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Influence of Plant-Based Structuring Ingredients on Physicochemical Properties of Whey Ice Creams

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Abstract: The dairy industry is actively seeking new applications for various types of whey. One promising direction is the development of nutritious ice cream, using a blend of different whey proteins. However, the production of whey ice cream is hindered by the occurrence of quality issues, primarily stemming from a low content of solids, particularly fat and protein. The development of natural components with distinctive technological attributes, such as the ability to bind excess moisture, enhance foaming properties, and replicate the taste of milk fat, is of significant relevance in food science. In this work, we investigated the influence of plant-based structuring ingredients on the viscoelastic characteristics of whey-based ice creams. Notably, mixes such as 0.4% Vianoks C45 + 0.75% oat β-glucan, 0.4% Vianoks C45 + 0.5% yeast β-glucan, and 0.4% Vianoks C45 + 3% whey protein complex + 10% vegetable purée from table beet have been proven to be effective stabilizing compositions. However, attempts to combine the whey protein complex with other types of vegetable purées like zucchini and broccoli did not yield satisfactory results. It has also been found that β-glucan from the yeast *Saccharomyces cerevisiae* and κ-carrageenan, a component of the Vianoks C45 stabilization system, forms a robust gel within the system. Analysis of the aqueous phase in whey-based ice creams revealed a consistent correlation between water activity, surface tension, and rheological behavior. Finally, the ice creams that exhibited the best viscoelastic characteristics also had the best sensory attributes.

Keywords: whey; ice cream; rheology; β-glucan; proteins; vegetable purée

Citation: Tomczyńska-Mleko, M.; Mykhalevych, A.; Sapiga, V.; Polishchuk, G.; Terpiłowski, K.; Mleko, S.; Sołowiej, B.G.; Pérez-Huertas, S. Influence of Plant-Based Structuring Ingredients on Physicochemical Properties of Whey Ice Creams. *Appl. Sci.* **2024**, *14*, 2465. https://doi.org/10.3390/app14062465

Academic Editors: Anna Lante, Katarzyna Marciniak-Lukasiak, Anna Zbikowska and Piotr Lukasiak

Received: 11 December 2023
Revised: 26 February 2024
Accepted: 8 March 2024
Published: 14 March 2024

1. Introduction

Whey ice cream is a frozen dessert made from sweet or acid whey, often enriched with vegetable or fruit juices, lactic acid bacteria, and flavoring additives [1,2]. Whey-based ice cream typically exhibits a low solid content, which can potentially result in consistency and taste issues during storage [3,4]. For instance, while dry sweet whey has been effectively employed in ice cream at low concentrations, the use of larger quantities has been observed to result in a sandy texture, possibly due to lactose crystallization [5]. The formation of ice crystals plays a pivotal role in determining the final quality of ice cream. Obtaining suitable crystal sizes and distribution is critical to achieve the desired texture of the final product [6]. Thus, the exploration of natural ingredients that can efficiently bind free water and prevent excessive crystallization during both the mix freezing process, as well as subsequent low-temperature storage, becomes significantly relevant for the quality of these ice creams.

Milk protein concentrates play a vital role in ice cream production, as they can effectively bind a portion of free water in ice cream mixes, provide structure, enhance the dispersion of air bubbles, thereby promoting the formation of small ice crystals, stabilize the product during storage, and increase both overrun and resistance to melting [7,8]. Furthermore, these proteins have an important technological function in formulations with high water content and low-fat content (0.5–5.0%) [9]. Ice creams with low solid content, including those with low-fat content, often experiences a significant decline in sensory characteristics, especially the loss of their creamy taste and consistency. The utilization of milk protein concentrates and stabilization systems in ice cream production allow for the attainment of ice cream with specific quality standards and elevates its nutritional value [10]. Also, this combination reduces the reliance on stabilizers or stabilization systems, which tend to incur significantly higher costs compared to protein-based ingredients.

One of the most popular milk protein concentrates in the food ingredient market is whey protein, derived through various methods of processing milk whey [11]. Whey powder serves as a source of milk solids and is known for its relatively lower cost compared to other whey protein ingredients. However, it contains high levels of lactose and minerals, which can have a detrimental impact on taste. The use of whey powder in food applications is limited not only by its distinct sensory properties but also by its adverse effects on certain technological processes [12,13]. Nevertheless, when subjected to specific processing, whey exhibits functional and technological properties that can prove valuable in the production of ice cream and frozen desserts [14]. Recent research by Ukrainets et al. [15] revealed that enriching whey powder with manganese (Mn) and magnesium (Mg) through electro-spark treatment alters its technological characteristics, thereby positively influencing the quality of bakery products. However, the impact of enriched whey powder in ice cream production remains unexplored, sparking interest in investigating its technological functions within the recipe composition of this product.

The use of demineralized whey powder is a more suitable choice due to its widespread availability and relatively low cost [16]. One of its primary advantages, as opposed to regular whey powder, is its higher protein content, typically ranging from 10% to 12%, which holds particular significance in the production of low-solid ice cream [17,18]. Highly demineralized whey powder, exceeding 90% demineralization, has a range of technological benefits, including exceptional solubility, low hygroscopicity, a predictable impact on sensory and physicochemical parameters due to its standardized chemical composition, and the ability to produce high-quality products from various types of whey. However, for more effective water binding, highly refined whey protein concentrates are employed [19,20]. Research by Akalın et al. [2] revealed that whey protein isolate (at a concentration of 4%) substantially elevated the viscosity of low-fat ice cream mixes (with fat content ranging from 3% to 6%). Additionally, Pandiyan et al. [21] found that the use of whey protein concentrates not only increased the protein content and nutritional value of ice cream but also allowed for the substitution of less technologically efficient ingredients, such as skimmed milk powder.

Simultaneously, combinations of milk protein concentrate with fruit-berry pectin-containing raw materials exhibit heightened technological effectiveness in ice cream production [22,23]. Rather than employing synthetic fillers, cost-effective vegetable byproducts, such as broccoli, zucchini, beets, and others containing pectin compounds, are commonly used in conjunction with proteins to create surface-active complexes [24,25]. Thus, numerous companies specializing in innovative ice cream technology offer milk-protein concentrates and polysaccharides or protein-polysaccharide blends to mimic the properties of milk fat [26]. Plant-based ingredients, such as β-glucan, have also garnered attention for their potential utility in ice cream. Depending on their source and production method, β-glucans may serve as biologically active additives and/or technological agents [27]. Particularly, oat β-glucans, derived from cereal grains, feature linear polysaccharide structures linked by (1→3) (1→4) carbon bonds, allowing them to form a cluster-like structure until a critical concentration is achieved, imparting a degree of plasticity [28,29]. This characteristic underscores the promise of oat β-glucan in ice cream production. In contrast, information about the functional and technological attributes of β-glucans from yeast, edible mushrooms, and algae remains limited [27], and their application in ice cream and frozen dessert technology has not been explored previously. In ice cream technology, especially for low-fat variants, β-glucans can fulfil multiple roles: (i) enhancing the product with dietary fiber [30]; (ii) efficiently binding free water [31]; (iii) reducing the freezing point of the mixes to prevent excessive freezing during the ice cream's preparation and long-term storage [32]; (iv) limiting the size of ice crystals during storage [4,33]; (v) increasing overrun and resistance to melting [3,34]; (vi) ensuring even distribution of the air phase throughout the product during freezing [35]; and (vii) contributing to a unique taste profile, particularly a milky one [3]. All these characteristics made β-glucans a good candidate to explore its use for further purposes.

In the light of the above, this study investigates the influence of natural stabilizing ingredients of vegetable origin—particularly, beets, zucchini, broccoli, and β-glucan from yeast and oat— on the functional and technological properties of whey-based ice creams. Four different types of whey protein, i.e., demineralized, manganese enriched, concentrate, and isolate, were used for the ice cream production. A comparative analysis of their viscoelastic properties, water activity, and surface tension was conducted to determine the most effective stabilizing composition. Furthermore, a sensory evaluation of the ice creams was carried out.

2. Materials and Methods

2.1. Materials

The primary ingredients used for the production of control ice cream included: demineralized whey powder 90% (JSC "Milk Alliance", Kyiv, Ukraine), a stabilization system Vianoks 45 (mono- and diglycerides of fatty acids (E471), guar gum (E412), locust bean gum (E410), and carrageenan (E407)) (VianoKs, Kyiv, Ukraine), sugar, and water. Additional ingredients such as whey powder enriched with manganese [35], 70% whey protein concentrate (Hadyach, Ukraine), 90% whey protein isolate ("Spomlek", Radzyń Podlaski, Poland), 70% oat β-glucan (AMULYN, China), 70% yeast β-glucan (*Saccharomyces cerevisiae*) ("GOLDCELL", Biorigin, Sao Paulo, Brazil), and fermented vegetable purées made from beets, zucchini, and broccoli were selected to assess their impact on whey-based ice creams.

2.2. Preparation of Samples

Dry ingredients were combined according to the recipe (Table 1), and reconstituted in water at atemperature of 40–45 °C. The mixture was pasteurized at 85–88 °C for 3–5 min in a beaker with a constant mixing using a magnetic stirrer, then cooled to 60–65 °C. Subsequently, the mixture was homogenized using an Unidrive X1000 laboratory homogenizer (Ingenieurbüro CAT M. Zipperer) at a speed of 15,000 rpm. The homogenized mixes were further cooled to 42 °C, and, if required, vegetable purées were incorporated, followed by a mixing duration of 1–2 min. The vegetable purées were obtained by grinding blanched vegetable pieces in a laboratory homogenizer with cutting knives at a speed of 15,000 rpm for 3–5 min. This resulted in purées with particle sizes not exceeding 0.001–0.002 m. Fermentation of vegetable purées was carried out using pectinase Pectolad (ENZIM DE, Ladyzhin, Ukraine) with a pectolytic activity of at least 30 units/g. The process parameters were as follows: content of pectinase—0.1%; temperature—40 °C; duration—2 h; pH—4.0. After fermentation, the enzyme was inactivated by heating the vegetable +-*purée to 90 °C without holding. The mixes were left to ripen for 24 h. The ripened mixes were frozen using an FPM-3.5/380-50 "Elbrus-400" periodic freezer ("ROSS" JSC, Kharkiv, Ukraine). First, the mix was cooled in a cooling cylinder (volume—7 L) to −1 °C for 120 s at a scraper stirrer rotation frequency of 4.5 s^{-1}. In the second step, the mix was frozen to −5.0 °C for 180 s. at a rotation frequency of 9 s^{-1}.

Table 1. Whey ice cream formulations.

Ingredient	Content (%)								
	S.1	**S.2**	**S.3**	**S.4**	**S.5**	**S.6**	**S.7**	**S.8**	**S.9**
Whey powder	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
White sugar	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
Stabilization system	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Oat β-glucan	–	0.75	–	–	–	–	–	–	–
Yeast β-glucan	–	–	0.5	–	–	–	–	–	–
Protein complex	–	–	–	3.0	4.5	3.0	4.5	3.0	4.5
Beet	–	–	–	10.0	10.0	–	–	–	–
Broccoli	–	–	–	–	–	10.0	10.0	–	–
Zuchinni	–	–	–	–	–	–	–	10.0	10.0
Water	75.60	74.85	75.10	62.60	61.10	62.60	61.10	62.60	61.10

The whey-based ice cream formulations are presented in Table 1.

The choice of a 0.4% content for the stabilization system was in line with the manufacturer's recommendations for the production of low-fat ice creams. The doses of oat β-glucan (0.75%) and yeast β-glucan (0.5%) were chosen based on findings from previous studies that investigated the effect of β-glucan content on the physicochemical properties and sensory attributes of low-fat ice cream formulations [1,3,36]. For the whey protein complexes (WPCs), a balanced ratio of 1:1:1 (whey powder enriched with Mn, whey protein concentrate 70%, and whey protein isolate 90%) was utilized.

2.3. Characterization of Ice Cream Mixes

Total solid content was determined by the arbitration method. This involves drying an ice cream mix sample diluted with distilled water and mixed with sand at 102 °C until a constant mass is achieved. The residue is then weighted to determine the total solid content. The fat content was determined by the adapted Gerber method [37]. Briefly, this method measures fat using a butyrometer containing sulfuric acid and isoamyl alcohol, which produces a reaction and provides a reading of the fat percentage. The protein content was quantified using the Kjeldahl method [38], a three-step approach involving digestion, distillation, and titration to determine the protein content. The viscosity of whey ice cream mixes was measured with an ultrasonic viscometer (UNIPAN, model 305, Warsaw, Poland). Before each measurement, the level of the ultrasonic signal was checked. The measuring probe of the magnetostrictive vibrator was completely immersed in the ice cream mix. The induced ultrasonic waves were damped by the test material, and the results were displayed as the product of viscosity and density in units of $mPa \times s \times g \times cm^{-3}$. Viscosity was determined at 20 °C [39].

Viscoelastic behavior measurements of ice cream mixes were conducted using plate geometry on a Kinexus lab+ device (Malvern, UK). Two serrated plates with a diameter of 0.044 m were used to minimize the slippage effect, and the gap between them was 0.002 m. The tests were performed in the range of 0.1–10.0 Hz at a strain of 0.01%, and changes in the storage (G') and loss (G'') moduli, as well as the phase angle (ϕ), were recorded. The research was conducted at 25 °C. The measurement results were registered on a computer in the Kinexus Malvern—rSpace program [40].

Surface tension was measured with a KSV Sigma 700 tensiometer (KSV Instruments, Ltd., Finland). This device registers and analyzes the forces acting on the sample using sensitive microbalances. The force registered by the scales is directly converted to surface tension using a platinum de Nooy ring. The dynamic surface tension was calculated using the Sigma 700 Force software complex. Before each analysis, the de Nooy ring was cleaned with distilled water and dried under a flame.

Water activity (aw) was measured using an AWMD-10 water activity meter (NAGY, Gäufelden, Germany) with an accuracy of ±0.001 aw unit. Prior to measurement, the device was calibrated according to a special humidity standard (95% HR). Measurements were performed at 20 °C.

A sensory analysis was carried out in accordance with ISO 22935-3:2009 [41]. The analysis considered the following sensory indicators: color, appearance, aroma, consistency, and taste. A panel of 12 experts, comprising six females and six males aged between 25 and 40 years, assessed these parameters using a 5-point scale (1—bad, 2—acceptable, 3—good, 4—very good, 5—excellent). The samples were presented in 50 mL plastic containers and evaluated at 24 ± 1 °C. The sensory analysis was conducted in three panel sessions.

Diagrams were created using the Microsoft Excel 2019 program. Data are expressed as mean with standard deviations (±SD), and differences between groups were assessed using Tukey's HSD test in "R" (version 4.3.1). The reliability of the obtained results was ensured by repeating the study three times.

3. Results and Discussion

3.1. Chemical Composition of Ice Cream Mixes

The chemical composition of whey-based ice cream mixes is given in Table 2.

Table 2. Chemical composition of ice cream mixes.

Sample No.	Total Solid (%)	Protein (%)	Fat (%)
1.	24.05 ± 0.53 ^{a}	0.75 ± 0.01 ^{a}	0.51 ± 0.01 ^{a}
2.	24.81 ± 0.28 ^{a}	0.79 ± 0.01 ^{a}	0.52 ± 0.01 ^{a}
3.	24.57 ± 0.55 ^{a}	0.76 ± 0.02 ^{a}	0.51 ± 0.01 ^{a}
4.	29.53 ± 0.40 ^{a}	2.41 ± 0.09 ^{b}	0.55 ± 0.02 ^{a}
5.	31.02 ± 0.51 ^{c}	3.23 ± 0.12 ^{a}	0.55 ± 0.01 ^{a}
6.	29.38 ± 0.46 ^{a}	2.39 ± 0.05 ^{b}	0.59 ± 0.02 ^{a}
7.	31.16 ± 0.11 ^{c}	3.18 ± 0.13 ^{c}	0.54 ± 0.02 ^{a}
8.	29.32 ± 0.59 ^{a}	2.30 ± 0.07 ^{a}	0.58 ± 0.01 ^{a}
9.	30.95 ± 0.52 ^{b}	3.28 ± 0.04 ^{c}	0.61 ± 0.01 ^{a}

$^{a–c}$—mean values denoted by different letters in the column differ significantly at $p \leq 0.05$.

The ice creams prepared with a protein complex and vegetable purées (samples 4–9) were in the typical range of traditional types of ice cream in terms of solids content (30–40%). Furthermore, the protein additions increased the ice cream mixes protein content to a range of 2.2–3.5%, which is consistent with the protein content typically found in traditional varieties of ice cream [42].

3.2. Rheological Characteristics

The viscosity of ice cream is a crucial factor in achieving the desired consistency of the final product. An increase in the ice cream viscosity hinders the ice crystal growth rate during recrystallization [43]. It depends on the solid content, especially fat, and the distribution of substances within the protein–carbohydrate matrix. Investigating the dynamics of viscosity changes in ice cream mixes under varying intensities of a disruptive force allows for a better understanding of the specificities of the freezing process. During this phase, the structuring of mixes is significantly diminished, but is partially restored after the formation of ice cream portions, thereby influencing the final quality of the product. Figure 1 displays the whey-based ice cream viscosities.

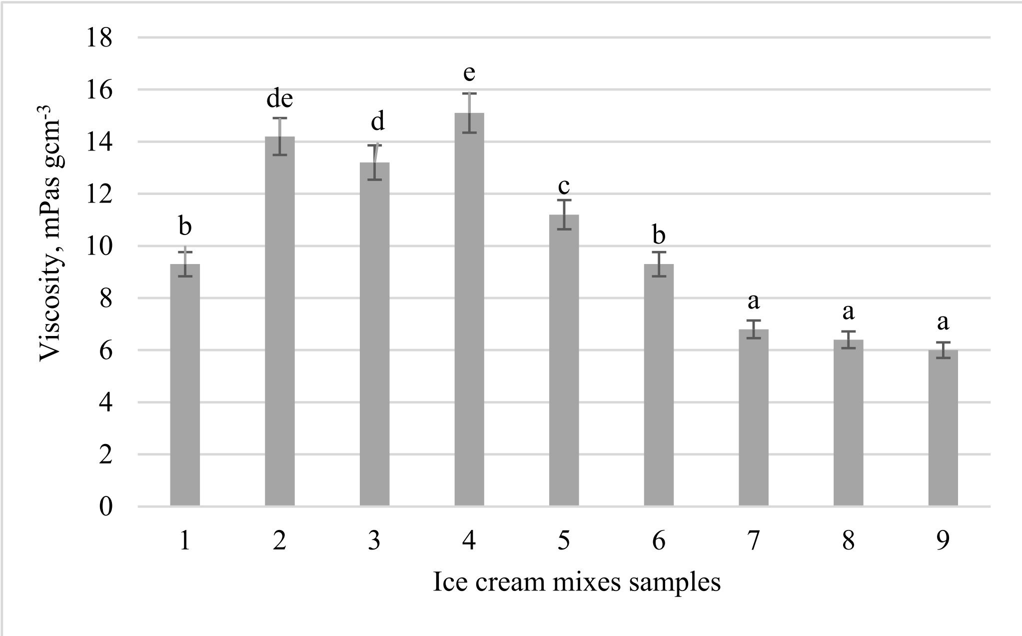

Figure 1. Ultrasonic viscosity of ice cream mixes. The differences between values denoted by different letters (a–e) are statistically significant at $p \leq 0.05$.

Figure 1 shows that the control ice cream had a low viscosity, which can be attributed to its relatively low solid content (Table 2). The addition of β-glucan, either from oat or yeast, to the control mix resulted in a notable increase in the viscosity of the resulting ice creams (sample 2–3). This is a common characteristic of water-soluble polysaccharides, attributed to the restricted mobility of their molecules [44]. The highest viscosity value was achieved with the combination of 0.4% Vianoks C45 + 3% WPC + 10% beet (sample 4). This outcome may be related to the structural changes resulting from the formation of metal complexes between Mn^{2+} ions in enriched whey and pectin substances in beet purée [45]. Thus, the higher viscosity of the beet ice cream, among the samples containing vegetable purées, may be attributed to the larger pectin content in beet compared to that in zucchini and broccoli [46]. It is interesting to note that yeast-derived β-glucan ice cream (sample 3) also exhibited a substantial viscosity increase. Although scientists primarily consider this polysaccharide as a biofortifier [47], these results suggest that it is also an effective thickener and stabilizer. Vyrova and Selezneva [48] proved that β-glucan from baker's yeast plays a pivotal role in structuring low-fat yoghurt mixes, providing the desired viscosity and influencing the product's taste. Compared to oat β-glucan, which is known for its pseudoplastic behavior in dairy systems and can lead to excessive product density [7], yeast-derived β-glucan forms a gel network with moderate strength. These unique properties make yeast-derived β-glucan particularly intriguing for further exploration in ice cream production, especially concerning the freezing process where the mix becomes saturated with air. The lowest viscosity values were obtained for the zucchini ice creams (samples 8, 9), suggesting its limited ability to form structures. Finally, increasing the protein complex content to 4.5% led to a decrease in viscosity for all ice creams. Consequently, β-glucan and combinations of 3% complex mix with beet were found to be the most effective ingredients in improving the texture of the resulting ice creams.

Figure 2 shows the complex viscosity, the storage modulus (G′), loss modulus (G″), and tan delta of samples 1–3. Analysis of the viscoelastic behavior of the control sample reveals the formation of a weak gel, despite the presence of a stabilization system in the control mixture (Figure 2a,b). Hence, the stabilization effect was insufficient and required strengthening. This can be attributed to the ice cream low solid content, which resulted in a high proportion of free water. Addressing this requires the incorporation of ingredients with high moisture-binding capacity in the mixture.

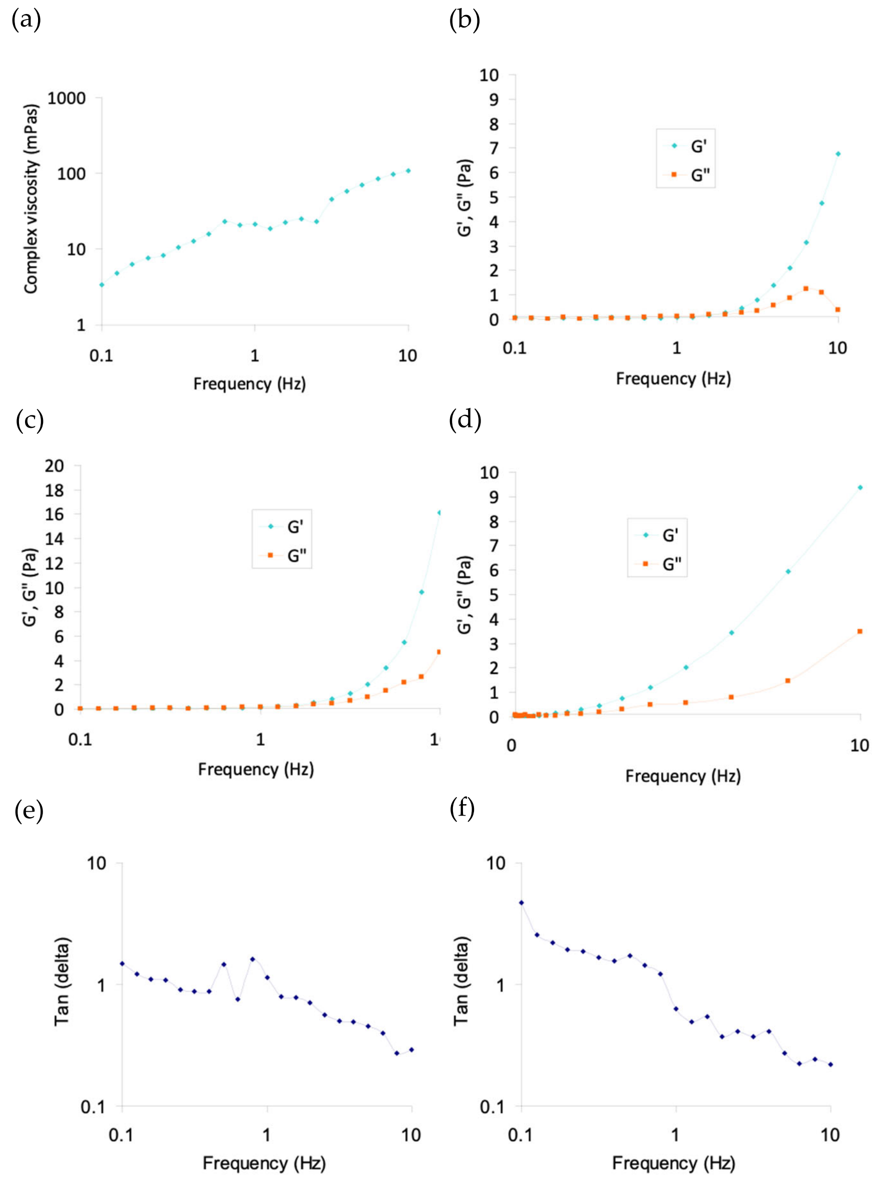

Figure 2. Frequency sweep of complex viscosity and the storage modulus (G′) and loss modulus (G″) of S.1, (**a**,**b**); S.2, (**c**); S.3, (**d**), and tangent of the phase angle of S.2 (**e**), and S.3 (**f**).

Similar changes in moduli values were observed for samples containing β-glucans from oat (Figure 2c) and yeast (Figure 2d). Therefore, although the viscosity increased in both samples with the addition of β-glucan, their rheological characteristics were similar to those of the control ice cream. It is interesting that a more stable system was observed for the sample 3 (Figure 2d). The influence of frequency on the tangent delta of the ice creams containing β-glucans from oat and yeast is shown in Figure 2e,f. Increased frequency caused the samples to behave as elastic materials with a tangent of the phase angle below 1. Furthermore, the tangent of the phase angle decreased with frequency, which is characteristic for food systems when elastic properties predominate over the viscous ones. The samples, in addition to β-glucan, contained κ-carrageenan, which is a component of the Vianoks C45 stabilization system. These two hydrocolloids have the potential to form a synergistic system. Xu et al. [49] studied the microstructure of the gel network formed by κ-carrageenan and β-glucan from brewer's yeast. Small-amplitude oscillatory rheology revealed that while κ-carrageenan plays a dominant role in the formation of the gel network, β-glucan also participates in the creation of energetic bonds that activate the gelation process, especially in mixtures with low κ-carrageenan content. Furthermore, SEM images showed that the β-glucan particles fill the cavity of the κ-carrageenan network, enhancing the rheological properties of the gel of the mixed system. Therefore, it can be assumed that these two polymers may stablish a synergistic stabilization system through the interaction of hydrogen bonds and entanglement between β-glucan particles with κ-carrageenan chains.

Figure 3 shows the elastic (G′) and viscous (G″) components of the ice creams containing vegetable purées, i.e., samples 4–9.

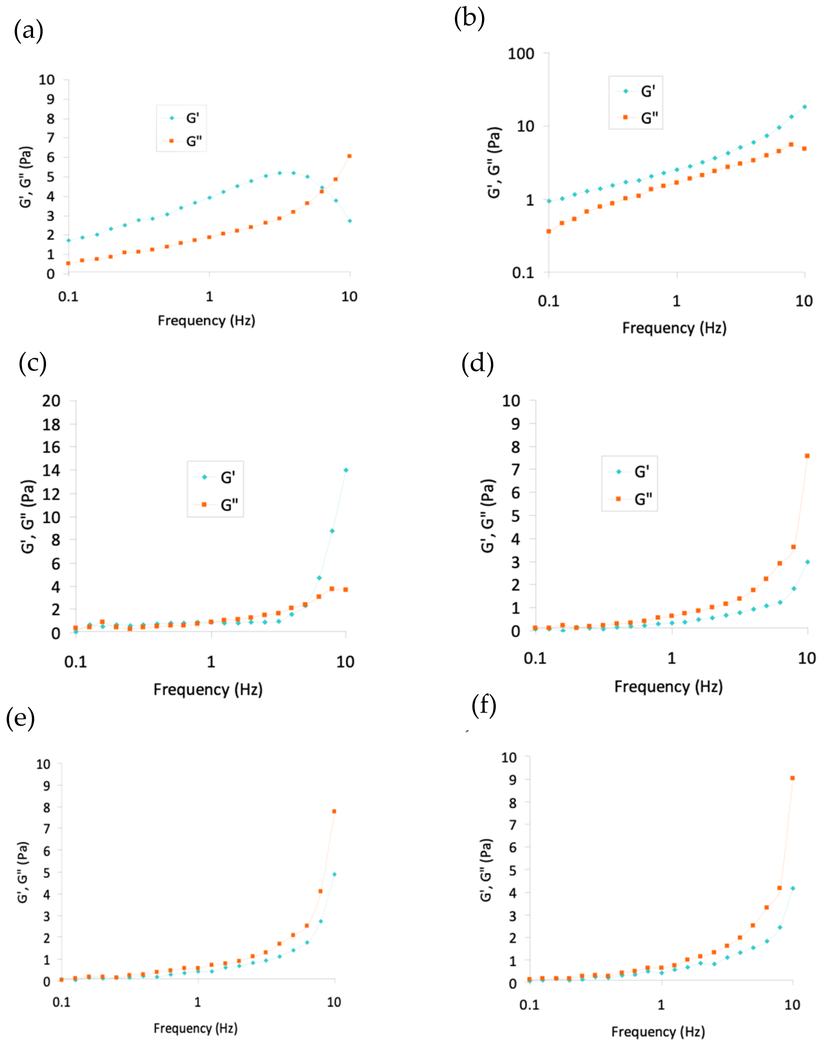

Figure 3. Frequency sweep of storage and loss moduli of S.4, (**a**); S.5, (**b**); S.6, (**c**); S.7, (**d**); S.8, (**e**); S.9 (**f**).

The sample containing 0.4% Vianoks C45 + 3% WPC + 10% beet (sample 4) demonstrated a notable technological effect, which may be attributed to the presence of pectin substances. This is in contrast to the sample with increased protein content to 4.5%, where a certain plasticity of the system during measurement is evident (Figure 3b). Whey protein isolate has the capability to form complexes with pectin substances derived from vegetables, fruits, and berries, resulting in stable polysaccharide–protein agglomerates that contribute to the stabilization of food systems [50]. Furthermore, according to Siew et al. [51], the combination of Mn^{2+} ions with pectin can form gels due to the formation of polymer-metal complexes involving one or two carboxyl groups. Therefore, the observed effect may be attributed to the probable complexation between proteins and pectin in the vegetable purée in the presence of whey enriched with Mn. However, increasing the protein complex content to 4.5% may lead to an undesirable excessive compaction of the final product's consistency.

The rheological properties of the samples containing vegetable purée from broccoli and zucchini are shown in Figure 3c–f. Compared to the previous samples, ice cream containing broccoli and zucchini showed moderate rheological properties with a more viscous-like behavior. This can be attributed to the lower pectin content in these vegetable raw materials [46]. On the other hand, a characteristic entanglement is observed in sample 6 at a certain frequency. However, hydrocolloids chains entanglement is not observed in the sample with increased protein complex concentration (Figure 3d). This was probably caused by a lower mobility of molecule chains at a higher concentration of protein complex. In order to elucidate this characteristic entanglement, Figure 4 shows the complex viscosity and tangent of phase angle of sample 6. At the entanglement point, a sudden increase in storage modulus, complex viscosity, and a decrease in tangent of the phase angle is observed.

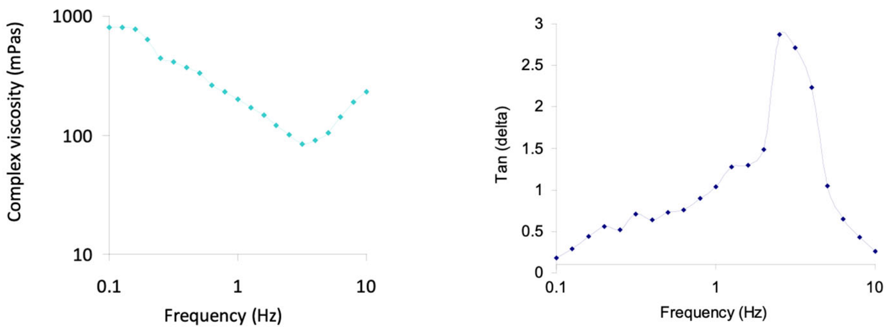

Figure 4. Frequency sweep of complex viscosity (**left**) and tangent of phase angle (**right**) for S.6.

A higher frequency caused a thinning effect by a higher energy input into the system. At the entanglement point, there was a sudden increase in elasticity of the dispersion. This resulted in an increase in complex viscosity and a decrease in the tangent of the phase angle.

3.3. Whey-Based Ice Creams Aqueous Phase Analysis

In order to study the aqueous phase of whey-based ice cream mixes, the surface tension and water activity are shown in Table 3.

Table 3. Surface tension and water activity of whey-based ice cream mixes.

Sample No.	Surface Tension mN/m	Water Activity a_w
1.	46.422 ± 0.748 [ab]	0.969 ± 0.008 [bc]
2.	35.801 ± 0.472 [d]	0.963 ± 0.007 [bc]
3.	36.448 ± 0.305 [d]	0.962 ± 0.004 [c]
4.	39.590 ± 0.451 [c]	0.960 ± 0.005 [c]
5.	40.484 ± 0.815 [c]	0.963 ± 0.006 [bc]
6.	46.609 ± 0.541 [ab]	0.969 ± 0.005 [ab]
7.	46.085 ± 0.885 [ab]	0.968 ± 0.007 [b]
8.	47.228 ± 0.992 [ab]	0.987 ± 0.003 [a]
9.	46.998 ± 1.087 [ab]	0.985 ± 0.007 [a]

[a–d] mean values denoted by different letters in the column differ significantly at $p \leq 0.05$.

The study of surface tension in food systems allows for drawing valid conclusions regarding the physicochemical behavior of emulsifiers and stabilizers. This can provide insight into potential interactions with other ingredients in the formulation, as well as stabilizing factors. A reduction in surface tension promotes emulsion formation and formulation stability from an energetic perspective [52]. A significant decrease in surface tension was observed for the samples with β-glucan, decreasing from 46.422 nM/m (sample 1) to 35.801 nM/m (sample 2), and to 36.448 nM/m (sample 3). This can be attributed to the gel network formed through the interaction of κ-carrageenan and the (1→3) framework with long (1→4), (1→6) chains of β-glucan. In this study, 0.5% of yeast β-glucan, and 0.75% of oat β-glucan were used, which was sufficient to establish a gel network with relative strength. According to Raikos et al. [53], the addition of 0.8% yeast-derived β-glucan can lead to a reduction in the duration of yogurt mix fermentation, resulting in the formation of a robust gel network. Thus, the content used in this study was suitable to form a gel network with relative strength. Gardiner and Carter [54] have highlighted the low solubility of β-glucan from baker's yeast due to its linear structure, potentially leading to complex formation with proteins. Meanwhile, Thammakiti et al. [55] emphasized the effectiveness of β-glucans from brewer's yeast as thickeners, water-retaining agents, and stabilizers in food technology. However, there is a scientific novelty in the application of β-glucans from baker's yeast *Saccharomyces cerevisiae* in whey ice cream technology. Another notable observation is the significant reduction in surface tension in the mix containing 0.4% Vianoks C45 + 3% WPC + 10% vegetable purée from table beets, in contrast to the samples containing broccoli or zucchini purée (samples 6–9), which exhibited surface tension values at or slightly above the level of the control ice cream. These differences may be attributed to both the distinct pectin content in vegetable raw materials, particularly soluble pectin, and the presence of anthocyanins, capable of forming complexes with whey proteins, thereby influencing color and rheological characteristics [56]. Regarding the water activity, the highest values were found for samples 8 and 9, which were also characterized by a tangent of the phase angle close to 1 across the entire frequency range. This means that these samples did not show a gel-like behavior, and therefore, the water was not strongly bound. For other samples, some structurization of the material was noted as the tangent of the phase angle decreased with increasing frequency (Figure 2e,f and Figure 4), which may explain their lower water activities.

3.4. Sensory Evaluation

Figure 5 shows the profiles resulting from the sensory evaluation of the whey-based ice creams. The incorporation of β-glucans to the control mix intensified the sensory characteristics of the resulting samples (Figure 5a). The most significant changes were found in appearance and consistency index. Oat β-glucan provided ice cream with better sensory attributes than yeast β-glucan. In other studies, the incorporation of oat β-glucan to low-fat ice cream formulation also induced changes in the consistency, color, and aroma index of the resulting ice creams [3]. The effect of purée from different vegetables on the sensory attributes of ice creams was also noticeable. The containing beet ice cream exhibited the highest index in taste, color, appearance, consistency, and aroma (Figure 5b). Compared with the control ice cream, Zucchini and broccoli improved the color intensity of the ice creams, but worsened other important sensory attributes such as aroma, and taste. Finally, increasing the whey protein complex content to 4.5% negatively affect the consistency of beet and broccoli containing ice creams (Figure 5c), which is consistent with the rheograms shown in the previous section.

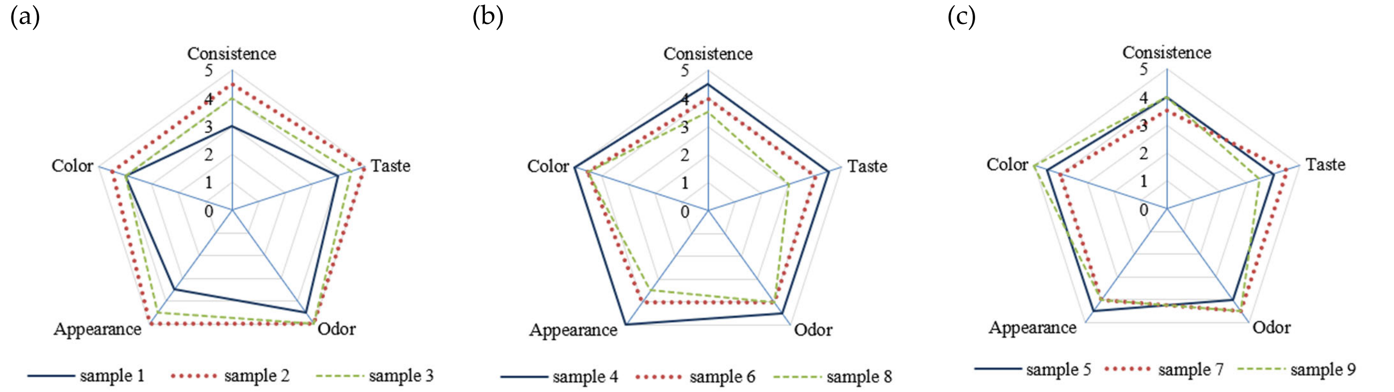

Figure 5. Sensory profiles of whey-based ice cream samples, (**a**–**c**)—comparison of different ice creams based on formulations presented in Table 1 (S.1–S.9).

The following mix compositions were selected based on their potential stabilizing effects, i.e., higher viscosity, lower surface activity, and enhanced rheological properties, as well as sensory attributes for further exploration in the formulation of whey ice cream: (i) sample 2: control mix + 0.75% oat β-glucan, (ii) sample 3: control mix + 0.5% yeast β-glucan, and (iii) sample 4: control mix + 3% WPC + 10% vegetable purée from table beet. It should be noted that the latter sample also corresponds to the average protein content found in traditional types of ice cream.

4. Conclusions

The most effective ingredients for increasing the viscosity of whey-based ice cream were 0.75% oat β-glucan, 0.5% yeast β-glucan, and 3% WPC + 10% beet. A noteworthy synergistic effect was found between β-glucan from yeast and κ-carrageenan from the Vianoks C45 stabilization system, resulting in the formation of a stable gel network. Among the different combinations of whey protein complexes and vegetable purées, the most efficient stabilizing effect was achieved with the ice creams that contained table beet purée and whey powder enriched with Mn. These hydrocolloids formed a stable gel network in whey ice cream mixes. A significant decrease in surface tension was observed for the ice creams containing β-glucan, which contributes to effective gelation and stabilization of the sample structure. Formulations containing β-glucan, especially from oat, and beet produced ice creams with the best sensory attributes. Three potential compositions of stabilizing substances for low-fat whey ice cream were identified for further investigation. These proposed compositions should be studied to assess their impact on ice cream quality indicators, with particular emphasis on the free moisture freezing process, especially during storage at sub-zero temperatures.

Author Contributions: Conceptualization, G.P. and A.M.; methodology, A.M., V.S., S.M. and B.G.S.; software, M.T.-M.; validation, S.M., B.G.S. and G.P.; formal analysis, B.G.S.; investigation, V.S., K.T., S.P.-H. and S.M.; resources, S.M. and K.T.; data curation, B.G.S.; writing—original draft preparation, A.M. and M.T.-M.; writing—review and editing, G.P., S.M. and S.P.-H.; visualization, S.P.-H.; supervision, G.P. and S.M.; project administration, M.T.-M.; funding acquisition, S.M. and M.T.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original data presented in the study are included in the article; further inquiries can be directed to the corresponding authors.

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

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