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PHYSICOCHEMICAL PROPERTIES OF DAIRY, FRUIT-BASED AND PLANT-BASED FROZEN DESSERTS: IMPLICATIONS FOR FUNCTIONAL PACKAGING DESIGN

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Abstract

This review compares dairy, fruit-based, and plant-based frozen desserts from a compositional and physicochemical perspective, with emphasis on their implications for functional packaging. The study is based on a literature review, focusing on fat, protein, pH, overrun, texture, viscosity, and melting behavior. Dairy ice cream demonstrated the highest structural stability due to its aerated fat-protein structure, resulting in slower melting. Fruit-based sorbets showed lower stability and faster melting, while plant-based products showed variable behavior depending on formulation. These differences directly influence packaging requirements. Products containing lipids require protection against oxygen and light, while structurally less stable systems demand improved thermal insulation and strict temperature control. Overall, adapted functional packaging solutions can represent an effective approach to maintaining quality and extending shelf life.

Key words*: ice cream, sorbet, plant-based frozen desserts, sensory properties, texture.*

INTRODUCTION

Ice cream is described as a multiphase system in which structural elements such as ice crystals, air cells, fat globules, and the unfrozen phase determine melting behavior and texture.
The relationship between these elements has been shown to directly influence hardness and melting rate, particularly through the interaction between air incorporation and fat structure (Muse & Hartel, 2004). In addition, the colloidal nature of ice cream systems highlights the importance of fat, proteins, and aqueous phases in defining stability and structural properties (Goff, 1997).
Milk is considered more than a basic dietary staple; it is a fundamental pillar of human nutrition that significantly supports overall health. As a complex food matrix, dairy products provide a vital balance of proteins, lipids, carbohydrates, and essential minerals necessary for physical development and well-being (Stefan et al., 2025).
The quality of finished dairy products is fundamentally determined by the integrity of the raw materials and ingredients used, making microbiological safety a critical factor in dairy product manufacturing (Şuler et al., 2024).
Furthermore, milk fat contributes significantly to both the physical manufacturing qualities and the nutritional profile of dairy products, as the balance of fatty acids is increasingly recognized for its impact on human health (Vasiliu et al., 2024).
This health-conscious trend is further driving the market toward non-dairy where novel formulations using plant-based milks not only aim to improve the biofunctional profile, such as antioxidant activity, but may also exhibit distinct technological properties, including modifications in overrun depending on the plant-based substrate and formulation strategy used (Acar et al., 2025).
Consequently, changes in formulation, particularly fat reduction and the use of fat replacers, influence viscosity, texture, and

melting behavior in ice cream by altering the properties of the unfrozen phase (Akbari et al., 2019). In dairy ice cream, fat globules form a partially coalesced network that stabilizes air cells and contributes to resistance to melting. The crystallization of lipids plays a key role in the development of this structure, influencing physical stability during freezing and storage (Adleman & Hartel, 2001).

The incorporation of fruit components leads to changes in physicochemical properties of frozen dairy systems. The addition of fruit and vegetable ingredients has been shown to influence acidity, texture, and overall stability, depending on their composition (Soodbar et al., 2025).

In systems where fruit juice is added, modifications in texture and melting behavior have been reported, indicating that fruit composition affects structural characteristics of frozen products (Marshall et al., 2003).

Studies on sorbet systems show that high water content and the absence of fat lead to differences in structural stability and melting behavior compared to dairy ice cream. Physicochemical analyses of sorbet matrices indicate lower overrun and faster melting rates, associated with higher water content and lack of fat structure (Petkova et al., 2022).

Understanding how composition influences physicochemical properties is essential for improving frozen dessert formulations. Research highlighting the role of fat content, stabilizers, and their impact on thermal behavior and ice crystallization (Akbari et al., 2019; Pintor-Jardines et al., 2018) provides a theoretical basis for comparing milk-based and fruit-based systems. Such comparisons help clarify how specific formulation differences dictate the final structure and melting characteristics of the product.

Therefore, this review aims to compare the compositional and physicochemical characteristics of dairy, fruit-based, and plant-based frozen desserts.

Differences in composition may lead to distinct sensitivities to temperature fluctuations, moisture migration, and oxygen exposure, which are key factors affecting shelf life and structural integrity. As a result, understanding these physicochemical variations provides a fundamental basis for developing functional packaging systems, such as moisture barriers, oxygen scavengers, and temperature-responsive materials, tailored to maintain the quality and stability of frozen desserts throughout storage and distribution.

MATERIALS AND METHODS

In order to compare the physicochemical properties of dairy, fruit-based, and plant-based frozen desserts, a literature review was conducted using scientific articles and review papers published up to 2025. The literature search was conducted between December 2025 and March 2026. A total of 78 articles were initially identified, of which 44 were selected based on their relevance to the physicochemical parameters investigated, including fat content, pH, overrun, melting behavior, texture, and thermal properties. Articles not directly related to ice cream or frozen desserts were excluded.

Scientific databases such as ScienceDirect, Wiley Online Library, MDPI, PubMed Central, and Taylor & Francis were used to identify relevant sources. Keywords included “ice cream”, “sorbet”, “fruit-based ice cream”, “plant-based ice cream”, “physicochemical properties”, “melting behavior”, and “texture”.

The selected studies were analysed comparatively, with particular emphasis on parameters that affect heat transfer, moisture migration, structural stability, and resistance to temperature fluctuations. The main variables considered included composition, fat content, water distribution, protein source, pH, overrun, and melting properties. The collected data were further interpreted to establish direct correlations between formulation-dependent physicochemical properties and packaging performance requirements. By identifying how structural differences influence heat sensitivity, melting resistance, and moisture loss, this analysis supports the development of targeted functional packaging solutions adapted to the specific stability challenges of each frozen dessert category.

Although efforts were made to include a wide range of relevant studies, the present review is limited by the variability in experimental conditions, formulations, and analytical methods reported in the literature, which may affect the direct comparability of results. In

addition, the correlations established between physicochemical properties and packaging requirements are based on secondary data interpretation and should be further validated through experimental studies.

RESULTS AND DISCUSSIONS

Dairy ice cream

Milk-based ice cream is formulated using milk, sugar, and stabilizing ingredients. A formulation reported in the literature includes sugar, dextrose, maltodextrin, stabilizer, milk powder, skim milk powder, water, fresh milk, and whipping cream, indicating the presence of fat, sugars, and milk solids (Limsuwan et al., 2014). Standard milk-based ice cream formulations are typically designed to achieve approximately 10% fat, 12% milk solids-not-fat (MSNF), and 12% sucrose in the mix, with a protein content of approximately 4.8% and total solids of approximately 34.26%. The dairy base may also include buttermilk, a by-product of butter production with a composition similar to skimmed milk, containing approximately 3.3% protein, 0.8% fat, 10.0% total solids, and a pH of 6.75 (Szkolnicka et al., 2020).

Buttermilk contains polar lipids derived from the milk fat globule membrane (MFGM), present at concentrations five times higher than in whole milk, which have been reported to confer emulsifying and stabilizing properties (Szkolnicka et al., 2020). Milk-based ice cream composition can be modified by replacing fat and sugar with alternative ingredients. The use of whey protein and maltodextrin as fat replacers has been reported to reduce fat content to less than 1%, while carbohydrate content increases (Limsuwan et al., 2014).

Proteins play a fundamental role in dairy ice cream, contributing to foam and lipid emulsion stabilization through partial coalescence of fat globules, while ice crystal sizes exceeding 50 µm have been associated with a rough texture and icy mouthfeel (Ng et al., 2024).

The physical properties of dairy ice cream are directly influenced by its formulation and processing conditions. Standard dairy ice cream mix exhibited an apparent viscosity of 112.33-132.83 mPas after aging, an overrun of 65.04%, and a melting rate of 0.29%/min, with a draw temperature of -5.42°C (Alvarez et al., 2005). The pH of dairy ice cream ranged between 6.47 and 6.80 (Beegum et al., 2022; Aydemir et al., 2025).

Differential scanning calorimetry analyses of dairy ice cream revealed an onset melting temperature of -7.12°C, an enthalpy of 170.3 J/g, and a freezable water content of 51.14% (Alvarez et al., 2005).

The hardness of dairy ice cream was reported at 7.08N, lower than the 19.99N recorded for plant-based ice cream formulated from cereal and legume ingredients (Pontonio et al., 2022). Milk protein concentrate ice cream exhibited the highest overall sensory acceptability score of 6.56 on a 9-point hedonic scale, demonstrating the closest resemblance to conventional dairy ice cream in terms of physical and sensory properties (Ng et al., 2024). The incorporation of probiotic cultures into dairy ice cream has also been investigated, with results indicating that propolis extract at concentrations up to 0.6% did not significantly affect color or texture, while higher concentrations resulted in decreased flavor and overall acceptability scores (Soodbar et al., 2025).

Fruit-based frozen desserts

Sorbets are non-dairy alternatives to ice cream, obtained by incorporating fruit pulp, juices, or pieces of fruit and other ingredients. Fruit-based frozen desserts may contain bioactive compounds derived from fruit, including phenolic compounds associated with antioxidant activity (Martins et al., 2025).

Fruit-based frozen desserts encompass several distinct product categories, each defined by specific compositional characteristics. While sorbets contain exclusively fruit-derived ingredients without any dairy components, sherbets represent an intermediate category incorporating both fruit and dairy ingredients such as cow's milk, and plant-based frozen desserts constitute a broader category produced using ingredients such as coconut, almond, oat, soy, cashew, or avocado as dairy substitutes (Sangteerakij et al., 2022; Taspinar et al., 2023).

The structural base of fruit-based frozen desserts differs fundamentally from that of dairy ice cream, being characterized by a high

water content and the absence of dairy fat. In mulberry sorbet, moisture content reaches 71.81 g/100 g, total fat is only 0.36 g/100 g, and pH is 3.32, reflecting the acidic nature of the organic acids naturally present in fruits (Sangteerakij et al., 2022). pH values in sorbet systems may range up to approximately 3.8 depending on formulation (Petkova et al., 2022). The sorbet exhibited higher acidity than sherbet ice cream, which was attributed to the absence of milk and the low pH of the fruit used in the formulation (Sangteerakij et al., 2022).

The absence of dairy components in fruit-based frozen desserts determines a fat and protein profile that differs fundamentally from that of conventional dairy ice cream.

Fruit-based sorbets are characterized by very low fat content, as reported in mango sorbet formulations where total fat reached only 0.50 g/100 g (Williams et al., 2022).

The protein content of fruit-based sorbets is equally low, as observed in peach sorbet matrices which presented reduced fat and protein contents (Petkova et al., 2022).

The sugar composition of fruit-based frozen desserts differs markedly from that of conventional dairy ice cream. While dairy ice cream contains sucrose as the primary added sweetener alongside lactose derived from milk, fruit-based sorbets are characterized by a predominance of fructose and glucose, as these are the dominant sugars naturally present in most fruits (Székelyhidi et al., 2025). Sorbets contain a minimum fruit content of 25%, with water and sugar as the other main components, and the fruit itself contributes substantially to the final sugar profile (Hipólito et al., 2016). In strawberry sorbet, fructose and glucose were each detected at approximately 41,663 mg/kg, while sucrose was present at only 7,932 mg/kg, the lowest concentration among the three sugars identified (Székelyhidi et al., 2025).

The total soluble solids content of peach sorbet matrices varied between 17.50 and 33.03%, depending on the formulation, reflecting the influence of both naturally occurring fruit sugars and added sweeteners on the overall sugar content of the product (Petkova et al., 2022).

In ice cream formulations enriched with increasing concentrations of persimmon puree, glucose and fructose contents increased progressively while lactose decreased from 7.30% to 3.76%, indicating that fruit incorporation modifies the sugar profile of frozen desserts (Karaman et al., 2014).

Beyond the naturally occurring sugars derived from fruit, the total sugar content of fruit-based frozen desserts is also influenced by the addition of sweetening agents during formulation.

In industrial sorbet production, added sugar and water content are typically higher than in artisanal products, where the fruit content is proportionally greater (Palka & Wilczyńska, 2023). Sugar addition increases viscosity, improves body and texture, and lowers the freezing point, thereby reducing the risk of large ice crystal formation during freezing and storage (Romulo et al., 2021). In frozen yogurt formulations, increasing sugar content from 18% to 22% resulted in a progressive increase in overrun from 22.15% to 31.63%, while complete melting time decreased, demonstrating the direct influence of sugar concentration on the structural and melting properties of frozen desserts (Güven & Karaca, 2002).

Sugar directly regulates the overall taste sensation of frozen desserts, and its removal or reduction requires the use of bulking agents and alternative sweeteners to compensate for its functional properties, including freezing point depression and body formation (Pinto & Dharaiya, 2014). The substitution of sucrose with alternative sweeteners and bulk fillers such as polydextrose, maltodextrin and sorbitol has been shown to achieve a 20% reduction in caloric value while maintaining acceptable physicochemical and sensory characteristics in the final product (Pinto & Dharaiya, 2014).

In mulberry sorbet, overrun was 44.72 and melting rate was 17.27 g/min, while in mulberry sherbet ice cream, overrun was 47.58% and melting rate was 13.81 g/min, with the higher overrun of sherbet attributed to the presence of cow's milk in its formulation (Sangteerakij et al., 2022). Sorbet melted faster than sherbet ice cream (Sangteerakij et al., 2022). In peach sorbet matrices, overrun ranged from 8.11 to 12.32%, with the control sample completely melted within 60 minutes, and low overrun values were attributed to the low

protein content of the sorbet matrices, with larger ice crystals detected at lower overrun (Petkova et al., 2022).

Fruit-based ice cream formulations incorporating dragon fruit and banana have also been investigated, with these tropical fruits contributing antioxidants, vitamin C, dietary fiber, and potassium to the nutritional profile of the final product (Van Thinh et al., 2025).

Novel frozen dessert formulations incorporating jujube fruit have been developed, with jujube contributing sweetening and coloring capacity, antioxidant activity, vitamin C content, and dietary fiber to the nutritional profile of the final product (Stan et al., 2025).

Persimmon sorbet mixes exhibited shear thinning behavior, with flow behavior index values between 0.29 and 0.37 and apparent viscosity between 1.14 and 1.40 Pa·s at a shear rate of 50 s^{-1}, while overrun ranged from 8.3 to 51% depending on the concentration of the foaming agent used, and higher overrun values were associated with slower melting rates due to the low thermal conductivity of air (Kilicli et al., 2025).

Plant-based frozen desserts

Plant-based frozen desserts are produced using ingredients such as coconut, almond, oat, or soy. An analysis of 358 commercial non-dairy frozen desserts reported that 90% of the products were classified as high in sugar and many contained saturated fat due to the widespread use of coconut oil (Craig & Brothers, 2022). Frozen desserts formulated with plant-based milk sources such as almond, hazelnut, or lupine differ in composition and physicochemical properties depending on the raw materials used (Akalın et al., 2024).

Among the plant-based alternatives to conventional dairy ice cream, coconut-based formulations represent the most extensively studied category. Non-dairy ice cream formulations produced from coconut milk, tender coconut pulp and water obtained overrun values ranging from 40.00% to 46.39%, significantly lower than the 86.00% recorded in the dairy control, and the incorporation of coconut products resulted in increased total phenolic content and mineral content compared to conventional dairy ice cream (Beegum et al., 2022). Cold-pressed coconut oil by-products have also been identified as a low-cost alternative source for plant-based ice cream production, with overrun values between 22.02% and 28.33% achieved without negatively impacting sensory qualities (Kasapoglu et al., 2023).

In non-dairy ice cream formulated from cashew milk and coconut cream, fat content varied from 6.04% to 10.46% and protein content from 3.71% to 4.60% as the proportion of coconut cream increased (Matabura, 2023).

Beyond coconut and fruit-based formulations, plant-based ice creams have also been developed using nuts, cereals, and legumes as dairy substitutes. Vegan ice cream produced from hazelnut cake contained 3.67% protein, 8.00% fat, 16.99% carbohydrate, and 3.22% dietary fiber per 100 g, with a caloric value of 133 kcal/100 g, representing an 18% reduction compared to conventional dairy ice cream.

The overrun of 4.01% compared to 15.39% in the dairy control (Aydemir et al., 2025).

Plant-based ice cream formulated from a fermented gluten-free and lactose-free base of rice, lentil and chickpea contained 3.52% protein, 4.65% fat, 25.69% carbohydrate and 5.20% dietary fiber, with an overrun of 19.3% (Pontonio et al., 2022).

Plant-based ice cream formulations produced from cereal-based milk sources such as oat, millet and spelt, combined with vegetable oleogels as fat sources, exhibited protein contents ranging from 1.32% to 3.40% and fat contents from 3.12% to 9.74% depending on the type of plant milk and oleogel concentration used (Ropciuc et al., 2024).

The physicochemical and rheological properties of plant-based ice creams vary with the type of plant milk and protein source used (Hidas et al., 2023; Leahu et al., 2022).

Hemp drink-based vegan ice creams produced with different plant proteins exhibited pH values ranging from 6.1 to 6.4 depending on the protein source used, with walnut protein yielding the lowest pH and hemp protein the highest (Hidas et al., 2023).

The rheological behavior of plant-based ice cream mixes was pseudoplastic, with apparent viscosity values between 0.016 and 0.426 Pa·s at a shear rate of 50 s^{-1} and flow behavior index values between 0.664 and 0.974, while

maximum meltdown rate decreased with increasing overrun (Hidas et al., 2023).
In almond milk and hemp milk ice creams, pH values of 6.2 and 5.3 were recorded for the control samples respectively, with fat content of 2.67% and protein content of 1.09% in almond milk formulations, and the addition of dietary fibers resulted in increased viscosity and hardness (Leahu et al., 2022).

Comparative analysis

The fundamental differences in raw materials and processing conditions significantly dictate the final technical and nutritional profile of the frozen desserts. Standard dairy ice cream mix exhibited an overrun of 65.04% (Alvarez et al., 2005) and a protein content of approximately 4.8% (Szkolnicka et al., 2020).
The pH of dairy ice cream was reported at 6.47 (Beegum et al., 2022) and 6.80 (Aydemir et al., 2025). Fruit-based sorbets exhibited a pH of 3.32 and a fat content of 0.36 g/100 g (Sangteerakij et al., 2022).
Plant-based formulations recorded overrun values as low as 4.01% (Aydemir et al., 2025), with fat content reaching values comparable to dairy ice cream depending on the fat source used (Matabura, 2023). Low overrun values in both fruit-based and plant-based categories were attributed to the low protein content of these matrices (Petkova et al., 2022).
Plant-based ice cream exhibited higher hardness than dairy ice cream (Pontonio et al., 2022). The primary physicochemical, textural, and nutritional parameters across the three categories are summarized in Table 1.

Table 1. Comparative Analysis of Frozen Matrices

Parameter	Dairy	Plant-Based	Sorbet	Source
pH	6.47–6.80	5.3–6.4	3.32–3.88	Beegum et al. (2022); Aydemir et al. (2025); Hidas et al. (2023); Leahu et al. (2022); Sangteerakij et al. (2022); Petkova et al. (2022)
Overrun (%)	65.04	4.01–19.3	8.11–44.72	Alvarez et al. (2005); Pontonio et al. (2022); Petkova et al. (2022); Sangteerakij et al. (2022)
Hardness (N)	7.08	19.99	-	Pontonio et al. (2022)
Fat (%)	~10	2.67–10.46	0.36–0.50	Szkolnicka et al. (2020); Leahu et al. (2022); Matabura (2023); Sangteerakij et al. (2022); Williams et al. (2022)

The melting rate of dairy ice cream was reported at 0.15 g/min (Ng et al., 2024).
The firmness of dairy ice cream was reported at 48.2 g, lower than the 350.8 g recorded for plant-based ice cream formulated with pea protein isolate (Ng et al., 2024). Vegan ice cream produced from hazelnut cake exhibited a melting time of 68 minutes, compared to 99 minutes recorded for dairy ice cream (Aydemir et al., 2025). Hemp drink-based vegan ice creams exhibited onset melting temperatures between -7.21 and -9.66°C, with unfreezable water content ranging from 25.27 to 48.10% (Hidas et al., 2023).

Table 2. Rheological, Textural and Thermal Properties of Dairy and Plant-Based Ice Cream

Parameter	Dairy	Plant-Based	Source
Melting rate (g/min)	0.15	-	Ng et al. (2024)
Firmness (g)	48.2	350.8	Ng et al. (2024)
Melting time (min)	99	68	Aydemir et al. (2025)
Onset temp (°C)	-7.12	-7.21 to -9.66	Alvarez et al. (2005); Hidas et al. (2023)
UFW (%)	51.14	25.27–48.10	Alvarez et al. (2005); Hidas et al. (2023)

Correlation between physicochemical properties and functional packaging requirements

The comparative analysis of dairy, fruit-based, and plant-based frozen desserts highlights significant differences in composition, structure, and stability, which directly translate into distinct packaging requirements.

Influence of fat content and structural network on oxidative and light sensitivity

Differences in lipid content and composition influence the susceptibility of frozen desserts to oxidative degradation, particularly under exposure to oxygen and light (Christophersen et al., 1992).
From a packaging perspective, products containing lipids require materials with effective oxygen barrier properties and protection against light in order to limit oxidation and preserve quality during storage (Christophersen et al., 1992).
Even in low-fat systems, packaging strategies should consider the protection of sensitive bioactive compounds, such as phenolics, which may also undergo oxidative degradation (Singh et al., 2022).

Influence of water content on moisture migration and recrystallization

Differences in water mobility and phase distribution influence the stability of frozen desserts during storage, particularly in relation to ice recrystallization and texture degradation.

From a packaging perspective, these variations require the use of materials with effective moisture barrier properties to prevent dehydration and freezer burn. Additionally, maintaining temperature stability throughout storage and distribution is essential to limit recrystallization and preserve product structure (Kummar et al., 2020).

Effect of overrun on thermal behavior and melting stability

Differences in overrun significantly influence heat transfer and melting behavior in frozen desserts. Products with lower overrun exhibit higher density and increased thermal conductivity, resulting in faster melting under temperature fluctuations (Kilicli et al., 2025; Hidas et al., 2023).

Consequently, these systems require enhanced thermal insulation and improved temperature buffering capacity during storage and distribution in order to maintain structural stability and delay melting (Kilicli et al., 2025; Hidas et al., 2023).

Impact of pH on material compatibility

Differences in pH influence the chemical stability of packaging materials and their interaction with frozen dessert matrices. Acidic systems may promote material degradation or increase the risk of compound migration.

Therefore, low-pH products require the use of acid-resistant materials with appropriate chemical stability, as well as polymers designed to ensure migration safety under acidic conditions (Gupta et al., 2024).

Role of sugar composition in freezing point depression and stability

Differences in sugar composition influence freezing behavior and sensitivity to temperature fluctuations in frozen desserts.

From a packaging perspective, systems with lower freezing stability require strict cold chain control and packaging solutions capable of minimizing temperature fluctuations in order to prevent partial melting and preserve product integrity during storage and distribution (Güven & Karaca, 2002; Kumar et al., 2020).

CONCLUSIONS

The three categories of frozen desserts show distinct physicochemical characteristics that directly influence their structural stability, melting behavior, and response to storage conditions. Differences in lipid composition, water mobility, air incorporation, pH, and sugar profile were identified as key factors governing thermal sensitivity, recrystallization, and overall product stability.

Dairy ice cream demonstrated greater structural stability due to its balanced multiphase system, while fruit-based desserts were more susceptible to temperature fluctuations and structural degradation. Plant-based systems showed high variability depending on the raw materials used, often presenting intermediate or less predictable stability profiles.

These compositional differences translate into specific packaging requirements. Systems with higher lipid content require effective oxygen and light barriers to prevent oxidation, while products with high water mobility demand strong moisture barriers and strict temperature control to limit recrystallization and dehydration. In addition, products with lower thermal stability or overrun require enhanced insulation and temperature buffering during storage and distribution.

Overall, the findings emphasize that frozen desserts should not be treated as a uniform category from a packaging perspective. Instead, the design of functional packaging systems must be tailored to the specific physicochemical characteristics of each product type in order to ensure quality preservation, extend shelf life, and improve product performance throughout the cold chain.

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