Effect of stabilizers on the colligative properties of whey-based ice cream

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Abstract

Introduction. The effect of β-glucans derived from oats and yeast on the physicochemical properties, cryoscopic temperature, frozen water content, and ice crystal growth in whey ice cream during storage was investigated.

Materials and methods. The cryoscopic temperature was measured using a cryoscope Marcel osm 3000. Based on the data obtained on the freezing point of the ice cream mixes, the frozen water content under variable low-temperature processing conditions and thermodynamic parameters were calculated. The growth of ice crystals in the ice cream was studied by microscopy and modeled using power-law equations derived from the experimental measurements.

Results and discussion. β-glucans from oats or yeast in the amount of 0.5% significantly affect the physicochemical and structural properties of ice cream. The β-glucan from oats reduces the cryoscopic temperature of the mixture the most (–6.040°C), compared to the sample without the stabilizer (–4.222°C) and the mixture with Cremodan SI 320 (–4.688°C). Along with its high cryoprotective ability, β-glucan from oats provides the maximum content of frozen water in ice cream 97.27% at –30°C, which is probably due to the formation of low-energy weak bonds between water molecules and β-glucan macromolecules.

At the same time, β-glucan from yeast with a lower effect on the cryoscopic temperature (–3.846°C) more significantly counteracted the growth of ice crystals, the average diameter of which did not exceed 11.08 μm on the 30th day of ice cream storage, compared to the control sample (27.5 μm). This fact indicates a different mechanism of the structuring effect of β-glucan from yeast, associated with the formation of a spatial gel matrix in the aqueous phase, which limits crystal growth and stabilizes the air phase of ice cream. The osmotic pressure in the samples with yeast β-glucan was slightly higher (up to 8.84 kPa) compared to the sample with oat β-glucan, which reflects the peculiarities of its colloidal structure and enhances the stabilizing effect. The heat of fusion decreased in the samples with oat β-glucan, indicating a decrease in the stability of the crystalline phase and an easier phase transition. On the contrary, an increase was observed in mixtures with yeast β-glucan, indicating an increase in the stability of the ice structure. The developed stepwise model of ice crystal growth based on experimental data makes it possible to predict and prevent changes in ice cream texture during long-term storage.

Conclusion. Addition of oat β-glucan to whey ice cream exhibited cryoprotective properties, while addition of yeast β-glucan contributed to structural gel stabilization, inhibiting the growth of ice crystals during low-temperature storage of ice cream.

Introduction

Colligative properties of food systems such as freezing point depression, osmotic pressure, and others are closely linked to the physicochemical transformations occurring during freezing. In ice cream production, the cryoscopic temperature serves as a critical parameter, as it governs the degree of free water removal through freezing and consequently determines the product's texture, structural stability, and ice crystal formation within the ice cream matrix (Harfoush et al., 2024). Simultaneously, osmotic pressure provides insight into the water-holding capacity of ingredients and their influence on the state of water in the system (Liu et al., 2021).

Whey is widely used as a raw material in the production of dairy desserts (Kuzmyk and Bohdanova, 2022; Mykhalevych et al., 2024a; Tomczyńska-Mleko et al., 2024). Unlike conventional ice cream, whey-based ice cream is formulated using fresh or dried milk whey, sometimes supplemented with milk, cream, and flavoring agents (Meneses et al., 2020). This product type is typically characterized by a reduced content of total solids and proteins, resulting in a higher proportion of free water, lowered osmotic pressure, and a relatively modest impact on the cryoscopic temperature (Shevchenko et al., 2022). These factors collectively promote intensive freezing of unbound water, which may lead to structural destabilization of ice crystals during low-temperature processing and storage. Accordingly, a more detailed investigation into the processes of water crystallization, the binding mechanisms of free water, and the morphological characteristics of the ice phase is essential to ensure the desired textural properties and stability of ice cream formulated with novel ingredients.

At the preliminary stage of the study, the formulation of whey-based ice cream was scientifically developed using a liquid hydrolyzed concentrate of demineralized whey, supplemented with whey protein isolate and stabilizing agents, specifically β-glucans derived from oats or yeast (Mykhalevych et al., 2024a, 2024b). This formulation has been shown to improve the rheological properties of ice cream mixes. However, the cryoprotective properties of β-glucans used as a natural alternative to traditional commercial stabilizing systems have not yet been fully studied, especially under low-temperature processing and long-term storage conditions.

Stabilizers traditionally incorporated into ice cream play a dual role, contributing both to structure formation and cryoprotection (Kamińska-Dwórznicka et al., 2022). These compounds influence the concentration of dissolved solids, viscosity, and water-binding interactions, thereby affecting the cryoscopic temperature, osmotic pressure, and phase transitions of water (Goff et al., 2025; Kot et al., 2023). In light of evolving consumer demands for clean-label formulations and enhanced product functionality, replacing synthetic stabilizing systems with natural, functionally active ingredients has become increasingly relevant.

In this context, β-glucans, especially those sourced from oats and yeast, have attracted significant attention. Their hydrophilic nature, gel-forming capacity, antioxidant activity, and ability to increase viscosity in food matrices position them as promising ingredients for ice cream applications (Ahmad et al., 2024; Mykhalevych et al., 2022; Shevchenko et al., 2023; Stabnikova et al., 2023; Tomczyńska-Mleko et al., 2024; Zhao et al., 2023). Nevertheless, the widespread adoption of β-glucans necessitates validation of their cryoprotective efficacy, particularly in terms of their ability to reduce the extent of free water crystallization and to enhance the structural stability of the final product.

A critical component in evaluating the functional-technological potential of β-glucans involves assessing the dynamics of free water removal through freezing within the ice cream

matrix. This is of fundamental importance, as free water participates directly in phase transitions and induces structural rearrangements in the product as temperature decreases (Tan et al., 2021). The rate of free water freezing determines the size, morphology, and fractional distribution of the resulting ice crystals (Petzold et al., 2009). Excessively large crystals can disrupt the protein–polysaccharide matrix, compromising textural integrity and diminishing the sensory quality of the product (Kamińska-Dwórznicka et al., 2015; 2020). Hence, the kinetics of ice crystal growth not only represent a physical parameter of the system but also serve as a critical indicator of structural stability and the efficiency of matrix formation. It is therefore imperative to investigate the influence of β-glucans on the cryoscopic temperature, the rate of free water crystallization during technological processing, and the subsequent ice crystal development during storage.

Accordingly, this study aims to conduct a comprehensive examination of the colligative properties of whey-based ice cream systems formulated with natural stabilizing agents. Such an investigation will advance the mechanistic understanding of structure formation and stabilization processes during hardening and storage of frozen dairy desserts.

Materials and methods

Raw materials and sample preparation

To produce the liquid hydrolyzed concentrate of demineralized whey (containing 40% total solids), the following ingredients were employed: spray-dried demineralized whey with 90% demineralization (PJSC "Dairy Alliance," Ukraine), the β-D-galactosidase enzyme (5000 NLU/g, Danisco, Denmark), the starter culture *Lactobacillus acidophilus* LYO 50 DCU-S (Danisco, Denmark), and potable water. Ice cream formulations were prepared with the addition of a commercial stabilizing system (Cremodan SI320), whey protein isolate with a protein content of 90% (Spomlek, Poland), white sugar, vanillin, and water.

The study employed two types of β-glucans:

- Oat β-glucan (Grupa Feniks 2050, Poland) is a 1→3, 1→4 β-D-glucan, a non-cellulosic polysaccharide extracted from Avena sativa L. grains or their derivatives (bran, oat fiber) using a proprietary method. According to the manufacturer's specifications, this highly purified product contains 72% oat β-glucan, with a moisture content not exceeding 6% and an ash content not exceeding 5%. The remaining composition consists primarily of starch, protein, insoluble fiber, and water. Its high purity is evidenced by complete solubility and the absence of odor, color, and taste. Even at low concentrations, it readily forms stable hydrogels upon interaction with water.
- Yeast β-glucan (GOLDCELL, Brazil) derived from the cell walls of baker's yeast (*Saccharomyces cerevisiae*), presented in spray-dried powder form ranging in color from light to dark bronze. The product contains no less than 70% (1→3),(1→6)-linked β-glucan, with moisture content not exceeding 8% and ash content between 5% and 8%.

The starter culture was activated in skim milk at 38–42 °C until reaching a pH of 5.4–5.2. The dry whey was reconstituted at 40–45 °C, followed by pasteurization (85–88 °C, 3–5 min), cooling to 40–43 °C, and enzymatic hydrolysis for 8 hours to achieve at least 95% lactose degradation, as previously described (Mykhalevych et al., 2024c).

Dry ingredients of the ice cream mix were blended with the liquid whey concentrate and water, filtered through a 1 mm sieve, pasteurized (80–82 °C, 1–2 min), homogenized at 12.0±2.5 MPa, cooled, inoculated with the activated starter, and fermented until pH 5.10–5.25 was reached. The fermented mixture was subsequently cooled and subjected to a two-

stage freezing process: preliminary cooling to −1 °C (shear rate 4.5 s^{-1}, 120 s), followed by dynamic freezing to −5.0±0.5 °C (shear rate 9 s^{-1}, 180 s). Ice cream samples were hardened and stored at −18±1 °C for 30 days. Each formulation was produced in triplicate to ensure data reproducibility.

The following sample groups were prepared:

- C – control sample without stabilizing ingredients;
- 0.6%SS – sample with 0.5% Cremodan SI320 stabilizing system;
- 0.25%OBG – sample with 0.25% oat β-glucan;
- 0.5%OBG – sample with 0.5% oat β-glucan;
- 0.25%YBG – sample with 0.25% yeast β-glucan;
- 0.5%YBG – sample with 0.5% yeast β-glucan.

The formulation of the ice cream mix was as follows (in% w/w): liquid hydrolyzed demineralized whey concentrate – 75.0%; sucrose – 9.0%; whey protein isolate – 3.0%; activated starter culture – 3.0%; vanillin – 0.01%; water – 9.39–9.74%; stabilizer – 0.25–0.6%.

Methods

The total solids content in the ice cream samples was determined using the gravimetric method by drying at 105 °C to constant weight, in accordance with standard arbitration procedures.

The mass fractions of carbohydrates, namely sucrose, lactose, glucose, and galactose, were quantified by high-performance liquid chromatography (HPLC) using a Shimadzu LC-6A chromatographic system (Kyoto, Japan) equipped with a refractive index detector. Separation was performed on an SCR-101-N column (250 × 4.7 mm), with degassed deionized water as the mobile phase. The flow rate was maintained at 0.5 mL/min (Mykhalevych et al., 2025).

The freezing point (cryoscopic temperature) was calculated theoretically based on the sucrose equivalence method, following the approach proposed by Marshall et al. (2003):

$$ES = (TS_w \times 0{,}765) + S,$$

where ES is the sucrose equivalence; TS_w is total solids of dried demineralized whey,%; S is the sugar content,%.

For samples containing stabilizing ingredients, the formula was modified to take into account their water-binding capacity:

$$ES = (WB \times MF) + (TS_w \times 0{,}765) + S,$$

where WB is the amount of bound water (g water per g stabilizing agent); MF is the mass fraction of the stabilizing ingredient in the mixture. Weakly bound water was not taken into account in the calculation, so coefficients of 0.66 for mixtures with a commercial stabilization system, 0.80 for mixtures with oat β-glucan, and 0.50 for mixtures with yeast β-glucan were introduced.

The cryoscopic temperature was also measured using a Marcel osm 3000 osmometer (Marcel, Poland) with an accuracy of 0.002 °C (Kamińska-Dwórznicka and Kot, 2024).

The difference between the calculated (Tf_t) and experimentally (Tf_e) measured cryoscopic temperature was determined by the formula:

$$\Delta Tf = Tf_e - Tf_t.$$

The content of frozen water at different stages of low-temperature processing of model ice cream samples was calculated using the Zhadan formula (Dibirasulaev et al., 2016):

$$\omega = 1 + \frac{1{,}12 - 0{,}05 \times t}{t},$$

where ω is the mass fraction of frozen water,%; 1.12 is the empirical coefficient; t is the cryoscopic temperature and the processing temperature without the "–" sign.

The molarity of ice cream mixtures was calculated using the formula (Atkins and de Paula, 2010):

$$b = \frac{\frac{n}{M}}{\text{m water}},$$

where b is the molarity, mol/kg of solvent (water); m is the mass of each osmotically active substance (glucose, galactose, lactose, etc.), g; M is the molecular weight of the substance, g/mol; m_{water} is the mass of water in the system, kg.

The osmotic pressure was calculated according to the Van Hoff equation:

$$\pi = i \times C \times R \times T$$

where π is the osmotic pressure, Pa; i is the isotonic coefficient (≈1); C is the molar concentration, mol/L; R is the gas constant (8.314 J/mol-K); T is the temperature, K.

The phase transition energy was determined by a modified thermodynamic formula (Atkins and de Paula, 2010):

$$\Delta Hf = \frac{R \times Tf2 \times b}{\Delta Tf},$$

where ΔHf is the heat of phase transition (J/mol), T_f is the freezing point of the pure solvent (273.15 K), b is the molarity, ΔT_f is the decrease in freezing point, K, calculated as a module of the experimental T_f; R=8.314 J/(mol-K) is the universal gas constant.

The molar Gibbs free energy was determined by the formula (Atkins and de Paula, 2010):

$$\Delta G = -R \times T \times \ln b,$$

where lnb is the natural logarithm of the molarity.

The size of ice crystals in ice cream was studied using an Olympus BX53 microscope with a Linkam LTS420 cooling system (measuring temperature range from -196 °C to -420 °C) and an Olympus SC50 digital camera. For each sample, 300 to 500 crystals were labeled and the area, equivalent diameter, and standard deviation were calculated using NIS Elements D Imaging software (version 5.30.00, Nikon).

To model the kinetics of ice crystal growth during whey ice cream storage, the authors developed an empirical power-law model that allows describing the change in the average diameter of ice crystals depending on storage time:

$$d(t) = a \times t^{b},$$

where d(t) is the average diameter of ice crystals at time t, μm; t is the storage time, days (1, 7, 30); a is the empirical growth coefficient characterizing the initial growth rate of crystals; b is the exponent (reflects the nature of changes: slowing or accelerating growth).

To determine the parameters a and b, the least-squares approximation in logarithmic form was used:

$$\ln(d) = \ln(a) + b \cdot \ln(t).$$

After linearizing the dependence and plotting ln(d) versus ln(t), the model parameters were determined from the straight line equation. For each sample, a regression analysis was performed in Microsoft Excel, based on which the coefficients a and b, as well as the coefficient of determination R^2 were determined (Montgomery and Runger, 2018).

Data were expressed as means with standard deviations in triplicate. Statistical analysis was performed using Statistika 10 software. Differences were considered significant at a validity of $\alpha = 0.95$.

Results and discussion

Chemical composition

The chemical composition of the main ingredients that affect the colligative properties of ice cream, in particular, the lowering of the freezing point, is given in Table 1. The appearance of ice cream samples with β-glucans is shown in Figure 1.

The total solids content in the investigated ice cream formulations ranged from 42.05% to 42.61%, which is consistent with full-fat premium ice cream standards (fat content 14–18%) (Goff and Hartel, 2013). The mass fractions of key saccharides, namely glucose (16.02–16.51%), galactose (15.79–16.35%), lactose (0.72–0.78%), and sucrose (8.97–9.05%), play a pivotal role in determining the cryoscopic behavior of the system, as their cumulative colligative activity significantly influences the freezing point of the food matrix.

The sucrose content in the samples was notably lower than the standard levels typically observed in conventional ice cream formulations. According to Goff and Hartel (2013), the total sweetener content in classical ice cream usually ranges from 14% to 22%. Similarly, Meneses et al. (2020) reported a sugar content of 17.44% in whey- and buttermilk-based ice creams. Meanwhile, Goff (2018) notes that sugar content in both commercial and artisanal ice creams can vary widely, from 9% to 28%, depending on the formulation and market segment.

Table 1

Chemical composition of the test samples

Ice cream	Solids,%	Lactose,%	Glucose,%	Galactose,%	Sucrose,%
C	42.05^{a}±0.91	0.73^{a}±0.05	16.45^{a}±0.02	15.90^{a}±0.02	9.02^{a}±0.03
0.6%CC	42.61^{a}±1.02	0.75^{a}±0.02	16.51^{a}±0.14	15.79^{a}±0.07	8.98^{a}±0.04
0.25%OBG	42.28^{a}±0.67	0.72^{a}±0.05	16.32^{ab}±0.08	16.07^{a}±0.52	8.97^{a}±0.02
0.5%OBG	42.50^{a}±0.95	0.75^{a}±0.03	16.02^{ab}±0.10	16.35^{a}±0.15	8.99^{a}±0.05
0.25%YBG	42.33^{a}±1.12	0.78^{b}±0.01	16.48^{ab}±0.17	15.88^{a}±0.12	9.05^{a}±0.02
0.5%YBG	42.24^{a}±1.04	0.76^{a}±0.06	16.39^{b}±0.23	15.94^{a}±0.05	9.01^{a}±0.04

Notes:
C – ice cream without stabilizing ingredients;
0.6%SS – ice cream with 0.5% of the Cremodan SI 320 stabilizing system;
0.25OBG – ice cream with 0.25% oat β-glucan;
0.5%OBG – ice cream with 0.5% oat β-glucan;
0.25%YBG – ice cream with 0.25% yeast β-glucan;
0.5%YBG – ice cream with 0.5% yeast β-glucan.
$^{a\text{-}b}$-mean values denoted in columns by different letters differ statistically significantly at $p \leq 0.05$.

a **b**

Figure 1. Appearance of soft whey ice cream at the exit of the freezer: a – with oat β-glucan, b – with yeast β-glucan.

In the present study, the reduced sucrose concentration is compensated by a high content of monosaccharides, which results from the hydrolysis of lactose in demineralized whey, which serves as the main raw material. This compositional feature directly affects water mobility, crystallization kinetics, and ice crystal growth, thereby influencing the microstructure and textural stability of the resulting frozen food system.

Freezing point and frozen water content

The freezing point characterizes the ability of a mixture to freeze, which directly affects the texture quality of ice cream. The theoretical and experimental values of the freezing point (Tf) of the ice cream samples, as well as the difference between them (ΔTf), are presented in Table 2.

Table 2

Freezing point of ice cream mixtures

Sample	Tf_t, °C	Tf_e, °C	ΔT_f, °C
C	–4.432	$-4.222^{b}\pm0.14$	–0.210
0.6%SS	–4.600	$-4.688^{b}\pm0.03$	+0.088
0.25%OBG	–5.111	$-5.108^{c}\pm0.25$	–0.003
0.5%OBG	–5.177	$-6.040^{d}\pm0.18$	+0.863
0.25%YBG	–3.926	$-3.888^{a}\pm0.07$	–0.038
0.5%YBG	–3.924	$-3.846^{a}\pm0.02$	–0.078

Notes:
C – ice cream without stabilizing ingredients;
0.6%SS – ice cream with 0.5% of the Cremodan SI 320 stabilizing system;
0.25OBG – ice cream with 0.25% oat β-glucan;
0.5%OBG – ice cream with 0.5% oat β-glucan;
0.25%YBG – ice cream with 0.25% yeast β-glucan;
0.5%YBG – ice cream with 0.5% yeast β-glucan.
a-d-mean values denoted in columns by different letters differ statistically significantly at $p \leq 0.05$.

For the control sample, the theoretical freezing point (Tf) was –4.432 °C, while the experimental value was –4.222 °C. The difference of 0.210 °C is within an acceptable deviation range, indicating accurate measurement procedures. The inclusion of 0.6% Cremodan SI 320 stabilizing system led to a decrease in the theoretical Tf to –4.600 °C, whereas the experimental Tf was –4.688 °C, yielding a positive deviation (ΔTf = +0.088 °C). This small difference suggests that Cremodan SI 320 contributes to a slight additional depression of the freezing point, likely due to its capacity to form stable colloidal structures that bind water and influence phase transitions.

The incorporation of β-glucans into the ice cream mixtures also affected their freezing points. The sample with 0.25% oat β-glucan exhibited nearly perfect agreement between theoretical (–5.111 °C) and experimental (–5.108 °C) values, with ΔTf = –0.003 °C, indicating a predictable system behavior at this low concentration. However, increasing the oat β-glucan concentration to 0.5% resulted in a significant decrease in experimental Tf to –6.040 °C, compared to a theoretical value of –5.177 °C. The corresponding deviation (ΔTf = +0.863 °C) demonstrates a marked impact of the polysaccharide on water–phase interactions.

This enhanced cryoscopic effect is likely attributable to the formation of more structured hydrogels capable of more effectively binding water. β-glucans are reported to form viscous gels and pseudoplastic solutions due to the complex conformational arrangement of their polymer chains (Wang et al., 2017; Vaikousi et al., 2004). As such, β-glucan solutions may function as stabilizers or thickeners in food formulations (Kaur et al., 2020).

Samples containing 0.25% and 0.5% yeast-derived β-glucan showed only minor differences between theoretical and experimental Tf values (–0.038 °C and –0.078 °C, respectively), indicating a moderate influence of this additive on the freezing behavior of the mixture.

Thus, the stabilizing system Cremodan SI 320 and the β-glucans exert differential effects on the freezing point of ice cream. Cremodan SI 320 contributes to a moderate depression of Tf through colloidal structuring, whereas elevated concentrations of oat β-glucan significantly intensify this effect. These findings are critical for optimizing ice cream formulations with respect to desired textural attributes and product stability.

A general trend was observed wherein the proportion of frozen water increased with decreasing temperature, in accordance with the fundamental freezing principle: the lower the temperature, the greater the amount of liquid transitioning into the solid phase (Table 2). For the control sample (C), this proportion ranged from 81.82% at –5 °C to 97.73% at –40 °C.

Table 3

Content of frozen water in ice cream at low temperature processing, %

t, °C	C	0.6%SS	0.25%OBG	0.5% OBG	0.25%YBG	0.5% YBG
–5	81.82	82.29	82.71	83.64	81.49	81.45
–10	90.91	91.14	91.35	91.82	90.74	90.72
–15	93.94	94.10	94.24	94.55	93.83	93.82
–20	95.46	95.57	95.68	95.91	95.37	95.36
–25	96.36	96.46	96.54	96.73	96.30	96.29
–30	96.97	97.05	97.12	97.27	96.91	96.91
–35	97.40	97.47	97.53	97.66	97.36	97.35
–40	97.73	97.79	97.84	97.96	97.69	97.68

Notes:
C – ice cream without stabilizing ingredients;
0.6%SS – ice cream with 0.5% of the Cremodan SI 320 stabilizing system;
0.25OBG – ice cream with 0.25% oat β-glucan;
0.5%OBG – ice cream with 0.5% oat β-glucan;
0.25%YBG – ice cream with 0.25% yeast β-glucan;
0.5%YBG – ice cream with 0.5% yeast β-glucan.

The impact of added stabilizing agents on the frozen water content was manifested in a slight increase in this parameter compared to the control sample across the studied temperature range. Specifically, the sample containing 0.6% Cremodan SI 320 exhibited a marginally higher frozen water content than the control, indicating a slight enhancement of the crystallization process due to the stabilizing system.

Oat β-glucan added at concentrations of 0.25% and 0.5% demonstrated a more pronounced effect: the frozen water content in these samples consistently exceeded that in the control and the sample containing the commercial stabilizer under all temperature

conditions. This suggests that the polysaccharide intensifies water freezing, which can be attributed to its ability to form hydrogel structures that modulate water molecule mobility within the mixture (Kaur et al., 2020).

Samples enriched with yeast-derived β-glucan showed frozen water contents comparable to the control and Cremodan-containing samples and were less pronounced in this regard than those with oat β-glucan. This may reflect structural differences and varying hydrophilicity between β-glucans, which in turn affect the freezing behavior of the aqueous phase. Lazaridou and Biliaderis (2004) found that β-glucans derived from cereals exhibit enhanced gelation at subzero temperatures, improving the functional properties of gel-forming materials. Regarding yeast β-glucan, Xu et al. (2009), based on small-amplitude oscillatory rheological analyses, and identified its unique capacity to actively participate in gelation processes. Yeast β-glucan possesses significant potential for energy-based bonding, with its effectiveness notably increasing in systems with a low κ-carrageenan content, where it acts not only as a structural component but also as an active element of the gel matrix. This suggests that while yeast β-glucan may not form structures as firm as those formed by oat β-glucan, it contributes strength through a high number of molecular interactions. Nevertheless, further investigation is required to elucidate the cryoprotective properties of yeast β-glucan. It is worth noting that the difference in the effect between 0.25% and 0.5% doses of yeast β-glucan was minimal, indicating a potential saturation effect at low inclusion levels.

Thus, the findings indicate that the presence of β-glucans, especially oat-derived, leads to an increase in the fraction of frozen water during low-temperature treatment of ice cream. This phenomenon may potentially enhance the product's textural attributes and structural stability (Hagiwara and Hartel, 1996). In ice cream systems, it is primarily the free (unbound) water that undergoes freezing. β-glucans were expected to bind more free water and thus reduce the amount of frozen water. However, the data in Table 3 indicate the opposite, an increase in frozen water content, which may be explained by the formation of low-energy, weak interactions between water molecules and β-glucan macromolecules. Therefore, a promising direction for future research lies in the comparative analysis of the binding energy between water and various glucans versus classical stabilizers. Different glucans may form a varying number of hydrogen bonds, which could influence the extent of water freezing during the dynamic freezing stage. In contrast, traditional stabilizers may bind water more strongly, with some of this bound water freezing only during the hardening phase.

Thermodynamic properties of ice cream mixtures

The total number of moles (Σ moles) and molality vary slightly between samples, indicating similar concentrations of solutes in the systems. The molality varies between 3.59-3.63 mol/kg (Table 4).

The osmotic pressure of the control sample was determined to be 8.73 kPa. The addition of 0.6% of the Cremodan SI320 stabilizing system led to a slight increase in osmotic pressure to 8.82 kPa, which may reflect modifications in the colloidal network and an increase in the total activity of dissolved solutes. The influence of β-glucans of different origins varied. Samples containing 0.25% and 0.5% oat β-glucan exhibited osmotic pressures close to that of the control, ranging from 8.73 to 8.76 kPa. In contrast, the corresponding yeast β-glucan samples showed slightly elevated osmotic pressures of 8.84 kPa and 8.78 kPa, respectively. These differences likely stem from variations in molecular architecture and solubility: yeast-derived β-glucans possess higher molecular weights and a tightly packed triple-helix conformation, rendering them largely water-insoluble (Wang et al., 2025), whereas oat β-glucans contain a higher proportion of water-soluble fractions (Yu et al., 2021).

Table 4

Thermodynamic and colloidal parameters of ice cream mixtures with different stabilizing ingredients

Sample	Σ moles	Mole content, mol/kg	Osmotic pressure, kPa	ΔHf, J/mol	ΔG, J/mol
C	0.2080	3.59	8.73	527 473.88	−3124
0.6%CC	0.2076	3.62	8.82	478 902.30	−3143
0.25%OBG	0.2072	3.59	8.73	437 817.36	−3124
0.5%OBG	0.2071	3.60	8.76	371 739.38	−3131
0.25%YBG	0.2092	3.63	8.84	576 367.85	−3151
0.5%YBG	0.2085	3.61	8.78	580 799.70	−3137

Notes:
C – ice cream without stabilizing ingredients;
0.6%SS – ice cream with 0
.5% of the Cremodan SI 320 stabilizing system;
0.25OBG – ice cream with 0.25% oat β-glucan;
0.5%OBG – ice cream with 0.5% oat β-glucan;
0.25%YBG – ice cream with 0.25% yeast β-glucan;
0.5%YBG – ice cream with 0.5% yeast β-glucan.

The phase transition enthalpy (ΔHf), representing the heat of fusion, decreased with increasing concentrations of oat β-glucan, from 527 473.88 J/mol in the control sample to 371 739.38 J/mol at 0.5% inclusion. This suggests a facilitation of the solid-to-liquid phase transition, likely due to the structural influence of polymeric networks on ice crystal stability. In contrast, an opposite trend was observed in samples with yeast β-glucan: ΔHf increased to 580,799 J/mol at 0.5% concentration, indicating enhanced crystalline phase stability and a higher enthalpic requirement for melting.

The molar Gibbs free energy (ΔG) values were negative across all samples, consistent with the thermodynamic favorability of the freezing process (Atkins and de Paula, 2014). ΔG values ranged from –3124 J/mol (control) to –3151 J/mol (0.25% yeast β-glucan), suggesting small but notable differences in system stability.

These thermodynamic observations underscore the distinct impacts of β-glucan types on the thermal behavior of ice cream matrices: oat β-glucan promotes phase transition by reducing fusion enthalpy, while yeast β-glucan enhances melting energy requirements, potentially contributing to greater structural integrity during storage. These results are in line with previous findings concerning the textural modifications induced by β-glucans, specifically, a softening effect from yeast β-glucan and an elasticity-promoting effect from oat β-glucan incorporation (Mykhalevych et al., 2024b).

Ice crystal growth

Table 5 presents the temporal evolution of the average diameter of ice crystals in the ice cream samples over storage periods of 1, 7, and 30 days. Both experimental measurements and predicted values derived from a power-law growth model are provided. The high coefficients of determination (R^2 ranging from 0.91 to 0.98) confirm the strong predictive capability and reliability of the applied mathematical model.

Table 5

Measured and modelled ice crystal sizes in ice cream samples over storage

Sample	Storage time, days	D_A, μm, measured	D_A, μm, modelled	Power-law model	R^2
C	1	18.50[a]±1.21	18.90	y = 0.1186x + 2.9389	0.9569
	7	25.01[b]±1.06	23.80		
	30	27.50[c]±0.78	28.28		
0.6%CC	1	15.80[a]±0.67	15.16	y = 0.2048x + 2.7186	0.9454
	7	20.50[b]±0.77	22.58		
	30	32.15[c]±1.18	30.42		
0.25%OBG	1	18.74[a]±0.04	18.69	y = 0.019x + 2.9282	0.9774
	7	19.29[b]±0.50	19.40		
	30	20.01[b]±0.72	19.94		
0.5%OBG	1	11.38[a]±0.17	11.08	y = 0.1031x + 2.4048	0.9114
	7	12.71[b]±0.16	13.54		
	30	16.31[c]±0.15	15.73		
0.25%YBG	1	8.49[a]±0.37	8.54	y = 0.0343x + 2.1449	0.9579
	7	9.26[b]±0.12	9.13		
	30	9.52[b]±0.16	9.60		
0.5%YBG	1	10.24[a]±0.02	10.19	y = 0.0227x + 2.3212	0.9322
	7	10.52[a]±0.49	10.65		
	30	11.08[b]±0.20	11.01		

Notes:
C – ice cream without stabilizing ingredients;
0.6%SS – ice cream with 0.5% of the Cremodan SI 320 stabilizing system;
0.25OBG – ice cream with 0.25% oat β-glucan;
0.5%OBG – ice cream with 0.5% oat β-glucan;
0.25%YBG – ice cream with 0.25% yeast β-glucan;
0.5%YBG – ice cream with 0.5% yeast β-glucan.
a-c-mean values denoted (according to storage time within the group) in the columns by different letters are statistically significantly different at $p \leq 0.05$.

The practical application of this model lies in its capability to predict changes in the textural properties of the product during extended storage, which is a critical factor for ensuring the stability, quality, and consumer attributes of ice cream. Additionally, the model can be utilized in further scientific research and in optimizing ice cream manufacturing technologies, taking into account the effects of various functional additives.

The analysis demonstrated that additives, particularly 0.5% oat and yeast β-glucans, effectively retard the growth of ice crystals, maintaining a fine-crystalline structure of the ice cream. This positively influences texture and quality throughout the entire storage period (Table 5).

Thus, the ice crystal growth model, developed based on empirical measurements, represents a reliable tool for evaluating and controlling ice cream stability and can be valuable for both researchers and food industry practitioners.

Figure 2 illustrates the linear dependencies of the changes of average ice crystal diameter during the storage of the studied samples. Both the actual experimental data (measured values) and the lines modeled using the power-law model are visualized, allowing for comparison between observed and predicted crystal growth over time. The high coefficients of determination (R^2) indicate a strong agreement between the model and the empirical observations.

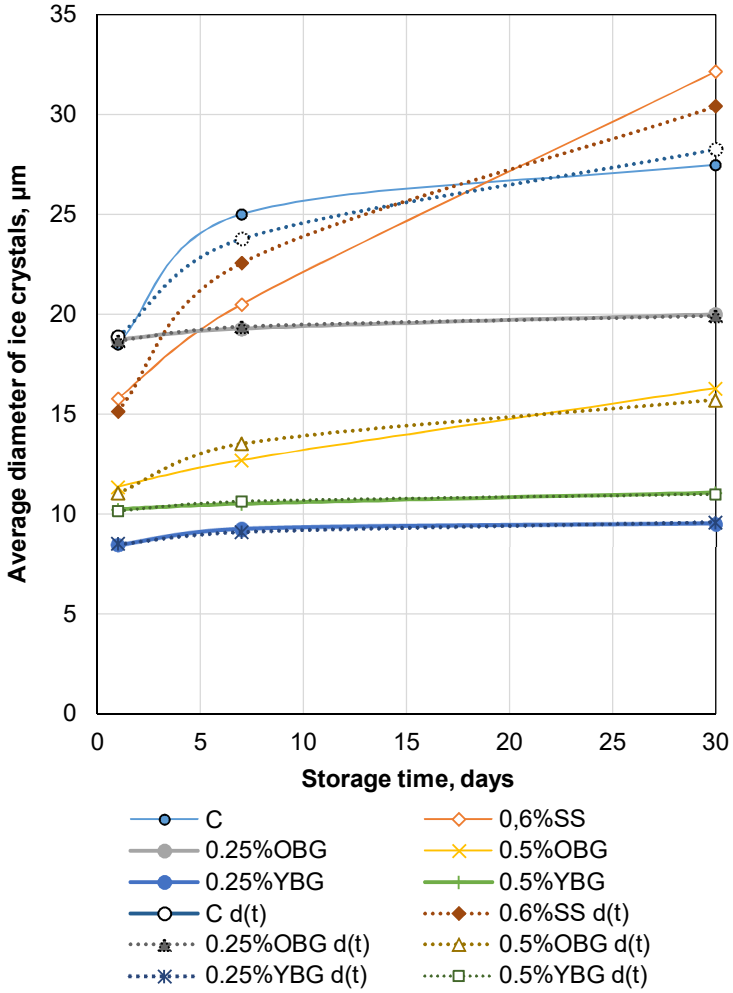

Figure 2. Ice crystal growth in ice cream during storage

Notes.

0.6%SS – ice cream with 0.5% of the Cremodan SI 320 stabilizing system;
0.25OBG – ice cream with 0.25% oat β-glucan;
0.5%OBG – ice cream with 0.5% oat β-glucan;
0.25%YBG – ice cream with 0.25% yeast β-glucan;
0.5%YBG – ice cream with 0.5% yeast β-glucan.
—— Solid lines – growth dynamics based on measured values,
····· Dashed line – modeled growth dynamics.

It is worth noting the specific behavior of yeast β-glucan, which results from a different mechanism of influence on the ice cream structure compared to oat β-glucan. Despite the increased cryoscopic temperature observed in samples with yeast β-glucan, this type of polysaccharide promotes the formation of the smallest ice crystals throughout the entire storage period. This indicates that yeast β-glucan exerts a structural rather than a colligative effect. It is likely that within the aqueous phase, it forms a spatial gel matrix that

inhibits ice crystal growth and modulates their morphology (Zhang et al., 2019). Such behavior is characteristic of hydrocolloids and polymeric stabilizers and holds promise for industrial applications aimed at improving texture and reducing undesirable structural changes in ice cream during storage.

Conclusions

1. Oat β-glucan at a concentration of 0.5% in ice cream acts as an effective cryoprotector, lowering the cryoscopic temperature to –6.04 °C, which indicates enhanced water binding and the formation of a structured gel matrix. In contrast, samples with yeast β-glucan increase the cryoscopic temperature but provide better control over ice morphology. The addition of β-glucans leads to an increase in the fraction of frozen water during low-temperature processing, which can be explained by low-energy weak bonds between water molecules and β-glucan macromolecules.
2. Yeast β-glucan exhibits a different structuring mechanism in ice cream by forming a spatial gel matrix in the aqueous phase that inhibits ice crystal growth and modulates their size and shape. This is confirmed by the stabilization of the smallest ice crystal sizes (8.49–11.08 μm) in ice cream over 30 days of storage, despite a smaller decrease in cryoscopic temperature. Conversely, oat β-glucan acts through enhancing the cryoscopic effect by lowering the freezing temperature and influencing water phase transitions.
3. Analysis of melting enthalpy (ΔHf) showed that oat β-glucan reduces the heat of phase transition, facilitating ice crystal melting, whereas yeast β-glucan increases this energy, enhancing the stability of the ice phase.
4. The power-law model of ice crystal growth, developed based on experimental data, demonstrates high accuracy with a coefficient of determination $R^2 > 0.91$ and allows forecasting changes in the textural characteristics of ice cream during storage. This makes it an effective practical tool for optimizing production technologies and quality control of ice cream.
5. A promising direction for further research is a comparative analysis of the binding energies of different types of glucans and classical stabilizers with water to substantiate the mechanism of action of glucans under subzero temperature conditions.

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