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Physical, Rheological and Nutritional Properties of Plant-Based Frozen Dessert

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Abstract. The objective of the current study was to create a frozen dessert with reduced fat and sugar content, using plant-based ingredients and to evaluate its physical, rheological and nutritional properties. The dessert formulations were developed using plant-based ingredients such as sweet potatoes, potatoes, carrots, and beetroot, combined with date sugar, corn starch and skimmed milk powder. Chemical analysis showed that the sweet potato (SP) sample had the highest energy value due to its carbohydrate and fat content, while the carrot (CR) sample had the lowest. Rheology tests revealed that beetroot-based (BR) samples exhibited the highest viscosity, likely due to the high dietary fibre content in beetroots, while the CR sample was the most fluid, attributed to its lower solids content.
The study showed that air bubble size influenced texture and melt behaviour. The overrun, a measure of air incorporation, was highest in the BR sample, contributing to a lighter texture. The hardness of the desserts was influenced by solid content and ingredient composition, with the CR sample being the hardest. Melting rate analysis revealed that all samples melted slowly, with the SP, SPP (sweet potato + potato), and BR samples melting uniformly over time. Overall, the study demonstrated that plant-based ingredients could effectively replace traditional high-fat animal-based ingredients, yielding frozen desserts with favourable nutritional profiles, acceptable rheological properties, and desirable physical characteristics.
Key words: frozen dessert, viscosity, air bubble, overrun, melting rate, rheological properties.

Introduction

Frozen desserts, which are aerated and frozen, broadly encompass products that resemble ice cream, but do not meet specific legal standards (VanWees *et al.*, 2020). This category includes sorbets, sherbets, mellorine, frozen custard, frozen yoghurts, and ice cream (Hasan *et al.*, 2023).

Milk and other dairy products are the main ingredients in many frozen dessert formulations, such as ice cream. Sugars and fats are crucial components of the solids in the formulation, contributing significantly to the body and texture of frozen desserts (Soukoulis & Tzia, 2018). Typically, ice cream contains 28–44% solids, with a substantial proportion being sugars and/or fats (Marshall *et al.*, 2003). However, the high fat and sugar content of frozen desserts is linked to an increased obesity risk, including childhood obesity, and associated health issues (Genovese *et al.*, 2022). These concerns have raised consumer demand for desserts lower in sucrose, saturated fats, and calories, prompting the development of new formulations with alternative ingredients.

The rheological properties of frozen desserts are influenced by the ingredients and their proportions in the formulation (Bahramparvar & Tehrani, 2011). To maintain the desired rheological and sensory properties while reducing sucrose and fat, producers must explore new ingredient alternatives that do not compromise the sensory and physical properties of the desserts. A growing trend is the use of vegetables, fruits, berries and other plant-based ingredients in the production of frozen desserts (Genovese *et al.*, 2022).

Plant-based ingredients are increasingly used in frozen desserts, offering improved physicochemical properties and additional health benefits compared to traditional dairy products (Putradamni & Pramitasari, 2024; Genovese *et al.*, 2022; da Silva *et al.*, 2020; Çam *et al.*, 2013). Nonetheless, challenges such as

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lower nutritional quality, the presence of antinutrients, and a diminished sensory appeal affect consumer acceptance (Hasan *et al*., 2023). Future research should focus on understanding these plant-based frozen desserts' sensory and rheological properties to meet consumer expectations.

Plant-based ingredients, with their diverse range of valuable compounds, are promising bases for frozen desserts for example, beetroots, sweet potatoes, potatoes, carrots, and dates. Beetroot (*Beta vulgaris*) provides carbohydrates (10 g 100 g^{-1}), which includes about 2.8 g 100 g^{-1} fibre. Beetroot is rich in vitamins A (73–109 µg 100 g^{-1}), C (11–20 mg 100 g^{-1}), and niacin (334 mg 100 g^{-1}), and minerals (Ca 16–35 mg 100 g^{-1}, P 38–87 mg 100 g^{-1}, K 260–407 mg 100 g^{-1}) (Bansal *et al*., 2016). The purple-red hue of beetroots is attributed to the presence of flavonoids (2.02–2.36 mg 100 g^{-1}) and betalain (0.5 g kg^{-1}), which consist of betacyanin and betaxanthin, both of which possess strong antioxidant properties (Mirmiran *et al*., 2020). Furthermore, sweet potatoes (*Ipomoea batatas*) provide carbohydrates (including maltose 83 mg, sucrose 32.5 mg, glucose 9 mg, and fructose 8 mg per kg dry weight), β- carotene (83 µg g^{-1}), and minerals (K 310–368 mg, P 42–45 mg, Mg 22–25 mg, Ca 22–27 mg, Zn 2.85–4.25 mg, Cu 0.25–0.67 mg, Fe 0.9–1.4 mg per 100 g dry weight), polyphenols, and anthocyanins (Xiao *et al*., 2022; Pang *et al*., 2021). Potatoes (*Solanum tuberosum* L.) offer crude protein (6.61–12.48 g 100 g^{-1}dry weight), crude fibre (1.34-2.36 g 100 g^{-1} dry weight), and minerals (K 1.27-1.84 mg 100 g^{-1}, Fe 1.03–3.12 mg 100 g^{-1}). Due to their nutrient profile, they have already been used in the production of desserts (Kince et al., 2023) which is not suitable for celiac patients who require a gluten-free diet. Potatoes are known as a good source of starch, minerals and vitamins. They also contain protein, dietary fibre and various phytochemicals. Their addition to pastry cream can both serve as a texturising agent and enrich the nutritional value of the final product. This study aimed to evaluate the suitability of potatoes as a replacement for wheat flour in pastry cream. For study purposes, the physicochemical attributes of eleven potato varieties were evaluated. Among other varieties, the boiled potato variety Gala exhibited higher fibre, fat, phosphorus and potassium content; however, significantly higher protein (12.48±0.08 g 100 g^{-1} DW. Carrots (*Daucus carota*) contain carbohydrates (10.6%), crude fibre (1.2%), and minerals (Ca 80 mg, Fe 2.2 mg, and P 53 mg 100 g^{-1}) (Sharma *et al*., 2012). Dates (*Pheonix dactylifera*) are high in carbohydrates (glucose, fructose, and sucrose) ranging between 65–80% of their dry weight (Almuziree & Alhomaid, 2023). Dates are also an excellent source of dietary fibre (6.5–11 g 100 g^{-1}), consisting of insoluble (84–94%) and soluble (6–16%) fibre (Fernández-López *et al.*, 2022) especially in the arid and semi-arid regions of the world, mainly due to the fact that it is considered an eco-efficient crop (based on its few growth requirements and the fact that it is economic and sustainable. They also provide vitamins and minerals, contributing to their status as a nutrient-dense food. Dates are rich in polyphenols, including flavonoids, phenolic acids, and tannins, which exhibit strong antioxidant activity. Despite their high sugar content, dates have a low to moderate glycaemic index (GI). The GI of dates ranges from 30 to 50, depending on the variety (Almuziree & Alhomaid, 2023).

Evaluating plant-based ingredients in frozen desserts is essential not only for their functional benefits, but also for their technological properties. As consumer trends shift, focusing on nutrient-rich and plant-based ingredients can provide innovative solutions while addressing health concerns associated with traditional frozen desserts. Dietary fibre, a key component of vegetables, plays a crucial role in the structure of frozen desserts, particularly influencing overrun.

Incorporating vegetables and fruits into frozen dessert formulations can enhance dietary fibre, phenolic compounds with antioxidant activity, natural colours and flavours. While recent studies have developed various frozen desserts with functional properties, vegetables have rarely been used as the main ingredient (Genovese *et al.*, 2022). The objective of the current study was to create a frozen dessert with reduced fat and sugar content, using plant-based ingredients, and to evaluate its physical, rheological and nutritional properties.

Materials and Methods

Materials

The following ingredients were used for the production of frozen desserts: sweet potatoes (*Ipomoea batatas*), potatoes (*Solanum tuberosum* L.), beetroots (*Beta vulgaris*), carrots (*Daucus carota* L.); dates (*Pheonix dactylifera*) sugar BIO (MAYA GOLD, Netherlands); gelatine (Santa Maria, Denmark); corn starch (Gustin, Slovakia); drinking water; and skimmed milk powder (93.0 g 100 g^{-1} dry weight; Euromilk, Poland). Sweet potatoes, potatoes, beetroots and carrots were boiled and cooled down before use in the dessert production.

The frozen desserts were produced according to the formulation given in Table 1.

Frozen dessert production

The frozen desserts were produced using the following method: dry ingredients were weighed according to the formulation and thoroughly mixed. The dry (date sugar, corn starch, skimmed milk powder

Table 1

The formulations of frozen desserts

Ingredients	Proportion, %			
	SP	SPP	BR	CR
Sweet potato	22.7	11	–	–
Potato	–	11	–	–
Beetroot	–	–	25.7	–
Carrot	–	–	–	26.7
Skimmed milk powder	9	9	9	9
Corn starch	7	7	5	4
Date sugar	10	10	10	10
Water	51	51.7	50	50
Gelatine	0.3	0.3	0.3	0.3
Total	100	100	100	100

SP – sweet potatoes, SPP – sweet potatoes + potatoes, BR – beetroot, CR – carrot

and vegetables) and liquid components were mixed and then combined to form the dessert mix. This mix was pasteurised at 78±1 °C for 20±5 seconds, then cooled and aged for 4 hours at 5±1 °C. After ageing, the mix was processed in an ice cream machine (Bartscher GmbH, Salzkotten, Germany) with a capacity of 700 g for 40 minutes. The temperature of the frozen dessert after freezing was -10±1 °C. The dessert was then transferred into 50 mL plastic containers and hardened at -20±2 °C for 6 hours. Three separate batches were made for each dessert.

The rheological properties of frozen dessert mix were analysed after 4 hours of ageing. The chemical composition, hardness (after 12 hours of hardening), overrun and rheological properties of the developed frozen desserts were analysed.

Analysis of frozen dessert chemical composition

The *fat content* was determined according to ISO 488:2008 using a centrifuge (Funke Gerber, Germany).

Protein content was determined using the Kjeldahl method (LVS NE ISO 8968-1:2014). This was done using Kjeltec™ 2100 (Foss, Denmark), and nitrogen content converted to protein using a conversion factor 6.38.

The *moisture content* of the frozen desserts was determined using a Memmert UF55 drying oven (Memmert, Germany). All measurements were performed in triplicate according to AOAC (1995).

The *fibre* and *salt* contents were calculated using the raw material specifications provided by the manufacturers. For ingredients without provided nutritional values, such as sweet potatoes, regular potatoes, carrots, and beetroots, the data were sourced from the online database Finnish Food Composition Database (Fineli).

Assessment of rheological properties of dessert mix

The rheological properties of the dessert mix were assessed using an MCR-302 rheometer (Anton Paar, Austria) following a modified methodology from Kurt and Atalar (2018). The measurements were conducted using a double plate geometry (CP-50) with a 1º cone angle and a 0.1 mm gap between the plates, all at a controlled temperature of 4.0±0.1 ºC.

Immediately after ageing, a 2 mL sample was placed on the base plate, followed by a stabilisation period of 30 seconds at a shear rate of 5 s^{-1}. The analysis consisted of three stages: (1) the shear rate was gradually increased from 0 to 100 s^{-1} 1; (2) a constant shear rate of 100 s^{-1} was maintained for 60 seconds; and (3) the shear rate was decreased from 100 to 0 s^{-1}. The hysteresis area A (Pa s^{-1}), yield point τ_0, and apparent viscosity η_∞ (mPa s) of the samples were calculated using the RheoCompass 1.25 software (Anton Paar, Austria). Each test was performed in triplicate.

Evaluation of frozen dessert physical properties

The texture analyser TA.HD plus (Stable Microsystems, Godalming, UK) was used to determine the *hardness* of the frozen dessert, which is the maximum force applied to penetrate a probe into a sample. The product was tested immediately after its hardening (-18±2 ºC). The measurements were made at a room temperature (18±2 ºC). The 5 mm in diameter stainless steel cylinder probe was penetrated to a depth of 15 mm at a test speed of 10 mm s^{-1} (Zagorska *et al*., 2022), speed before and after penetration 2 mm s^{-1}. Data were collected from ten measurements per batch (Stable Microsystems, UK).

The *microstructure* of frozen desserts was examined using a Leica DM3000 LED microscope (Leica Microsystems, Germany). Samples were sliced with a sterile knife, applied in a thin layer to a slide, and covered with a coverslip for analysis. Images were captured using a Leica DFC290 HD digital camera (Leica Microsystems, Germany) at the magnification of 10 × 10. A total of 50 measurements were recorded for air bubbles and lamella thickness for each sample in triplicate using *Leica Application Suite* 4.2.0 software.

The *overrun* was evaluated according to the method described by Zagorska *et al*. (2022).

Rheological properties of frozen desserts

An *oscillatory thermo-rheometry test* was conducted on the frozen dessert samples using a MCR-302 rheometer (Anton Paar, Austria), following a modified methodology by Zagorska et al. (2022). A deformation amplitude sweep test was performed at a constant angular frequency ($\omega = 10\ s^{-1}$) to determine the linear viscoelastic region (LVR). The measurements utilised parallel plate geometry PP-25 (1 mm gap) with a frequency of 1.59 Hz. The temperature was increased from -7 °C to 5 °C at a controlled rate of 0.5 °C min^{-1}. Frozen dessert samples were analysed after hardening carefully spreading in thin layer on the base plate. The RheoComass 1.25 software (Anton Paar, Austria) was used to record the storage modulus (G′) and loss modulus (G″). The measurements were conducted for each batch, with the average values from tree runs reported.

The *melting rate* of frozen dessert (g min^{-1}) was determined using a modified version of the method by Kurt and Atalar (2018). Briefly, a 26 g sample of frozen dessert (-18 °C) was placed on a metal sieve (pore diameter 0.1 mm) at room temperature (18±1 ºC). The sieve was positioned over a pre-weighed beaker. The weight of the beaker was recorded every 15 minutes for 60 minutes. Photographs of the melting process were taken at 0, 15, 30, 45, 60 minutes using the iPhone 14 (Apple, Čennai).

Statistical analysis

The obtained data were processed using Microsoft Excel (Microsoft Office Enterprise 2007, Licence: Shareware N/A); Applying ANOVA, differences among results were considered significant if p-value <0.05. Significant difference among ice cream sample attributes was detected by Tukey's test. For the interpretation of the results, it was assumed that $\alpha=0.05$ with 95% confidence. Dessert mixes and frozen dessert samples were prepared in triplicate; overrun, melting rate and microstructure were done in triplicate; other research replicates are mentioned in the description of the methods.

Results and Discussion

Nutritional and energy value of the dessert mixes

The current research aimed to develop a new type of frozen desserts, similar to ice cream, but with reduced fat and sucrose content in the formulation. The nutritional values of the dessert mixes developed are given in Table 2.

The SP sample had the highest energy value, with – 115 kcal per 100 g of product, which can be attributed

Table 2

Nutritional and energy values of dessert mixes per 100 g

Type of frozen dessert	Energy value, kcal/kJ	Fats, g	including saturated fatty acids, g	Carbohydrates, g	including sugars, g	Fibre, g	Proteins, g	Ash, mg
SP	115/483	0.4±0.07[c]	n.d.	16.5[d]	15.1	1.4	11.5±0.12[b]	40.3±0.5[b]
SPP	112/470	0.2±0.01[b]	n.d.	14.9[c]	13.7	1.2	12.7±1.4[b]	32.0±0.2[a]
BR	102/428	0.1±0.07[a]	n.d	13.3[b]	11.9	1.4	12.1±0.9[b]	31.4±0.3[a]
CR	68/286	0.1±0.01[a]	n.d	8.7[a]	7.3	1.4	8.2± 0.9[a]	32.3±0.2[a]

SP – sweet potatoes, SPP – sweet potatoes + potatoes, BR – beetroot, CR – carrot. Data are expressed as mean (n=3) ± standard deviation. Different letters indicate significant difference at p<0.05 in the same column. Values without letters were calculated using Fineli data base.

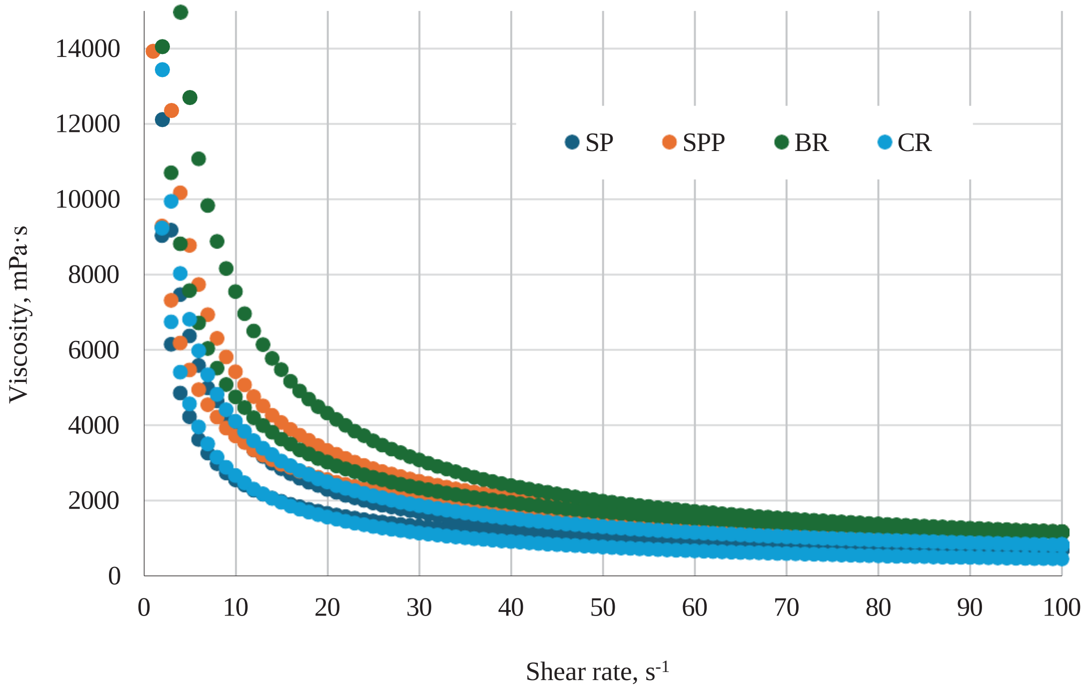

Figure 1. Viscosity of frozen dessert mixes.

to the significantly higher ($p<0.05$) carbohydrate and fat content of sweet potatoes compared to other raw materials used in the frozen dessert formulation. At the same time, it is significantly lower than in traditional milk ice cream, which has 170 kcal per 100 g (Tagliamonte et al., 2023). Conversely, the CR sample had the lowest energy value, largely due to its carbohydrate content being nearly half of that of the SP sample ($p<0.05$). Among all samples, the CR sample also had the lowest protein content ($p<0.05$). From the data in Table 2, it can be concluded, that carbohydrate and protein content are the primary nutrients influencing the properties of all the samples analysed. Since no raw materials with a high fat content were used in the formulation of frozen desserts, alternative ingredients were selected to compensate for the lack of fat. These included skimmed milk powder, which contributed high protein content, along with corn-starch, and date sugar, both of which are high in carbohydrates.

In traditional ice cream formulations, dairy products with high fat content, such as cream or butter, are usually used (Clarke, 2012), leading to a high energy value and high content of saturated fats. When comparing the energy value of the classic ice cream with the frozen desserts developed in this study, the latter emerges a healthier option due to its lower energy value. Considering that some ice cream functionalisation techniques involve replacing sugars and fats with compounds that offer health benefits (Genovese *et al.*, 2022), incorporating plant-based ingredients into dessert formulations appears to be a promising approach.

A key factor for frozen desserts to meet specific standards is their solid content. The solid content of the SP (30%) and SPP (24%) samples is comparable to that of traditional milk ice cream indicated by Clarke (2012). The CR sample, however, had the lowest solid content, which is related to its lower carbohydrate content compared to other ingredients used in this study. This lower solid content could also influence the product's physical properties, which are analysed further.

Rheological properties of dessert mix

One of the most important indicators of frozen dessert quality is the mix's viscosity, which measures the mix's resistance to stirring. The results of the analysis indicate how easily each sample flows and how its flow rate changes under varying conditions, such as different temperatures or pressures. A higher viscosity score means more force is required to whip the dessert. Viscosity depends on several factors, including the shear rate, the type and concentration of stabiliser used, the dry matter and protein content, the temperature at which the stabiliser is added, and the timing of its addition (Marimon-Valverde *et al.*, 2024).

According to Figure 1, all samples exhibited a decrease in viscosity with increasing shear rate, indicating that the mixes behave as non-Newtonian fluids – solutions whose viscosity is not constant and

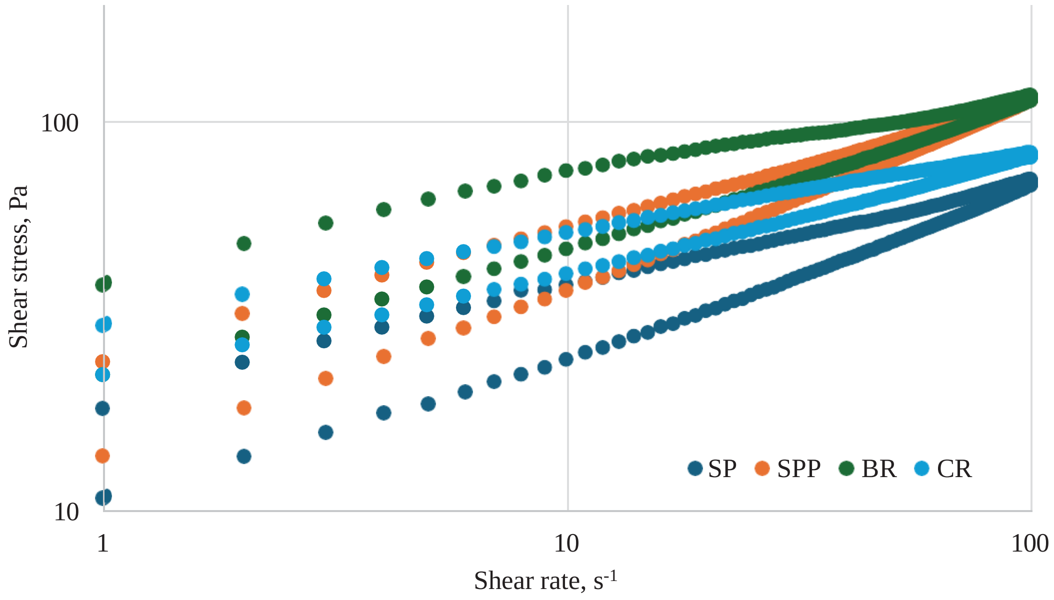

Figure 2. Flow curves (shear stress vs. shear rate) for frozen dessert mixes.

changes under applied force (Marimon-Valverde *et al*., 2024).

Since in all samples the same gelatine content was used, this ingredient did not account for differences in the properties of the samples. Instead, higher viscosity can be attributed to a higher content of soluble solids in the formulation (Marimon-Valverde *et al*., 2024).

The BR sample exhibited the highest viscosity, indicating that this sample requires the most force to move. While this sample did not have the highest content of soluble solids, its increased viscosity can be attributed to the composition of its main ingredient. Beetroots are rich in fibre, particularly pectin, which binds water and forms a gel-like structure, leading to a thicker consistency (Hotchkiss *et al*., 2022). It is important to note that a higher content of soluble solids does not always result in increased viscosity. During pasteurisation, the high temperature can enhance molecular motion potentially reducing the viscosity of mixes with high soluble solids content. Additionally, the BR sample's formulation includes more protein than the CR sample, which most likely contributes to its higher viscosity. As the frozen dessert mix cools, the protein molecules form a network-like structure that retains water making the mix thicker (Marimon-Valverde *et al*., 2024).

In contrast, the CR sample was the most fluid, likely due to the high water content in carrots and the formulation using 43% less corn starch compared to the SP and SPP samples. Analysis of the nutritional value (Table 2) reveals that the CR sample has a lower protein content, which affects the content of soluble solids, leaving more free water in the mixture and resulting in more liquid consistency. This is consistent with findings by Marimon-Valverde *et al*. (2024), which indicate that as the content of soluble solids decreases, the viscosity of the mix also decreases.

The viscosity of the SP and SPP samples fell between that of the CR and BR samples. According to Marimon-Valverde *et al*. (2024), these two samples were expected to have the highest viscosity due to their formulation, which includes ingredients rich in fibre, carbohydrates, and proteins. These components contribute to a high soluble solids content, typically resulting in a firm and thick consistency.

As the shear rate increased, the shear stress also increased, and this relationship was consistent across all samples (Figure 2). The viscosity of the dessert mix depended on the shear rate, this behaviour is indicative of pseudoplastic solutions, which exhibit rheological properties that allow them to maintain a liquid consistency when pressure is applied. The uniform increase in shear stress with rising shear rate across all samples, without large fluctuations, further supports the pseudoplastic nature of the dessert mixes (Yu et al., 2021).

Thixotropy, also known as hysteresis, reflects the dessert's ability to restore its structure when the shear rate decreases or changes (Kroger, 2004). Factors that may contribute to an increase in the sample's hysteresis area include the raw materials used (particularly sugar, water or stabilisers), their proportions in the formulation, and the parameters of the technological processes. For all samples (SP, SPP, BR, CR), the hysteresis area (Table 3) was positive, indicating that the mix became more fluid under shear

Table 3

Rheological properties of dessert mixes

Properties	SP	SPP	BR	CR
Apparent viscosity η_∞, mPa s	497.5±5.7[c]	871.1±6.1[a]	600.7±2.9[b]	448.9±9.5[d]
Hysteresis (thixotropic) area A, Pa s^{-1}	841.8±88.6[b]	1010.8±47.9[a]	1020.1±52.7[a]	730.0±79.2[b]
Yield point τ_0, Pa	22.8±2.8[d]	33.4±0.2[c]	37.3±0.1[b]	41.1±1.7[a]

SP – sweet potatoes, SPP – sweet potatoes + potatoes, BR – beetroot, CR – carrot. Data are expressed as mean (n=3) ± standard deviation. Different letters indicate significant differences at p<0.05 in the same row.

force, leading to a loss of structure. The BR sample exhibited the largest hysteresis area, corresponding to its denser consistency, but also showed the weakest ability to recover its original form after the shear force was removed.

Physical and rheological properties of frozen desserts

Microstructure. The microstructure of the frozen desserts was analysed using light microscopy, revealing key components such as the matrix or serum, air bubbles, and lamella. Microstructural properties are closely linked to processes such as homogenisation, pasteurisation, mix aging, as well as rheological and physical characteristics such as viscosity, foaming, and the choice of raw materials in the formulation. Among these factors, temperature plays a crucial role in determining the crystallisation behaviour during the ice cream manufacturing process (Hossain *et al.*, 2021). In high-quality frozen desserts, the diameter of air bubbles typically ranges from 20 to 50 µm, while fat globules measure between 0.4 and 2.0 µm (Goff, 2002). The average values from 50 measurements are summarised in Table 4.

The diameters of air bubbles in the SP, SPP, and CR, samples fall within the levels for ice cream 20 to 50 µm (Goff, 2002). The CR sample exhibited the thickest lamella and the largest diameter of air bubbles while the SPP sample had the smallest air bubbles.

Smaller, more uniform air bubbles contribute to increased viscosity after melting and enhance the sensory properties of the product, resulting in a creamier texture and slower melting (Goff, 2002). This effect was confirmed by the viscosity measurements for the BR and SPP samples, though the viscosity for the SP sample was expected to be higher. Additionally, smaller and more uniform air bubbles are influenced by overrun; higher overrun typically leads to smaller and more uniform air bubbles. The air bubble sizes in the SP, SPP, and BR samples were within the expected range, consistent with literature on overrun (Daw & Hartel, 2015).

The largest air bubbles, with the thickest lamella, were observed in the CR sample (74.35±21.28 µm), indicating that this sample's structure is the least stable and homogeneous, despite the same technological process. According to El-Hadad *et al*. (2020) it can be concluded that low overrun may lead to larger air bubbles in CR sample.

The air bubble diameters and lamella thickness in the SP, SPP, and BR samples, align with other research results (Zagorska *et al.*, 2022). The most important rheological parameters that affect the size of air bubbles and their thickness of lamella are viscosity and overrun. The viscosity of the SP sample was notably lower than expected.

Overrun. Air plays a crucial role in the foaming of frozen desserts, significantly affecting both the rheological properties (such as melting and hardness) and the sensory qualities of the final product (Goff, 2002).

Table 4

Microstructural components of frozen dessert

Parameter	Samples			
	SP	SPP	BR	CR
Diameter of air bubble, µm	24.26±8.27[a]	20.50±8.91[a]	31.58±16.42[a]	71.35±21.28[b]
The thickness of air bubble lamella, µm	6.52±3.13[a]	5.98±2.78[a]	12.70±8.55[a]	14.28±5.43[a]

SP – sweet potatoes, SPP – sweet potatoes + potatoes, BR – beetroot, CR – carrot. Data are expressed as mean (n=50) ± standard deviation. Different letters indicate significant differences at p<0.05 in the same row.

Table 5

Physical properties of frozen desserts

Properties	SP	SPP	BR	CR
Overrun, %	14.37±2.00[b]	18.63±**3.00**[c]	59.41±**5.00**[d]	1.25±0.05[a]
Melting rate, g min^{-1}	0.02±0.001[a]	0.02±**0.001**[a]	0.02±**0**.001[a]	0.07±0.001[b]
Hardness, N	64.90±15.40[b]	68.15±18.07[b]	19.71±2.79[a]	161.00±32.64[c]

SP – sweet potatoes, SPP – sweet potatoes + potatoes, BR – beetroot, CR – carrot
Data are expressed as mean (from triplicates) ±standard deviation. Different letters indicate significant differences at p<0.05 in the same row.

During the study, overrun – the measure of air incorporated into the product during preparation – was assessed (Table 5). In high-fat ice creams overrun can range from 50% to 100%, while in low-fat ice creams, it may only reach 10% to 15% (Clarke, 2012), which coincides with the desserts developed in this study. The low overrun in the CR sample could be explained by the high free water content in a mix and the high crude fibre content in carrots (Sharma et al., 2012), which have no foaming properties. The same tendency was found in the dessert mix, the lowest viscosity was in the CR sample (Figure 1). A high overrun contributes to a fuller flavour, but if the overrun is too high, the dessert may taste bland or "empty." Ideally, the overrun should not exceed more than three times the total solids content of the product, as this helps to ensure that the frozen dessert melts slowly. In the current research, overrun in all analysed samples, except BR sample, was 2.0 times (SP), 1.3 times (SPP), 14.0 times (CR) lower, respectively, higher than solid content in frozen desserts. Conversely, low overrun results in a dense, solid structure where ice crystals may be detectable (Silantjeva *et al*., 2022however, as consumers are watching their calorie intake, ice cream is starting to lose its leading position due to rich fat content. Therefore, development of low-fat or non-fat ice cream can provide a good alternative for consumers. At the same time, reduced fat is a challenge to a producer because it strongly affects the texture and sensory properties of ice cream. The aim of the current study was to assess the physicochemical and rheological properties of whey-based non-fat ice cream, depending on the ingredients used in the formulation. In total, 11 ice cream formulations were developed and evaluated, with differing proportions of the main ingredients. Chemical composition, hardness (after6hof hardening and subsequent two-week storage; Sofjan & Hartel, 2004).

This study evaluated the effect of different raw materials on the overrun of frozen desserts. The overrun results are consistent with those of da Silva *et al*. (2020) medium-chain inulin, oligofructose and polydextrose, 5 g/100 g, with the highest overrun (59.41 ± 0.65%) observed in the BR sample. Since the quantities of other raw materials across all formulations were nearly identical and the technological process remained consistent, the high overrun in the BR sample is probably due to the chemical composition and variety of beetroot used. Beetroot is rich in both soluble and insoluble fibres, with a particular emphasis on soluble fibres such as pectin (Hotchkiss *et al*., 2022).

Although the same amount of skimmed milk powder was added to all four samples, the physico-chemical analysis revealed that the CR sample contained 8.20 ± 0.94 g of protein per 100 g, while

Table 5

Physical properties of frozen desserts

Properties	SP	SPP	BR	CR
Overrun, %	14.37±2.00[b]	18.63±3.00[c]	59.41±5.00[d]	1.25±0.05[a]
Melting rate, g min^{-1}	0.02±0.001[a]	0.02±0.001[a]	0.02±0.001[a]	0.07±0.001[b]
Hardness, N	64.90±15.40[b]	68.15±18.07[b]	19.71±2.79[a]	161.00±32.64[c]

SP – sweet potatoes, SPP – sweet potatoes + potatoes, BR – beetroot, CR – carrot
Data are expressed as mean (from triplicates) ±standard deviation. Different letters indicate significant differences at p<0.05 in the same row.

the SP, SPP, and BR samples each had more than 11 g per 100 g. Additionally, the CR sample had the lowest carbohydrate content, contributing to a lower solids content and a more fluid consistency in the dessert. Previous research suggests that in formulations lacking high fat ingredients, it is advisable to replace them with high protein or high carbohydrate ingredients (Genovese et al., 2022). The CR sample's lower overrun may be due to its insufficient protein and carbohydrate content, which also affected its soluble solids content, potentially leading to increased ice crystal formation (Hossain *et al.*, 2021) a commercial microparticulated whey protein (MWP.

For the SP and SPP samples, there was a significant difference in overrun ($p<0.05$), with SPP showing an increase in foaming despite the SP sample having a higher soluble solids content. A possible explanation for this could be the starch content in the raw materials used for dessert production. Both sweet potatoes and potatoes contain high levels of starch *(Kince et al.*, 2023which is not suitable for celiac patients who require a gluten-free diet. Potatoes are known as a good source of starch, minerals and vitamins. They also contain protein, dietary fibre and various phytochemicals. Their addition to pastry cream can both serve as a texturising agent and enrich the nutritional value of the final product. This study aimed to evaluate the suitability of potatoes as a replacement for wheat flour in pastry cream. For study purposes, the physicochemical attributes of eleven potato varieties were evaluated. Among other varieties, the boiled potato variety Gala exhibited higher fibre, fat, phosphorus and potassium content; however, significantly higher protein (12.48 ± 0.08 g 100 g^{-1} DW; Sharma *et al*., 2012), which has been used for decades as a foaming agent in ice cream production. This outcome may suggest that an excessively high solids content in the frozen dessert mix may limit overrun.

Hardness

Freezing, hardening, and storage are all critical stages in the development of frozen desserts. Rapid freezing is essential as it promotes the formation of smaller ice crystals in the final product. During the hardening process, 75–80% of the free water in the frozen dessert solidifies. Once solidified, it is important to avoid temperature fluctuations, as this can lead to rapid ice crystal growth (VanWees *et al*., 2020). Frozen desserts should be stored between -18 °C and -25 °C.

The formation of ice crystals, which can result in a harder product structure, is influenced not only by temperature, but also by the choice and proportions of raw materials in the formulation, resulting in the free water content of a frozen dessert. The quality of frozen desserts can be affected by stabilisers and other ingredients that impact water binding capacity (Góral *et al*., 2018).

All samples were produced according to the same technological process, meaning that maturation, freezing, hardening and storage were consistent and could not have influenced the differences in hardness. However, the hardness for the SP, SPP, BR, and CR samples varied significantly ($p<0.05$).

The relatively high hardness observed in the CR sample can be attributed to its low overrun (Table 5), which results in a dense and icy product structure. This higher hardness is also likely related to the chemical composition of the product and used ingredients (Hossain *et al*., 2021); the CR sample had the lowest dry matter content (18%) among all analysed samples. It can be concluded that a lower carbohydrate content in the formulation contributes to a harder structure of frozen desserts. Carbohydrates play a crucial role in frozen dessert production, as they create a creamy consistency by binding water, which helps prevent icy, solid structure formation (Soukoulis & Tzia, 2018).

Melting behaviour of frozen plant-based desserts

Rheological properties. Figure 3 provides a detailed analysis of the frozen dessert samples observing product at three stages:
-7 ºC, -7 °C to 0 ºC, and 5 ºC. According to Mezger (2018), these three stages (solid, melting, and molten) are crucial to consumers during dessert consumption. All samples demonstrated elastic behaviour during the measurements, indicating that the frozen desserts possess a gel-like structure ($G' > G''$).

The frozen dessert is placed on a rheometer at an initial temperature of -7 ºC. At this stage, the dessert should remain solid yet portionable. The BR and CR samples exhibited the highest values of storage modulus G´, suggesting that these samples will be more difficult to divide into portions. In contrast, the SP sample showed the lowest storage modulus G, likely due to its higher carbohydrate and solids content. This composition may reduce the amount of free water, resulting in a softer texture (Silantjeva *et al*., 2022) however, as consumers are watching their calorie intake, ice cream is starting to lose its leading position due to rich fat content. Therefore, development of low-fat or non-fat ice cream can provide a good alternative for consumers. At the same time, reduced fat is a challenge to a producer because it strongly affects the texture and sensory properties of ice cream. The aim of the current study was to assess the physicochemical and rheological properties of whey-based non-fat ice cream, depending on the ingredients used in the formulation. In total, 11 ice cream formulations were developed and evaluated, with differing proportions of the main ingredients.

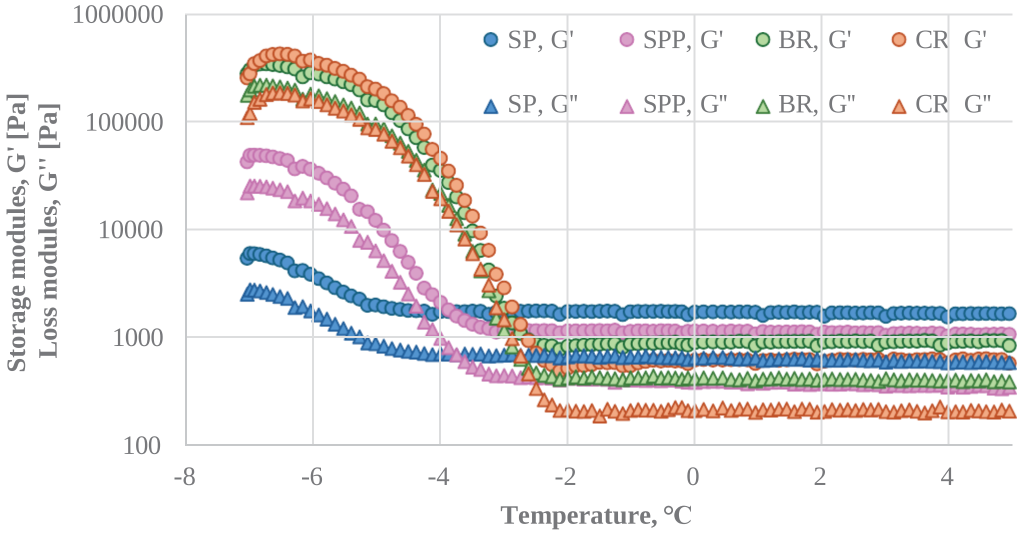

Figure 3. Steady shear rheological behaviour of frozen desserts.

Chemical composition, hardness (after6hof hardening and subsequent two-week storage; Muse & Hartel, 2004).

Within the melting range of frozen desserts, there is a decline in the values of G´ and G´´, which influences the consumer's sensory experience while enjoying desserts (Zagorska *et al*., 2022). A rapid decrease in these indicators can result in an unpleasant cold sensation in the mouth. According to Kurt & Kahyaoglu (2017), a slower decrease indicates a broader melting range, allowing the consumer to perceive the dessert as cooler and more enjoyable.

Once the dessert has melted and its temperature exceeds 0 °C, a higher storage modulus value is associated with a creamier consistency, giving the impression that the sample is richer in fat (Zagorska *et al*., 2022; Kurt & Kahyaoglu, 2017). Among the four samples, the SP sample had the highest G´ value, indicating a thicker consistency.

Melting rate. As the frozen dessert melts, heat from the surrounding warm air transfers into the dessert causing ice crystals to begin melt. Initially, the ice melts from the outer layers, creating a localised cooling effect. The water released from the melting ice must then diffuse into the viscous unfrozen serum phase. This diluted solution flows downward by gravity through the dessert's structural elements - air cells, and remaining ice crystals – and eventually drips through the sieve on which the dessert is placed during analysis.

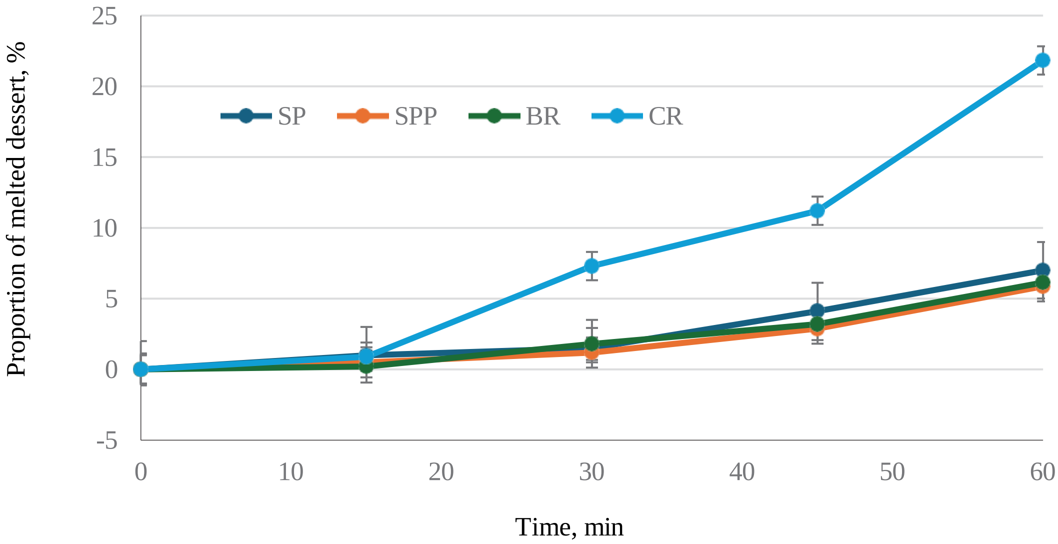

Figure 4. Melting rate of frozen desserts.

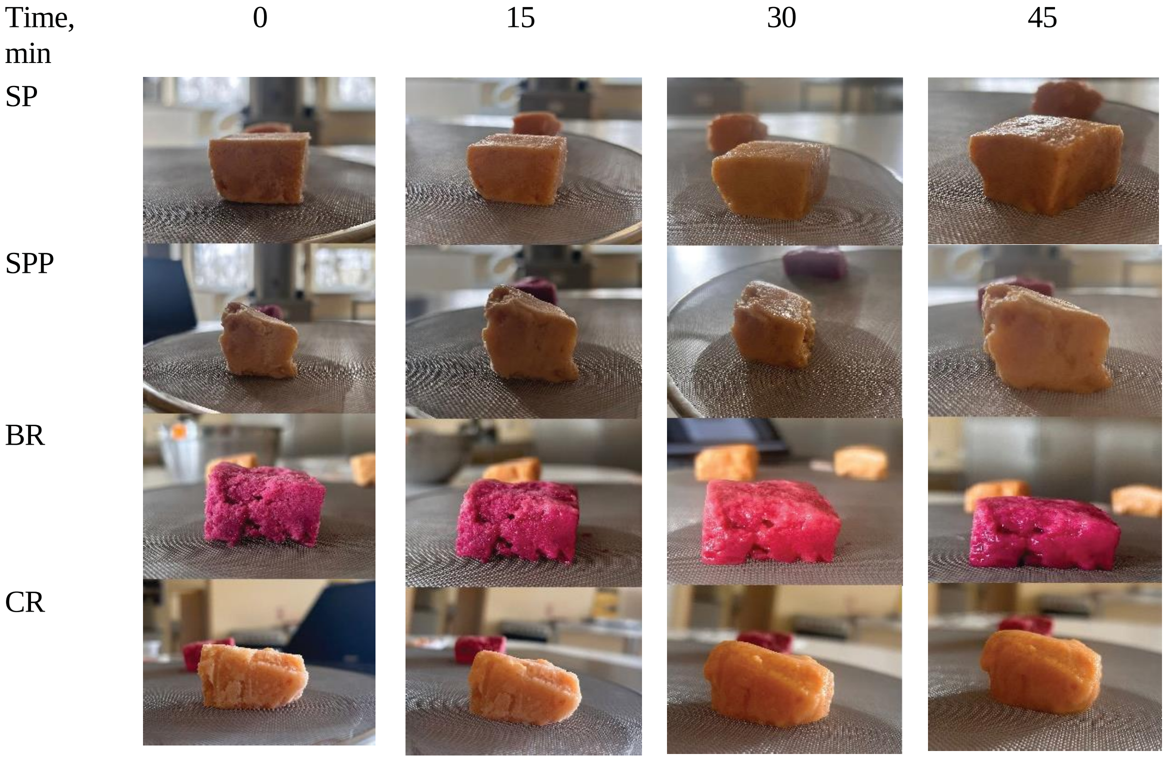

Figure 5. Photographs of the frozen dessert melting process.

As more heat penetrates the dessert and melts the ice crystals deeper within, the diluted solution begins to flow from the inside as well. The rate at which a dessert melts can be affected by several factors, including overrun, and the size of the ice crystals and fat globules. Frozen desserts with lower overruns tend to melt faster, while those with higher overruns melt more slowly due to their greater resistance to melting. The slower melting rates for high-overrun frozen desserts are often attributed to reduced heat transfer rates, resulting from the large air volume. Additionally, these desserts may have a more complex structural path that slows the flow of the melted solution (Muse & Hartel, 2004).

The melting rate analysis for all samples was conducted at 23±2 °C with an initial sample temperature -20 **°C** weight 20.1±0.08 g. The dynamics of the frozen dessert melting process are given in Figure 4.

As shown in Figure 4, all analysed samples melted very slowly in the first 15 minutes and retained their shape (Figure 5). The SP, SPP, and BR samples melted evenly and uniformly over 60 minutes. While the melting rate increased in the last 15 minutes for these samples, they lost ~ 3.0% by the end of 60 minutes.

The CR sample also melted slowly and maintained its shape during the first 15 minutes. However, after this period, the melting rate accelerated rapidly until the end of the analyses, resulting in a 21.8% loss of its initial mass. Despite losing the most mass of the sample, the CR sample had not completely melted after 60 minutes.

All samples (SP, SPP, BR, CR) exhibited slow melting in the first 15 minutes, with an average melting rate of just 0.1 g min^{-1}. The SP, SPP, and BR showed no change in shape even after 30 minutes with an average melting rate of 0.3 g min^{-1}, indicating a slight acceleration. After 45 minutes, these three samples began to develop a shiny surface, indicating ice melting (Figure 5). The average melting rate increased to 0.7 g min^{-1} at this stage which is 2.5 times faster than earlier; however, according to the literature, ice creams with low solid content melt more quickly. After 60 minutes, the SP sample had lost 17.0%, the SPP sample 6.1%, and the BR sample 5.9% of their initial mass. According to Liu *et al.* (2022), the melting rate for this type of frozen dessert should be higher than observed in the current study. The melting rate of frozen desserts is often affected by fat destabilisation; fat globules help support air bubbles, form fat networks in ice creams and ice crystal melting (Liu *et al*., 2022).

Conclusions

Plant-based ingredients significantly affected the hardness and foaminess of frozen desserts, depending on their chemical composition. Incorporating vegetables into frozen desserts offers a way to reduce sugar and fat content, providing a healthier alternative to traditional sweet sorbets. Each vegetable used (sweet potato, beetroot, carrot, and potato) influenced the viscosity of the dessert mix and affected the melting behaviour, with significant differences found in the carrot-based samples.

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