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Original Research Article

Effects of Stabiliser-Thickener Combinations on the Physical Quality of Plant-Based Ice Cream Analysed Using Mixture Design Methodology

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Abstract: This study examined the effects of various stabiliser-thickener combinations on the physical properties of plant-based ice cream and aimed to determine the optimal combination for improved formulation. Carboxymethyl cellulose (CMC), carrageenan, and cornstarch were used. The key physical properties analysed included melting rate, hardness, and overrun (OR), assessed using mixture design methodology in Design Expert 13 software. Results were compared with a commercial plant-based ice cream sample. The optimal stabiliser-thickener combination was 0.135% CMC, 0.138% carrageenan, and 0.128% cornstarch, predicted to yield an OR of 34.2%, hardness of 66.3 N, and a melting rate of 0.33 g/min. The commercial sample showed a faster melting rate (1.27 g/min), lower hardness (33.2 N), and a similar OR (28.3%).

Keywords: stabiliser; thickener; plant-based ice cream; mixture design methodology

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1. Introduction

Ice cream is an enormously popular food and known for its soft texture, temperature sensitivity and creamy mouthfeel. The term "ice cream" in its broadest sense covers a wide range of different types of frozen dessert. Ice cream, a globally recognised dessert, encompasses a variety of types such as dairy ice cream, gelato, and non-dairy alternatives (Clarke, 2012). What all these have in common is that they are sweetened, flavoured, contain ice, and, unlike any other frozen food, they are normally eaten in the frozen state. Today, ice cream is found in almost any restaurant or corner store, and is recognised globally as the perfect summer treat. Textural attributes of ice are the key factors determining the market success of the product. Ice cream comes in numerous varieties, including standard ice cream, low-fat ice cream, and non-dairy ice cream. Ice cream is created using cream and milk; however, low-fat ice cream is made with milk and contains less fat. Non-dairy ice cream is produced with milk substitutes such as soy, almond, or coconut milk (Martinez & Bourff, 2017).

Ice cream consumers nowadays have started to shift towards affordable, functional and non-dairy alternatives. These requirements have posed challenges to ice cream manufacturers globally. The alternatives also attract consumers who are lactose-intolerant and consumers with environmental concerns associated with dairy products. Normally, widely available resources such as plant starches and dietary fibres have the potential to be used as milk fat and protein replacers in ice cream to produce non-dairy and plant-based ice cream. However, the removal and/or replacement of an ingredient affects the physical–chemical properties, which in turn affect the multiple related sensory characteristics which are important to consumers.

The freeze and whipping methods are critical unit activities for achieving adequate model, texture, and consumer acceptability of ice cream, which is an iced dairy product consumable in its frozen state. The texture and acceptability of ice cream are influenced by a variety of formulation and processing factors. One such element that gives the completed product specialised and crucial functions despite its low level in the formulation is stabilisers. A set of compounds that were formerly classified as holders, colloids, binders, and fillers were given the name stabiliser in 1915 (Bahramparvar & Tehrani, 2011).

Consumer demand for functional and non-dairy alternatives is rising, driven by concerns over lactose intolerance and environmental issues related to dairy (Genovese *et al.*, 2022). The advantage of developing a functional ice cream is that it can benefit people of all ages and social classes. Among the ice cream functionalisation strategies are the replacement of fats, sugars and the use of ingredients with proven beneficial effects (Hossain *et al.*, 2020; Munk *et al.*, 2018; Samakradhamrongthai *et al.*, 2021; Soukoulis & Tzia, 2018). These ice creams are designed to provide specific functionalities or to promote wellness, while still providing a delectable frozen dessert experience. It is crucial to choose the best components and concentrate on the characteristics of the ice-cream mix since the relevant quality of the ice-cream mix determines the physicochemical and organoleptic features of ice cream (Kot *et al.*, 2021).

Recently, there has been tremendous growth in the plant-based protein sector, notably for new alternatives to traditional meat and dairy. As a result, consumers have shifted toward ice cream that contains no dairy ingredients. Nonetheless, due to the distinct flavour and structure provided by milk and dairy products, producing plant-based ice cream is a technological difficulty (Pontonio *et al*., 2022). Yet, the demand for vegan or plant-based ice creams has grown because of changes in people's dietary patterns, allowing for the addition of fruits with useful components including carotenoids, fibre, and phenolic compounds (Mendonça *et al*., 2022).

The stabilisers are a class of substances, mainly polysaccharide food gums, that give viscosity to the mix and the unfrozen phase of the ice cream. The migration of free water and the formation of existing ice crystals would cause the ice cream to turn coarse and icy very fast if the stabilisers were not in the formulation (Goff, 2021a). The stabilisers in use today include locust bean gum, guar gum, carboxymethylcellulose (CMC), Xanthan gum, sodium alginate and carrageenan. Stabilisers, though used in small amounts, play a critical role in maintaining the texture and preventing ice crystal formation (Bahramparvar & Tehrani, 2011). Ice crystals in stabilised ice cream have a smaller maximum diameter (measured in micrometres) than those in unstabilised ice cream (Kot *et al*., 2021).

Different stabilisers have different functions in ice cream. The combination of stabilisers has synergistic effects on the quality of ice cream (Goff, 2021a). CMC can be used to control water mobility and texture of ice cream, which helps to stabilise against heat shock, control the size of ice crystals, give excellent overrun (OR), and provide a good melting profile. Hence, CMC could improve the melting profile of ice cream. Carrageenan is usually used due to its gel-forming functionality and reactivity with casein that prevents whey separation. It is important to add carrageenan if an ageing step exists in the manufacturing process (Naresh & Merchant, 2006). Cornstarch is considered as a thickener that can increase the viscosity, thus affecting the OR during the freezing process (Goff & Hartel, 2013).

The use of mixture design methodology was conducted previously by Razak *et al*. (2019). The study obtained the combination of CMC, carrageenan and sodium alginate stabilisers to be used in ice cream, and the outcome was satisfactory. To the best of our knowledge, there is no established data on the use of a mixture design methodology to predict the optimum stabilisers and thickener combination to be used in plant-based ice cream. The aim of this study was to obtain the optimum stabiliser-thickener combination for plant-based ice cream and compare the ice cream quality, such as OR, melting rate and hardness, with the commercial sample. The current study explores the optimal stabiliser-thickener combination for plant-based ice cream.

2. Materials and Methods

2.1. Experimental Design

Design Expert (Version 13, Stat-Ease, USA) was used to determine the optimum stabiliser-thickener combination in plant-based ice cream formulation. The stabilisers chosen for the study were CMC and carrageenan, while cornstarch was chosen as the thickener. The factors are the percentage of each stabiliser and thickener in the mixture combination. The range was set from 0.1 (lower limit) to 0.2 (upper limit) to compose a total of 0.4% mixture. The responses were based on the OR, the melting rate and the hardness of ice cream. A total of eight stabiliser-thickener mixtures were generated based on the D-optimal mixture design, and the associated mixture designs are shown in Table 1.

Table 1. Mixture design generated for stabilizer-thickener combination composition

Sample	CMC %	Carrageenan %	Cornstarch %
1	0.150	0.100	0.148
2	0.117	0.116	0.166
3	0.150	0.149	0.100
4	0.100	0.200	0.100
5	0.200	0.100	0.100
6	0.100	0.100	0.200
7	0.150	0.149	0.100
8	0.100	0.149	0.150

2.2. Ice Cream Production

Plant-based ice cream mix compositions formulation created based on the elements used, the amount of mix necessary and can range from standard to super premium quality. The base mix composition included 9% pea protein powder, 10.25% non-dairy creamer, 9% sucrose, 0.4% stabiliser-thickener mixture, and 0.2% emulsifier. The dry ingredients were dispersed under agitation into the wet ingredients at room temperature by manual stirring. The mixture was then batch pasteurised at 80°C for 15 s and consequently made to go through a two-stage homogenisation process using a laboratory-scale homogeniser. Then, the liquid ice cream mixture was rapidly cooled at a constant temperature of 4°C overnight for ageing. The aged mixture was then frozen using a batch ice cream freezer (MK25ETBPA, Sunwins, Malaysia), which has a capacity of 25 L. The ice cream was further hardened and stored in a deep freezer under quiescent freezing conditions at -18°C (PFZ-402, Pensonic, Malaysia).

2.3. Ice Cream Testing

2.3.1. Melting test

An ice cream sample of 50 g was weighed into a paper cup and kept frozen overnight. All samples were stored at -20ºC until testing. The ice cream was removed from the paper cup and directly placed on top of a 4 mm x 4 mm wire mesh. The surrounding temperature was 22ºC. The first dripping time of the ice cream was recorded. The mass of the melted ice cream that flowed through the screen mesh was recorded at 5 min intervals for 30 min using an electronic balance (Model TX323L, Shimadzu, Japan).

2.3.2. Penetration Test

The ability of ice cream to be scooped is one of the most essential characteristics of a quality texture. The penetration (hardness) test resembles the action of scooping in terms of the force required to break the structure. All the samples were first put into a mould until full, and the top surface flattened to ensure the penetration test can be conducted correctly and smoothly. Three samples were prepared for each ice cream formulation. Then, all the samples were stored in a freezer overnight prior to testing. A texture analyser (TA.XT Plus, Stable Micro System, England) with Texture Exponent software version 6.1.16.0 was used to conduct the hardness test. The probe used was the 45° conical probe, and the penetration depth and velocity used were 10 mm and 2.00 mm s^{-1}, respectively, in compression mode.

2.3.3. Overrun (OR)

OR was calculated by weighing a known volume of ice cream mix and ice cream, and the OR was computed using the following Equation 1 (Goff, 2021b):

$$Overrun = \frac{M_{mix} - M_{icecream}}{M_{icecream}} \times 100\% \quad (1)$$

with M_{mix} is the mass of a volume of ice cream mix and $M_{icecream}$ is the mass of the same volume of ice cream.

3. Results and Discussions

Table 2 shows all eight stabiliser-thickener combinations together with the associated responses (melting rate, hardness and OR of ice cream).

Table 2. Combinations of stabilizer-thickener in the samples (factors) and the resulting responses.

Sample	CMC %	Carrageenan %	Cornstarch %	Overrun %	Melting rate g/min	Hardness (N)
1	0.150	0.100	0.148	35.66	0.470 ± 0.176	52.238 ± 1.88
2	0.117	0.116	0.166	31.13	0.315 ± 0.240	53.337 ± 1.46
3	0.150	0.149	0.100	31.37	0.645 ± 0.149	61.842 ± 1.33
4	0.100	0.200	0.100	18.67	0.430 ± 0.020	38.230 ± 1.59
5	0.200	0.100	0.100	18.79	0.466 ± 0.137	70.710 ± 1.02
6	0.100	0.100	0.200	18.56	0.372 ± 0.212	26.252 ± 1.46
7	0.150	0.149	0.100	31.58	0.655 ± 0.158	61.842 ± 1.76
8	0.100	0.149	0.150	20.00	0.778 ± 0.613	54.818 ± 1.73

3.1. Melting of Plant-Based Ice Cream

Ice cream has distinct physical features such as hardness and melting properties that are influenced by ingredients, air entrapment, and ice content (Roland *et al*., 1999). Ice cream with a slower melting rate gives more satisfaction to the consumers, as the consumers can indulge in the ice cream for a longer time. Stabilisers and emulsifiers content and types may influence the meltdown of ice cream (Wu *et al*., 2019). From Table 2, Sample 8 (with 0.1% CMC, 0.149% carrageenan, and 0.15% cornstarch) exhibited the fastest melting rate of 0.778 g/min, while Sample 2 (0.117% CMC, 0.116% carrageenan, and 0.166% cornstarch) showed the slowest melting rate of 0.315 g/min. The combination of stabilisers and thickeners significantly influenced the melting rate. The combination of stabilisers has synergistic effects on the quality of ice cream. CMC has the effect of reducing the melting rate of ice cream due to its ability to control water mobility and the texture of ice cream. Lower CMC content in the stabiliser combination affects the way ice cream holds water. This results in faster melting rates.

Additionally, the stabiliser-thickener combination composition has a significant effect ($p < 0.05$) on the melting rate of ice cream samples. Figure 1 shows the contour plot generated from the software in which the effects of stabiliser-thickener combinations on the melting rate of plant-based ice cream can be observed. The plot shows that the combination of CMC and carrageenan reduces the melting rate of plant-based ice cream, while the combination of carrageenan and cornstarch increases the melting rate. CMC's ability to control water mobility likely contributed to the reduced melting rate, as corroborated by Razak *et al*. (2019), which is similar to the data obtained in this study.

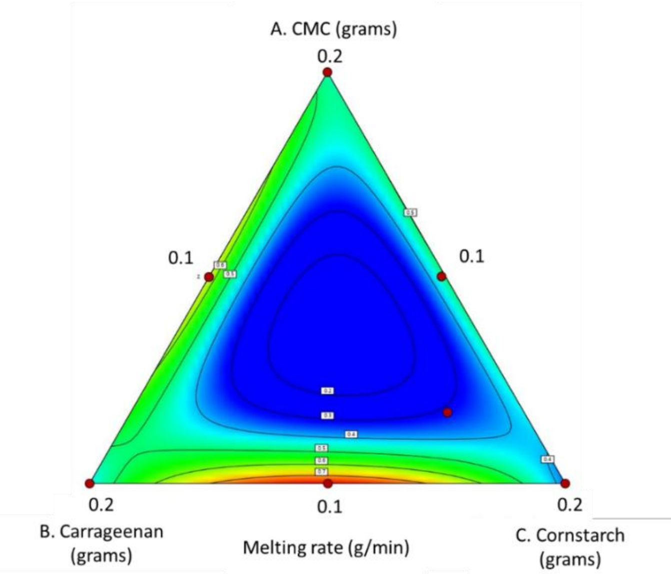

Figure 1. Contour plot for the effects of stabilizer-thickener combinations on the melting rate of plant-based ice cream

Figure 2 shows the remaining structure of melted ice cream after 30 minutes of testing. The impact of stabilisers on ice cream melting varies according to the type and amount of stabiliser used, along with other parameters such as ice cream formulation, freezing procedure, and storage circumstances (Arsanti Lestari *et al*., 2019). After the melting test ended, the remained structure indirectly indicated the air content in the samples. The trapped air inside the matrix, together with the fat network, was left as a foamy structure on the wire mesh after the ice crystals in the ice cream samples melted and drained through the wire mesh. Sample 1 retained its structure better than the other samples. The higher CMC content in sample 1 contributed to a better OR, i.e. air content, which gives the highest OR value of 35.66% as shown in Table 2. The high content of cornstarch in sample 1 also contributed to the OR, where it acts as a thickener that increases the viscosity of ice cream.

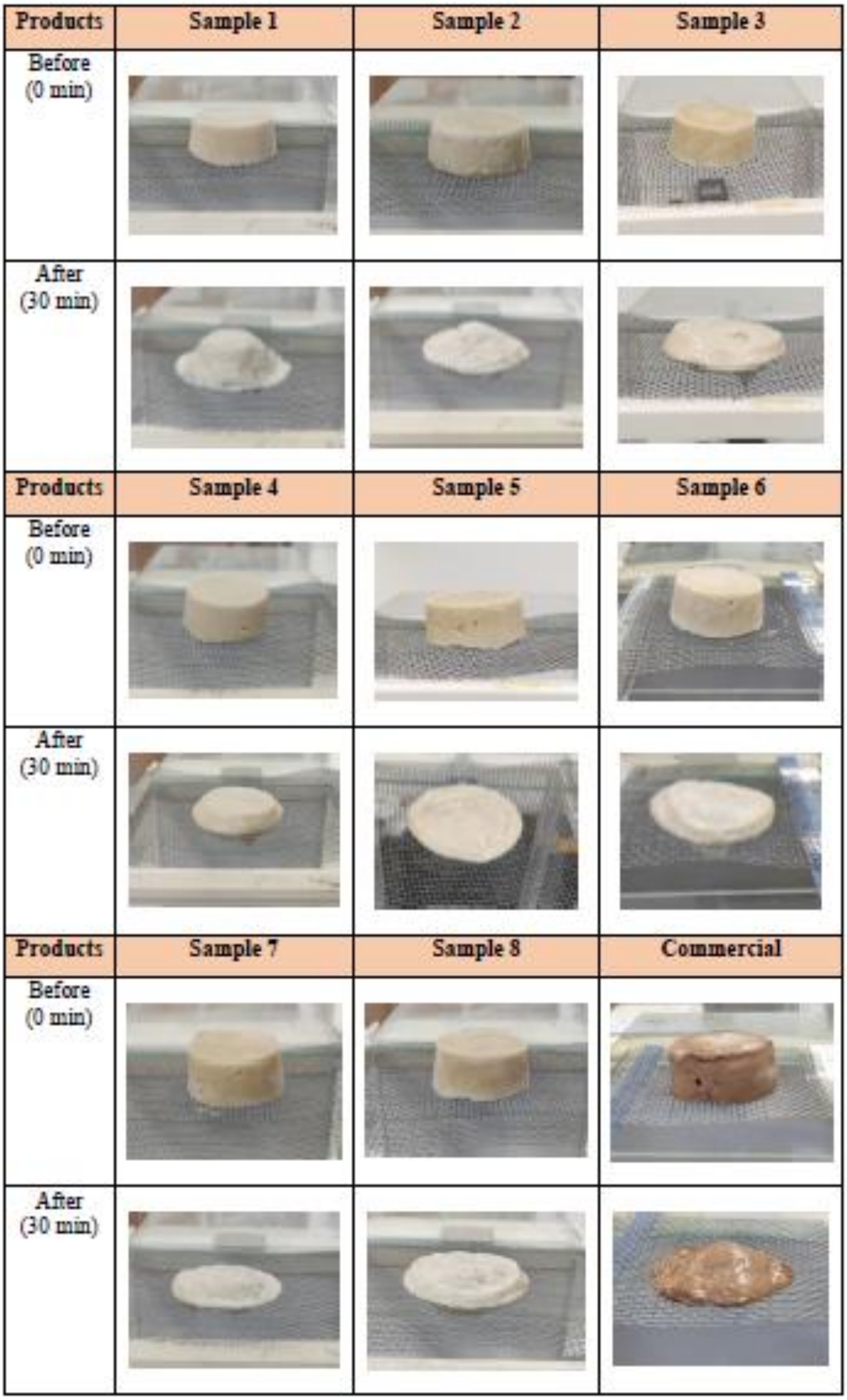

Figure 2. Structure of the remaining melted ice cream after 30 minutes of melting test

3.2. Hardness of Plant-Based Ice Cream

From Table 1, Sample 5 with 0.2% CMC, 0.1% carrageenan and 0.1% cornstarch had the highest hardness of 70.71 N, while Sample 6 with 0.1% CMC, 0.1% carrageenan and 0.2% cornstarch had the softest texture, i.e. (lowest hardness). The OR of both samples 5 and 6 were almost the same, 18.79% and 18.56%, respectively. The melting rates of both samples 5 and 6 were 0.466 g/min and 0.372 g/min, respectively. The hardness of plant-based ice cream in this study showed higher values than the ones obtained from the study done on the plant-based ice cream by Pontonio et. al. (2022) with guar gum as the texture modifier, which gave the OR values of 7.08–19.99N.

It can also be seen from Table 1 that higher CMC content in stabiliser blends gives ice cream of a higher hardness value for plant-based ice cream. A study done by Razak *et al*. (2019) on dairy-based ice cream observed that lower ice cream hardness showed a trend of faster melting rate. This indicates that stabiliser blends have different effects on the characteristics of dairy-based and plant-based ice cream.

From Figure 3, the value of hardness decreases as carrageenan and cornstarch composition increase. Cryo-protective characteristics of carrageenan can be the reason for low hardness in ice cream. A higher CMC content in the stabiliser combination gives a higher hardness value. A combination of CMC and cornstarch can be seen to be very significant ($p < 0.05$) as the value for hardness was the highest when both stabilisers were at the same or almost the same level. The hardness of ice cream is attributed to its viscosity which reflects the easeof scooping ice cream before consumption. Ice cream with a lower hardness is easier to scoop out than ice cream with a higher hardness value.

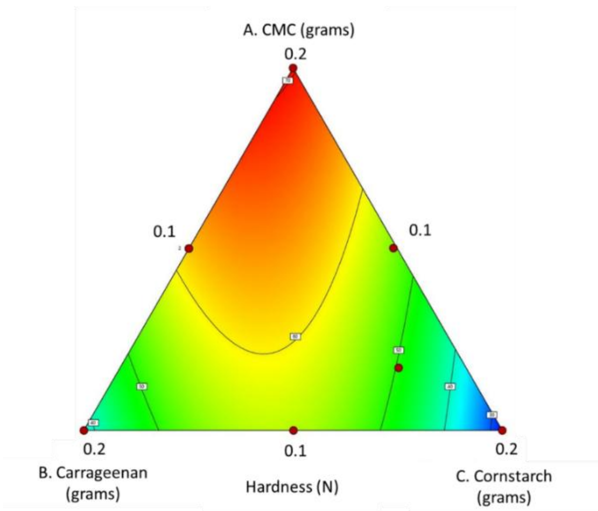

Figure 3. Contour plot for the effects of stabilizer-thickener combinations on the hardness of plant-based ice cream

3.3. OR of Plant-Based Ice Cream

OR is when ice cream is frozen, where nearly half of its volume is air (Goff, 2021b). Since there is the existence of air, it has an insulating characteristic that makes it harder for heat to penetrate the ice cream (Wu *et al*., 2019). From the results, the OR percentage obtained for all samples was in the range of 18%–35%. In Table 1, Sample 1 with stabiliser-thickener combinations of 0.15% CMC, 0.10% carrageenan and 0.148% cornstarch shows the highest percentage of OR (35.66%). From Figure 4, Sample 6 with stabiliser-thickener combinations of 0.1% CMC, 0.1% carrageenan and 0.2% cornstarch resulted in the lowest OR percentage of 18.56%. OR of plant-based ice cream in this study showed higher values than the ones obtained from the study done on the plant-based ice cream by Hidas *et al.* (2023) with guar gum as the thickener, which gave the OR values of 0.5–11.5%.

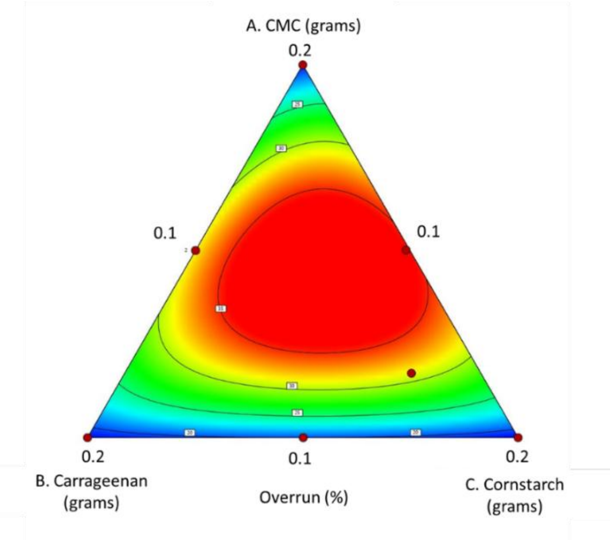

Figure 4. Contour plot for the effects of stabilizer-thickener combinations on the overrun of plant-based ice cream

Combination with a higher percentage of carrageenan gives a lower OR as seen in the contour plot in Figure 4. Higher value for any of the stabiliser-thickener compositions resulted in lower OR of ice cream. This shows that the effect of stabiliser-thickener on OR is significant ($p < 0.05$). Increased content of dairy-based ice cream OR resulted in decreased hardness of ice cream hardness (Sofjan & Hartel, 2004) while Prindiville *et al*. (1999) found the reverse effect. Our study also shows the opposite effect of OR where the highest value of OR (35.66%) resulted in higher hardness (52.238 N), and the lowest OR (18.56%) resulted in the lowest hardness (26.252 N). This phenomenon may be due to the use of plant-based protein isolate in ice cream mixture, and some studies found that plant-based protein isolates have a negative effect on air inclusion during the freezing process, which reduces OR (Guler-

Akin *et al*., 2021). OR has effects on the mouthfeel during consumption, where the air content in ice cream contributes to the airiness of the texture, which is normally perceived as a smooth texture and easy to swallow.

3.4. Optimisation

Ice cream manufacturing requires a correct combination of ingredients and processing methods to produce high-quality products. Stabilisers are crucial in ice cream due to their water-holding and structure formation functions in ice cream. For ice cream, the end outcome would be deemed optimal if the melting rate is minimal but the sample's OR, viscosity, and hardness are maximal (Razak *et al.*, 2019). After superimposing all the contour plots of all responses, the optimal proportion of each stabiliser and thickener was established. The optimum stabiliser-thickener combination was found using numerical response analysis, and the predicted combination is to be 0.135% CMC, 0.138% carrageenan and 0.128% cornstarch. The predicted responses for melting rate, OR and hardness are 0.328 g/min, 34.205% and 66.334 N, respectively.

3.5. Comparison with Commercial Ice Cream

The optimised sample was then compared to the commercial plant-based ice cream in terms of the OR, hardness and melting rate (Table 3). The commercial plant-based ice cream had slightly similar OR with the predicted responses of the optimised sample. The melting rate of the commercial ice cream was faster than the predicted optimised sample and the rest of the samples tested in the optimisation study. The difference in the ingredients' composition is believed to have contributed to the better body retention of the plant-based ice cream produced in this study. The lower hardness value of the commercial sample reflected the higher OR and might have contributed to its fast-melting rate.

Table 3. Comparison between the commercial sample with the predicted optimized responses

Samples	Overrun (%)	Hardness (N)	Melting rate (g/min)
Optimized plant-based ice cream (predicted)	34.205	66.334	0.328
Commercial plant-based ice cream	28.341	33.152	1.274

4. Conclusions

This study successfully applied mixture design methodology to determine the optimal stabiliser-thickener combination for plant-based ice cream. From the mixture design analysis, the optimum combination generated for stabiliser-thickener composition was 0.135% CMC, 0.138% carrageenan and 0.128% cornstarch. The optimised combination was predicted to yield improved melting rate, hardness, and OR compared to commercial samples. These results offer valuable insights for the development of non-dairy ice creams, particularly for food manufacturers seeking to enhance texture and stability.

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Conflicts of Interest: The authors declare no conflict of interest.

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