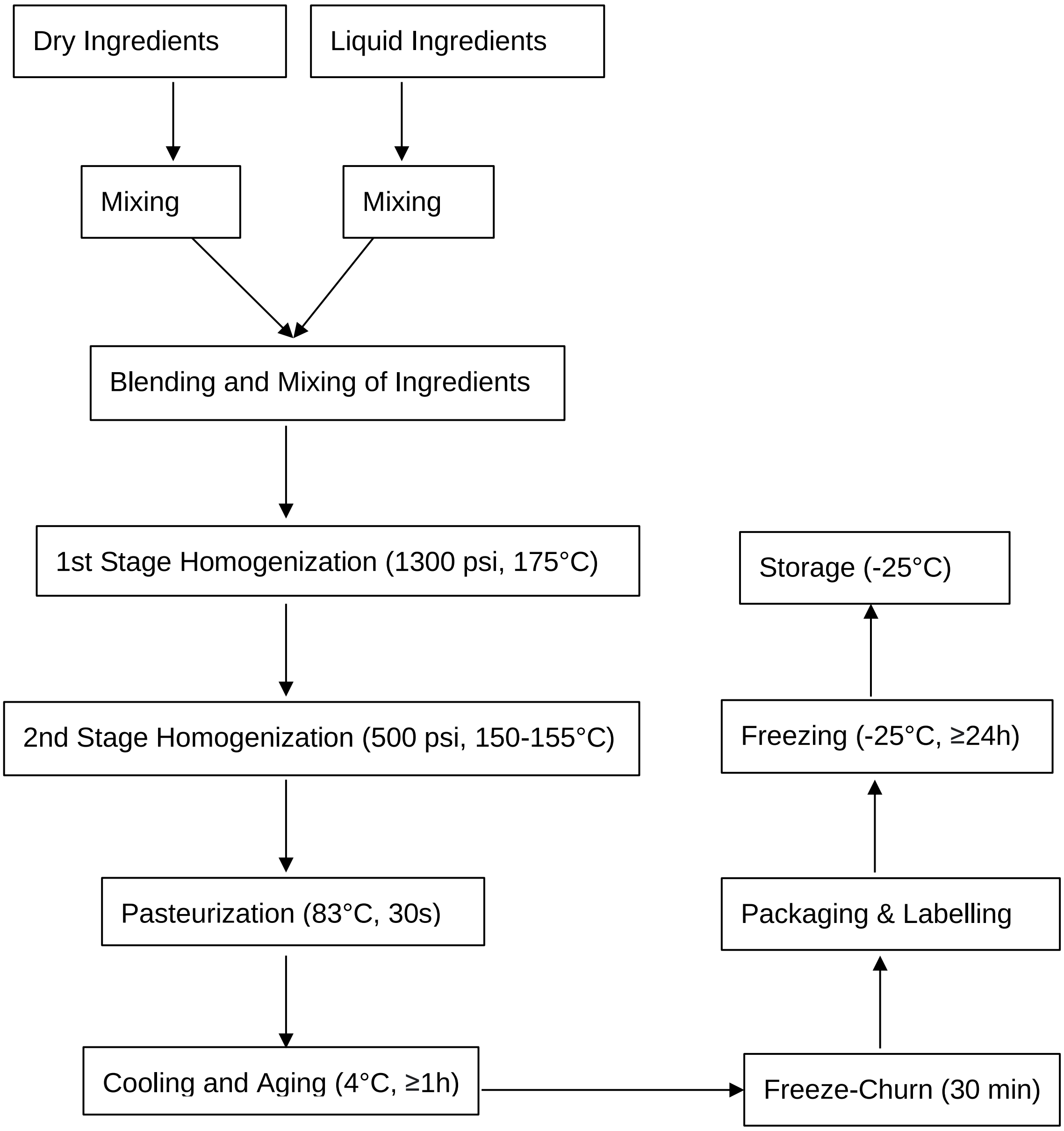

Figure 5. Process Flowchart. Overview of plant-based frozen dessert production.

Detailed description of the process includes the following steps:

I. Plant-based frozen dessert (approximate volume of our pilot plant trial was 12 kg) was prepared by first, mixing the dry ingredients, and then mixing the wet ingredients, both separately and evenly by hand according to preparation methods stated in Tables 6A and 6B.

II. Wet ingredients were placed into a large (i.e. at least 12 kg capacity) mixing bowl, with a high-speed shear homogenizer (Ross HSM-100LSK, Charles Ross & Son, Hauppauge, New York, U.S.A.) attached, running at 5000 rpm for at least 5 min. Then, dry ingredients were slowly incorporated. Mixture is homogenized for a total of at least 5 min until uniformity is achieved.

III. Mixture was then put through the microthermics unit UHT/HTST Lab-25 HVHW that has a tubular pasteurizer with an in-line homogenizer (MicroThermics, Raleigh, North Carolina, U.S.A.) set for 2-stage homogenization (Stage 1: 1300 psi/ 175°C, Stage 2: 500 psi, 150-155°C).

IV. Mixture is then poured out on wide, metal trays to cool and age at 4 °C for 1 hour.

V. After cooling, the mixture was placed into an ice cream machine (Cuisinart Supreme Commercial Quality Ice Cream Maker ICE-50BC) to churn for 30 min.

VI. The ice cream was scooped out and placed into clean containers. The filled containers were transferred into freezers (-25 °C) for at least 24 hours to chill.

Table 6A. Dry Ingredients, Weight Percentage and Preparation Method of One of the Four Selected Formulations (about 16% of final formulation).

Ingredient	W/w (%)	Preparation Method (If Any)
Rice milk powder	1.47	NA
Inulin	0.61	NA

White sugar	11.77	NA
Sunflower lecithin	0.92	NA
Salt	0.55	NA
Gum blend	0.60	Add one part gum blend to at least ten parts of the other dry ingredients to ensure optimal hydration.

Table 6B. Liquid Ingredients, Weight Percentage and Preparation Method One of the Four Selected Formulations (about 84% of final formulation).

Ingredient	W/w (%)	Preparation Method (If Any)
Water	62.17	NA
Coconut oil	9.17	Coconut oil, which is a solid at room temperature) should be warmed to 24 - 26°C to be well mixed with the other wet ingredients
High oleic sunflower oil	4.78	NA
Agave syrup	5.80	NA
Vanilla essence	1.60	NA

Formulation optimization. A preliminary study was conducted to understand how the plant-based frozen dessert behaved in terms of traditional ice cream quality indicators. A total of 6 quantitative variables (pH, water activity, emulsion stability, percent overrun, color, particle size) were identified but 1 was focused on particle size distribution based on the relatively large amount of scientific evidence to support particle size as a good quality indicator of ice cream. Several tests were conducted varying the formulations (% of sugar, rice, oat or pea milk-bases, stabilizers, fat source) to achieve the best quality. Based on the particle size profiles, it was decided to move forward with a formulation that had a base of both oat and rice milk with pH in the range of 6.1 - 6.4 and water activity in the range of 0.95 - 0.97.

Figure 6. Visual Comparison of Plant-based Frozen Desserts Made With Oat Flour (Left), Rice Milk Flour (Middle), Commercial Dairy Ice Cream (Right).

Analytical Measurements

pH. Samples were left to thaw at room temperature (about 28 °C), before measuring pH with a Thermo Electron Corporation Orion 3 Star pH meter (Thermo Fisher Scientific, Waltham, M.A., U.S.A.).

Total Soluble Solids measured as Brix. Samples were left to thaw at room temperature (about 28 °C). The brix of each sample was measured with a refractometer (Portable refractometer C-2 REF-104, Spectrolab, England, U.K.) at room temperature.

Percent overrun. One overrun measurement was taken per sample by comparing the weight and corresponding volume of the mix and post-processing ice cream or frozen dessert. The percent overrun of the plant-based frozen dessert was measured, using Equation 1, with a measuring cylinder, beakers and containers.

$$Percent\ overrun\ = \frac{Volume\ of\ ice\ cream - Volume\ of\ mix}{Volume\ of\ mix} * 100\%$$

Equation 1. Percent overrun equation for ice cream.

Color. Samples were left to thaw at room temperature (about 28 °C). The color components of L, a and b were measured with a HunterLab UltraScan VIS spectrophotometer (HunterLab, Reston, VA), calibrated with white and black tiles. Reflectance mode was used to measure color components using a 10 mm cuvette. The colorimeter was first calibrated with a white standard plate, whose values are stored in the machine by default, and then used to measure the samples. According to the HunterLab color scale, the lightness, L*, represents the darkest black at L* = 0, and the brightest white at L* = 100. The color channels, a* and b*, represents the true neutral gray values at a* = 0 and b* = 0. Red/ green opponent colors are represented along the a* axis; where negative a* values represent green and positive a* values represent red. Yellow/ blue opponent colors are represented along the b* axis; with negative b* values representing blue and positive b* values representing yellow (Rodgers et al. 1994). For this experiment that looks into the quality of vanilla-based frozen dessert, the HunterLab scale is preferred over the use of the CIELAB color scale, as the HunterLab scale generally gives a better approximation to visual evaluation of color difference for lighter colors (i.e. vanilla).

Particle size. Samples were first left to thaw at room temperature (about 28 °C), diluted with water and then stirred as proposed by Ursica et. al. (2005) until an acceptable obscuration rate (about 5-10%), as deemed by the machine, was obtained. Dilution and stirring helps disrupt any weakly flocculated droplets and leave the strongly flocculated droplets intact, allowing us to see clearer trends with small formulation changes. Before the particle size of the sample was measured, its refractive index was taken. Small drops of the sample were placed onto the Leica Auto Abbe benchtop refractometer (Leica Camera, Wetzlar, Germany) and its refractive index was recorded. These values were inputted into a Malvern Mastersizer 2000 laser diffraction particle size analyzer equipped with wet sample dispersion unit HydroG (Malvern Instruments Limited, Worcestershire, UK), and results recorded. Using the volume mean diameter D (4/3) as the particle size for comparison, these results were used in calculations to determine the final particle size distribution.

2.3 Results and Discussion

pH. It was observed that all formulations in this experiment had pH readings ranging from 5.96 (Commercial Plant Based) to 6.38 (formulation based on pea and oat) as shown in Tables 7 and 9.This range corresponds to what is found in ice cream and frozen desserts commercially available; dairy ice cream has a pH range from 5.82 to 6.62, depending on the flavor and composition, while plant-based frozen desserts have a much broader pH range from 5.7 (cashew-based) to 7.41 (peanut-based) (Guner et al. 2007). The broader pH range is because plant-based frozen desserts use a wider variety of plant materials as sources (e.g. peanut, cashew, almond, soy), while dairy-based ice cream usually comes from certain mammals like cows and goats. Each source has a unique composition that affects acidity of the mix and thus, final pH of the product. In this experiment, plant-based frozen dessert formulations were based on rice, oat or pea, which upon adding water to produce their nut-milks, resulted in similar pH values (Abou-Dobara, Ismail, and Refat, 2016), thus corresponding to current findings. Appropriate pH values are important to maintain proteins in solution during pasteurization and homogenization.

Brix. Brix refractometers show the concentration of total soluble solids in a water-based solution. In the case of ice cream and frozen dessert, total solids refer to the sum of sugars, stabilisers, emulsifiers, and solids-non-fat.

Table 7. Physiochemical properties of vanilla-flavored conventional ice cream and plant-based frozen dessert (Brix vs Total Solids %).

Frozen Dessert Sample	pH	Total Solids % w/w	Total Solids- Non Fat % (This value should correlate better to Brix than total solids, which include fat - Brix is only measuring soluble solids /linear correlation)	°Brix
Oat based, highest sugar content (Formulation 1)	6.2	36.3	11.2	37.1
Oat based, mid sugar content (Formulation 2)	6.2	34.5	12.9	30.5
Oat based, lowest sugar content (Formulation 3)	6.21	33.1	13.1	28.4
Commercial Dairy Ice Cream (CD)	6.62	38.3	10.9	39.3
Commercial Cashew Plant-based (CPB)	5.96	39.2	12.3	38.9

From Table 7, it can be seen that the higher the total soluble solids and total solids content, the higher the Brix values. Industry trials have found that a minimum total solids content of 36% in plant-based ice cream provides good emulsion stability, meltdown and hardness (Rakes, 2019). An academic study on premium vanilla ice cream also showed that a Brix value of 36.2% gives similar desirable qualities as well. Theoretically, as the total solid content increases, the resistance to flow of the serum phase increases as ice melts, leading to slower meltdown (Choi and Shin, 2014). Increasing the number of emulsifiers, which add to total solids content, also increases the extent of fat destabilization, improving emulsion stability and decreasing hardness. Based on these correlations, formulation based on oat-milk, which had the highest sugar content (Formulation 1) showed the most potential for further optimization.

Percent overrun. In general, consumers prefer ice creams and frozen desserts with overrun between 80-120%. From all the formulations tested, three that fell within the target range are shown in Table 8.

Table 8. Comparison of overrun and sensory attributes between frozen dessert formulations made with the same base formula but different total solids, gum type and percentage.

Sample	Gum % w/w	Name of gum	Gum components	Overrun %	Sensory attributes (estimates)
Formulation 4	0.5	Gum A	Xanthan gum, locust bean gum, guar gum	113%	Higher melting resistance, very gummy, less hard
Formulation 5	0.25	Gum A	Xanthan gum, locust bean gum, guar gum	98%	Lower melting resistance, less gummy, hardest
Formulation 6	0.3	Gum B	Gum acacia/ arabic, guar gum, locust bean gum	109%	Middle melting resistance, no gummy mouthfeel, middle hardness

Based on the observed results, mixes with lower overruns were harder than those with higher overruns. On the other hand, mixes with higher overruns had higher melting resistance, which is desirable. Overrun is also seen to increase as the percentage of gum increases.

Based on these observations, formulation 6 showed the greatest potential, mostly because it did not have an undesirable gummy texture. In order to improve the melting resistance and hardness, further iterations of formulation 6 would use the same gum (Gum B), but with a higher gum percentage.

As mentioned in Section 1.4, the types of gums and their proportions directly affect overrun levels and other quality indicators like melting rate, hardness and texture (Kurultay, Öksüz, and Gökçebağ 2010). Thus, for further experiments, specialized equipment to measure the melting rates and hardness, instead of using just sensory estimates, should be used to understand the combined effects of these parameters on the structural properties of frozen dessert.

Color. The color of molten frozen dessert was assessed using colorimetry. L*, a* and b* values are reported in Table 9.

Table 9. Physiochemical and color components of vanilla-flavored conventional ice cream and plant-based frozen dessert.

Frozen Dessert Sample	pH	Total Solids %	Fat %	Protein %	L*	a*	b*
100% Pea Protein (Formulation 7)	6.31	34.1	12.79	4.31	82.61	3.98	10.29
1:1 Pea:Oat Base (Formulation 8)	6.38	34.3	13.21	4.02	83.89	3.32	9.89
100% Oat Base (Formulation 9)	6.23	37.1	14.75	3.82	84.40	3.16	11.12
Control (Formulation 10)	6.16	26.2	14.9	0.01	80.89	2.98	10.03
Commercial Dairy Ice Cream (CD)	6.62	36.9	13.84	3.82	81.39	3.20	10.60
Commercial Cashew Plant-based Frozen Dessert (CPB)	5.96	32.5	11.42	2.81	79.28	2.60	8.48

Based on the results, the a* and b* values were not significantly affected by formulation or processing changes. However, L* values, which indicate whiteness/lightness, were affected by the composition of the mix. As the proportion of fat and protein increased (i.e. proportion of total solids increased too), the L* values increased. This trend is consistent with other findings indicating that when the fat content in ice cream samples were reduced, the samples were less white (Roland, Phillips, and Boor, 1999). Theoretically, whiteness is due to the light-reflecting off insoluble components, primarily casein protein micelles and fat globules. The smaller the particles and larger their number, the more light reflection there will be and the lighter the appearance of the color (Clark and Bodyfelt, 2009). Thus, increasing the protein and fat proportion in the mix does increase the whiteness of the final product.

In cases where formulations such as cashew-based are used (Table 9), the presence of additional acids in the cashew, including anacardic acids, may be responsible for decreasing the pH in the CPB mix. With more acids to digest proteins and fats, there could be fewer insoluble components to reflect color, reducing the whiteness value (Aroyeun et al., 2022).

As mentioned in Section 1.4, controlling the color of ice cream can significantly affect the consumer’s perception of its quality. For vanilla-flavored ice cream, the shade of color needs to appropriately match the natural color of cream, cannot be too pale or vivid and should be in harmony with the stated flavor, vanilla, on the package (Clark and Bodyfelt, 2009). Color also impacts many psychological aspects of the consumer’s eating experience. People make assumptions about what their food would taste like using color. When the real flavor of the food fails to meet expectations, the brain may not perceive the difference and conclude that it is of poor quality or that it shows signs of spoilage (Rodgers et al., 1994). Thus, instrumental color measurements play a significant role in quality assessment of frozen dessert and ice cream.

Based solely on these guidelines, Formulation 9.2 (refer to Table 10 for formulation details) showed the most potential to have the highest quality of vanilla-flavored plant-based frozen dessert, because of its highest L* score.

Particle size. Particle size, in the case of ice cream and frozen dessert, refers to the physical dimensions of solid particles (e.g. protein, ice, cocoa powder), liquid droplets (e.g. fat) and gas bubbles (e.g. air) with physical dimensions ranging from 0.02 um to 500 um. In addition to chemical composition, the behavior of particulate materials is often dominated by the physical properties of its constituent particles. These can influence material properties such as texture, mouthfeel, emulsion stability and viscosity (Elmisaoui et al. 2021). Specifically, particle size analysis was conducted on the ice cream and frozen dessert mixes as results provided insight about the interactions between the various components of the mix (e.g. fat aggregation and protein-fat emulsification), which affected quality factors like melting rate, hardness and overrun. Thus, particle size analysis was key in deciding which formulations can be selected for further optimization.

As the mixes are not perfectly mono-disperse (i.e. every particle has the identical dimensions), volume-weighted distributions were used so that the relative contribution of each particle will be proportional to the size. We decided to measure D [4, 3], or volume moment mean since we wanted to know how the particle size distribution changes with a change in formulation. D [4, 3] helps monitor the size of the coarse particles that make up the bulk of the sample and the particle size distribution graph shows what particles contribute to certain peaks.

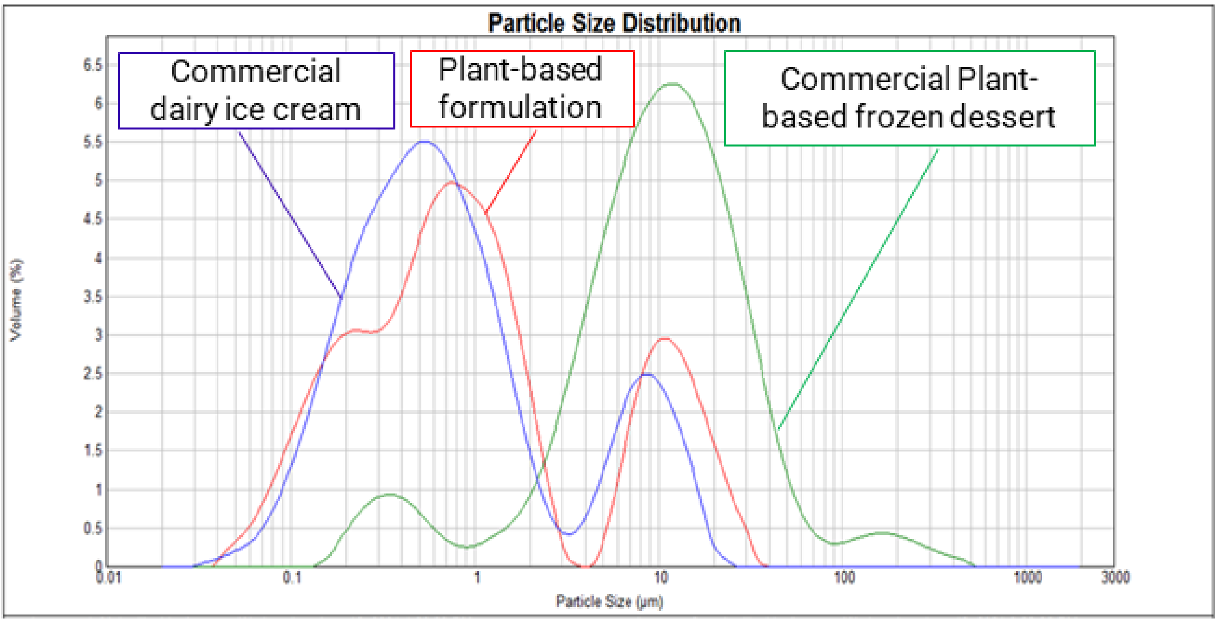

Figure 7. Particle size analysis of thawed, diluted and stirred samples of commercial dairy ice cream, commercial plant-based frozen dessert and plant-based formulation made of oat-based mix, without homogenization and pasteurization (Formulation 11)

A comparison between the particle size graphs of the Formulation 11 (oat-based mix, without homogenization and pasteurization), commercial dairy ice cream (CD) and commercial plant-based frozen dessert (CPB) showed that all 3 formulations have similar particle size distributions, with Formulation 11 showing more similar peaks and troughs as commercial dairy ice cream. In the Formulation 11 sample, particles below 3 μm are assumed to be protein aggregates, particles between 3-10 μm are dispersed fat globules, particles around 10 μm are clustered fat globules that have aggregated together, with protein adsorption and particles beyond 10 μm are bigger, such as oat β-Glucan, a soluble dietary fiber that is prevalent in oats. The double peak between 0.2 and 8 μm shows peaks for both protein and dispersed fat globules. This double peak could possibly be smoothed out and reduced to one continuous peak after the homogenization step, which was not done in this formulation.

In the commercial dairy ice cream sample, particles below 3 µm are assumed to be casein micelles, particles between 3-10 µm are dispersed fat globules, and particles around 10 µm are large clusters of aggregated fat globules. In the commercial plant-based frozen dessert sample, particles below 1 µm are assumed to be cashew milk protein and particles around 10 µm are clusters of aggregated fat globules.

As the commercial plant-based frozen dessert showed a particle size distribution with a larger range and larger particle sizes, which is associated with less smooth and more sandy mouthfeel (Marshall, 2003) we did not use it as a guide to influence further iterations.

As observed above, particle size distribution of Formulation 11 was very similar to that of commercial dairy ice cream. Since the goal was to have a frozen dessert with a similar texture and mouthfeel of commercial dairy ice cream, we decided to proceed with formulation 11 as a base for future iterations. To confirm our hypothesis that homogenization helps reduce the number of peaks in Formulation 11, we conducted another particle size comparison.

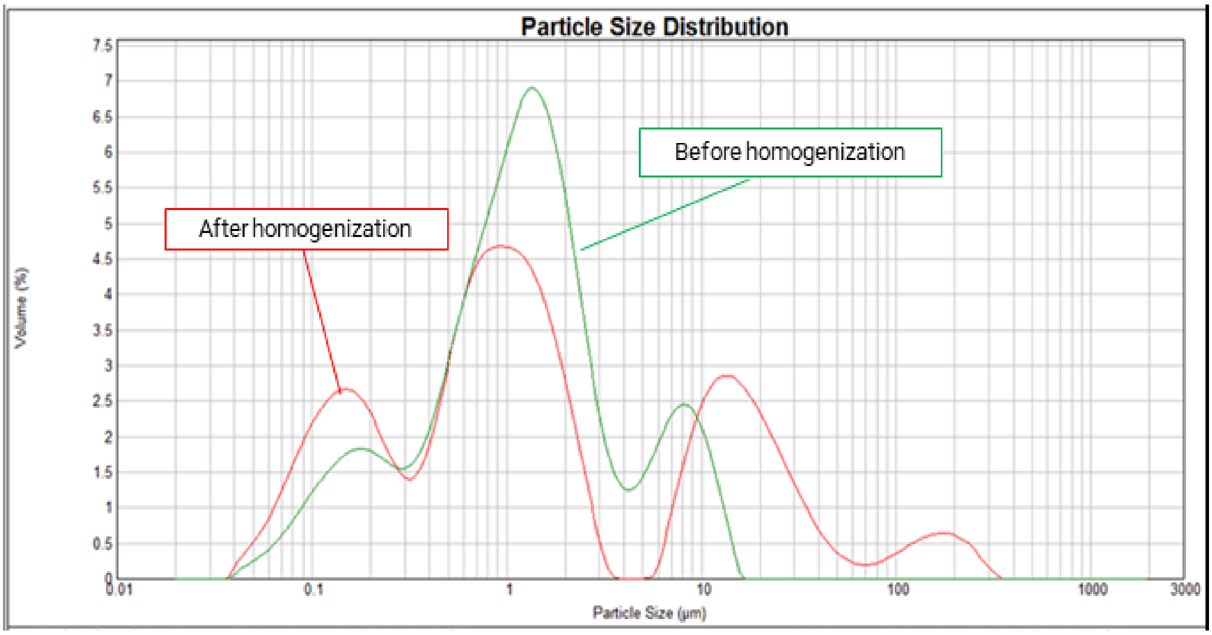

Figure 8. Particle size analysis of thawed, diluted and stirred samples of rice-based frozen dessert (Formulation 9) before and after homogenization.

Figure 8 shows the particle size distribution of an experimental frozen dessert sample, based on a rice-milk formulation 9, before (green line) and after homogenization (red line). Focusing on particle sizes below 10 μm (i.e. large fat globules), we see that after homogenization, the curve in *red* shifted to the left and had narrower peaks and a smaller span. According to Ghaderi et. al., the narrower the width of the shape of the curve, the smaller the width (i.e. span) and consequently, the greater uniformity and stability of the mixture (Ghaderi, Mazaheri Tehrani, and Hesarinejad, 2021). Theoretically, homogenization breaks up large fat globules into smaller ones and reduces the tendency of these globules to coalesce. Thus, the average particle size of the mix post homogenization, is smaller. Beyond particle sizes 10 μm, we see that after homogenization, there is a slightly larger proportion of particles with larger particle size. This aligns with the observations in Bushek's study on the effects of homogenization on the particle size of pea protein frozen dessert, where it was found that homogenized protein suspensions result in a larger range of particle sizes (Bushek, 2020).

As these findings prove that homogenization significantly affects the particle size, it was decided that particle size analysis on subsequent iterations should be done post-homogenization, to get a better idea of the final quality of frozen desserts.

The effect on particle size distribution after adding cocoa powder to plant-based frozen desserts was also investigated, to assess opportunities for new products offerings.

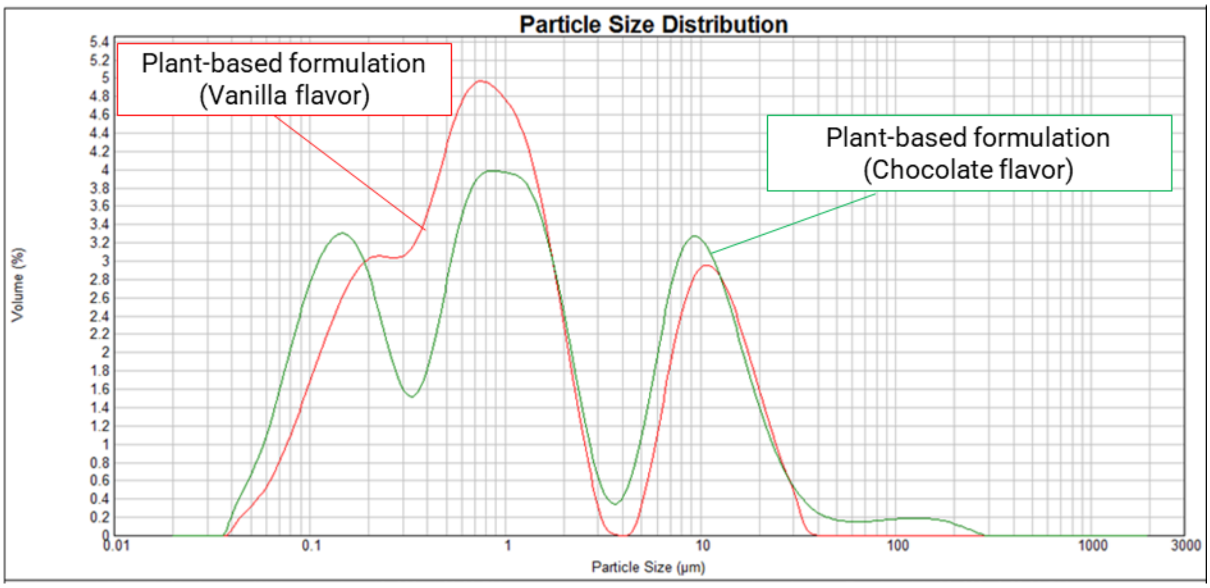

Figure 9. Particle size distribution of thawed, diluted and stirred samples of plant-based frozen desserts: vanilla (Formulation 11) and chocolate (Formulation 11.2).

The particle size of cocoa powder ranges from 25 to 106 μm (Kalic et al., 2018). Upon adding cocoa powder, there is a slight shift of the graph to the right, and a larger proportion of particles in the peaks with higher particle size. In unflavored ice cream and frozen dessert mixes, solids like sugar and protein interact with the fat to form the matrix. Adding cocoa powder, which has a similar particle size to sugar, competes with sugar to interact with fat, affecting the particle size agglomeration. Studies show that cocoa particles act as better nucleation agents compared to sugar particles (Kalic et al., 2018). Thus, it is possible that the shift in particle size distribution after adding cocoa could be due to increased nucleation of cocoa powder particles with the fat, instead of sugar, causing fat crystallization and formation of larger sized agglomerates.

Since the addition of ingredients such as cocoa powder significantly affects matrix formation and shifts the particle size distribution, consideration must be given to future formulations should additional ingredients be added.

The addition of lactose in ice cream mixes on particle size distribution was also investigated at a point of time to better understand the homogeneity of dairy ice cream and how it affected mouthfeel and texture.

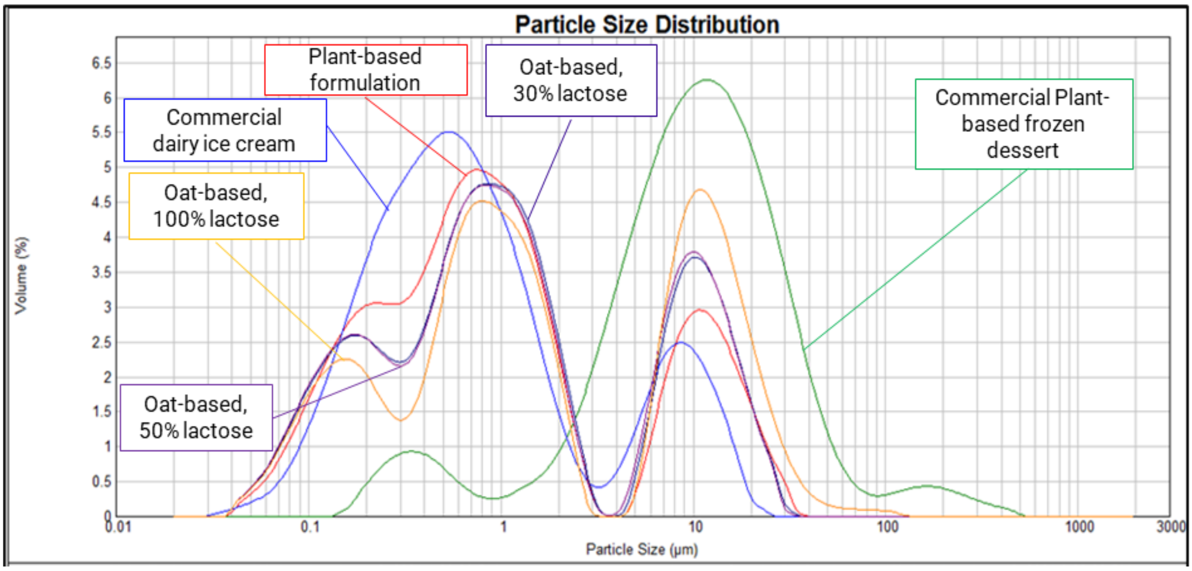

Figure 10. Particle size analysis of thawed, diluted and stirred samples of plant-based formulation (Formulation 11), CD, CPB, Oat-based 100% lactose (Formulation 12), Oat-based 50% lactose (Formulation 13) and Oat-based 30% lactose (Formulation 14).

In general, adding lactose produces a higher peak around 10 um and more particles between the 10 μm and 150 μm range. Lactose crystallization in ice cream is common. Upon crystallization, lactose forms α-monohydrate and β-anhydride. α-monohydrate crystals, when grown to at least 15 μm, cause a sandy mouthfeel (Goff & Hartel, 2013). If left unchecked, the unfrozen phase can become supersaturated, causing even more lactose crystallization and the formation of larger lactose particles. From the graphs, Formulation 12 (orange) shows the highest peak at about 15 μm, followed by Formulation 13 (light purple) and Formulation 14 (dark purple). Thus, this suggests that lactose crystallization significantly affects the homogeneity of dairy ice cream. Plant-based frozen desserts should be wary of ingredients that could possibly cause similar crystallization phenomena, which may lead to sandiness in the final product.

Table 10. Labels, descriptions, and volume mean diameter D [4,3] values for formulations analyzed in this paper.

Formulation Label	Description	Pre- or post-homogenization?	D [4,3] (μm)
1	Oat-based (pre-made), sugar sources: granulated sugar and agave syrup, high sugar content, gum B	Pre-homogenization	3.92
2	Oat-based (pre-made), sugar sources: granulated sugar and agave syrup, mid sugar content, gum B	Pre-homogenization	3.89
3	Oat-based (pre-made), sugar sources: granulated sugar and agave syrup, low sugar content, gum B	Pre-homogenization	3.83
4	Oat-based (powder+water manually mixed), sugar source: agave syrup, gum A	Pre-homogenization	4.89
5	Oat-based (powder+water manually mixed), sugar source: agave syrup, gum A (50% less than in Formulation 4)	Pre-homogenization	4.68
6	Oat-based (powder+water manually mixed), sugar source: agave syrup, gum B	Pre-homogenization	3.68
7	Pea-based (pre-made), sugar source: agave syrup, gum B	Pre-homogenization	5.10
8	Pea (pre-made) and oat-based (pre-made) at 1:1, sugar source: agave syrup, gum B	Pre-homogenization	4.98
9	Oat-based (pre-made), sugar source: agave syrup, gum B	Pre-homogenization	4.13
9.2	Oat-based (pre-made), sugar source: agave syrup, gum B	Post-homogenization	3.81
10	No plant-based protein base, sugar source: agave syrup, gum B	Pre-homogenization	1.98
11	Base formulation (oat-based, sugar sources: granulated sugar and agave syrup, gum B, vanilla flavored)	Pre-homogenization	3.76
11.2	Base formulation, chocolate flavored	Pre-homogenization	4.23
12	Oat-based (pre-made), sugar source(s) replaced by 100% lactose, gum B	Pre-homogenization	5.77
13	Oat-based (pre-made), sugar source(s) replaced by 50% lactose, gum B	Pre-homogenization	5.46
14	Oat-based (pre-made), sugar source(s) replaced by 30% lactose, gum B	Pre-homogenization	5.09
CD	Commercial dairy ice cream	Pre-homogenization	4.34
CPB	Commercial plant-based frozen dessert	Pre-homogenization	10.41

2.4 Conclusion

The plant-based frozen dessert formulations that were developed generally performed well on benchtop and pilot plant tests, displaying good texture, mouthfeel, flavor and color. Specifically, there were formulations that displayed exceptional quality. These formulations corresponded with the following physicochemical properties: pH 6, Brix value of 36%, overrun of 100%, L* value above 80, smooth and bimodal particle size distribution with volume mean diameter D [4,3] of 4.125 μm, composition of: 14.75% fat, 37.1% solids, with gum sources or blends with gum acacia, locust bean gum, and guar gum. Depending on the desired quality (e.g. mouthfeel, nutritional content), these components will vary: plant-based source, protein and sugar source. Based on these findings, it was decided that these parameters would guide future formulations.

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CHAPTER 3
RECOMMENDATIONS AND FUTURE WORK

3.1 Impact

The plant-based frozen dessert market has seen significant growth in the early stages and is expected to grow even further. Accelerated by the pandemic-driven supply disruptions and health concerns, dairy-free indulgent treats that are better-for-you are in demand more than ever. With the broader shift towards alternative desserts, food companies across the world have started to produce plant-based frozen desserts and even accommodate various flavor extensions. Unilever, a key player in the ice cream market, launched its vegan Magnum ice cream range with new salted caramel flavor in March 2020 (Scattergood, 2019). This is an extension of its pea-protein and coconut oil-based plant-based ice cream line which originally just had a classic vanilla and almond flavor.

Chilean company NotCo, Latin America's leading contender in the plant-based alternatives market, has expanded beyond its mayonnaise and meat analogues to include vegan ice cream. Since its founding, NotCo has acquired multiple partnerships with leading fast food chains like Shake Shack, produced two new flavors and is successfully selling in major grocery chains (Novotaste, 2020).

However, consumers are not entirely satisfied with the alternatives available; flavor, taste and texture and cost are huge determinants of their purchasing dynamics. Without an optimized balance of these indicators, consumers will be less likely to purchase the product again. Moreover, as the plant-based flavor profiles improve, consumers will get pickier (Decker, 2019). Thus, more research and development in exploring other plant sources (instead of the usual coconut, soy, almond and cashew (Ambegaonkar et al., 2020), formulation and processing conditions, is needed.

3.2 Future Work

The findings in this experiment can provide guidance in what plant sources, formulation and processing conditions work. While the 26 formulations performed well, further testing should be conducted to confirm the trends observed.

As the formulations chosen in this study were primarily led by the client's sensory preferences, sequential experimentation and statistical design methods should be conducted in the future so each experimental variable can be closely studied. For instance, in order to check if the homogenization pressure affects particle size, various homogenization pressures in equal intervals should be used, all other factors remaining constant, and particle size measured. Each experiment should be done in triplicate to give greater validity to the findings. Statistical tests like a two-way ANOVA can help measure variation in the experiment to understand if the differences are significant or not.

In order to truly understand how particle size affects ice cream and frozen dessert quality factors like melting rate and hardness, more can be done with particle size analysis. Besides looking at just the peaks and troughs through volume-weighted means, the destabilization behavior of the ice cream and frozen dessert mixes can be analyzed. The primary mode of destabilization of milk is by sedimentation of dense solid particles and creaming of low density oil droplets. Thus, particle size analysis on sedimentation can be conducted to understand the settling behavior of the mix. To best characterize the settling behavior of particles, the Sauter mean, or D [3, 2], should be used instead of D [4, 3] (Durand, Franks, and Hosken, 2003). This experiment also postulated that the shifts in particle size distribution was caused by certain formulation changes. To accurately confirm this, range-specific particle size analysis can be performed using specialized equipment such as the

FBRM-focused beam reflectance measurement (FBRM G400, Mettler Toledo), which measures particle structures in real-time (Kyoda et al., 2019). With real-time analysis, the peaks, troughs and shifts in particle size distribution can be modeled. Specifically, this can be used to confirm the findings in Section 2.4 of Results and Discussion > Particle size, when the effect of adding cocoa powder to particle size was investigated.

Besides using indicators like pH, Brix, overrun, color, and particle size, specialized equipment like a rheometer (to study viscosity), texture analyzer (to study texture), a penetrometer (to study hardness), light microscope in an isolated chamber with controlled heating and freezing rates (to measure ice crystal size), can be used. This would give more information about the product's rheological properties, thermal behavior and shelf-life.

Another improvement would be to include a trained sensory panel, which would help quantify the differences between formulations and potential commercial acceptance for a wider demographic. Descriptive tests, which elaborate on the nature or magnitude of sensory differences, and affective tests, which establish consumer preferences, can be combined. For instance, an initial evaluation by highly skilled panelists can give quantitative descriptions on flavor and texture. A following survey can include an affective test in the form of a 9-point hedonic scale (ranging from like extremely to dislike extremely). This allows the evaluator to compare for instance, the acceptability of a newly developed product. Preference tests can also be used to find out how the product compares against its market competitors. This would inform marketing and distribution decisions.

As packaging, pricing and distribution play important roles in consumer acceptability, the effect of various packaging materials on indicators like temperature fluctuations, cost of production and shelf-life should be investigated as well.

Sustainability has taken over personal health as consumers' biggest concern in trying plant-based products in 2022 (Orr, 2022). Quantifying the long-term impact of the product from cradle to grave can significantly impact consumers' purchasing decision. One way to quantify is by conducting a Life Cycle Assessment (LCA). An LCA properly evaluates the global extent of the inputs, outputs, and potential environmental impacts throughout the life cycle of a product system. Although it has been scientifically proven that a wide variety of plant-based alternatives leave a significantly smaller carbon footprint (Saget et al., 2021), every product is different. Each product has a unique composition and production process, and not all products may have a net zero or negative carbon footprint. For instance, Grant and Hicks' LCA comparison revealed that almond milk, a popular plant-based dairy alternative, scored the highest in all impact categories (e.g. cumulative energy demand, water intake) amounting to at least two times higher than dairy milk (Grant and Hicks, 2018). Thus, doing an LCA on this plant-based frozen dessert would be one way to gain clarity on the manufacturing process and significantly influence long-term sustainability practices and decisions made in the final distribution stage.

Functionality of plant-based sources are limited. Formulations can be improved by exploring other sources instead of the conventional, naturally occurring ones. Novel cellular agriculture techniques like precision fermentation, strain development and genetic engineering cell lines can produce specific ingredients that can provide unimaginable functionality to the final product. Bold Cultr, a brand developed under General Mills, has launched its non-animal dairy cream cheese made with The Urgent Company's (i.e. Perfect Day) dairy proteins created by precision fermentation (Poinski, 2021). Using Perfect Day's engineered proteins have helped improve the taste, texture and functionality of Bold Cultr's final product.

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