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Formulation and characterization of basil-flavoured oat-based milk substitute ice cream as a sustainable alternative to dairy ice cream

Deepika Shrestha, Alisha Pradhan, V. Sai Sharanya Palletti, R. B. Swethapriya and M. Srijaya*

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The growing demand for sustainable dairy alternatives has driven innovation in plant-based frozen desserts like oat-based milk substitutes (OMS). In this study, whole oat groats were processed into a plant-based milk substitute using the combined acid–enzyme hydrolysis technique, leveraging their low environmental impact and desirable techno-functional properties, including effective emulsifying and stabilizing capacities to develop basil-flavored oat-based milk substitute ice cream. Among the various formulations explored, OMS replacing dairy milk at 50% and 100% levels, in combination with 10% basil leaf extract, demonstrated superior acceptability and was used for the development of ice cream. The physicochemical, rheological, textural, nutritive, storage, organoleptic, and microbial parameters of the Basil-Flavoured Oat-based Milk Substitute (BF-OMS) ice creams were assessed and compared with full-cream dairy milk (FCDM) ice cream as the control. The experimental samples showed optimum pH and titrable acidity values, *i.e.*, 6.91–6.94 and 0.25–0.27%, respectively. The resultant higher total carbohydrate (40.7–51.76%), total solids (48.70–55.95%), and total ash content (1.05–1.15%) in OMS ice creams led to an increased viscosity of the OMS ice-cream mix, ranging from 35.13 to 146 cP, improving their melting properties and structural integrity. BF-OMS ice creams exhibited pseudoplastic, non-Newtonian behaviour with higher viscosities than the control and a strong power law model fit (R^2 = 0.998). The presence of β-glucans in the OMS might have contributed to enhanced gelling and water-binding capacities, resulting in desirable firmness and a smooth texture. The nutritional analysis showed that the partially substituted BF-OMS ice cream maintained the protein content (4.69%), comparable to the control (5.39%). Both 50% and 100% BF-OMS ice-creams had lower fat content (1.1–2.25%) compared to the control (4.1%). Additionally, OMS ice creams exhibited significantly higher total polyphenol content (45.44–46.68 mg GAE/100 g) and DPPH inhibition activity (89.85–92.81%) than the control. More importantly, an increment was observed in total polyphenols (26.34–58.05%) and DPPH inhibition activity (1.70%) in experimental samples at the end of 15 days of storage, indicating enhanced antioxidant potential during storage studies. Overall, the findings suggest that BF-OMS ice creams with dairy milk substitution can support a more sustainable industry transition with high consumer acceptance.

Sustainability spotlight

Rising concerns about the environmental impact and potential health risks of dairy production and consumption have encouraged many consumers to seek plant-based alternatives. Basil-flavoured oat milk ice cream offers a delicious and creamy dessert that matches conventional dairy milk-based ice cream in taste and texture, while also providing health-promoting bioactive compounds. Oats, being a climate- and resource-friendly crop, make it possible to expand the availability of oat-based products and support food security. Additionally, producing ice cream from oat milk requires significantly less energy and resources, resulting in fewer greenhouse gas emissions and a notably smaller carbon footprint. This not only encourages more sustainable consumption patterns but also contributes to efforts against climate change. In this way, our research directly supports UN Sustainable Development Goals 2 (Zero Hunger), 12 (Responsible Consumption and Production), and 13 (Climate Action), leading toward a healthier and more resilient global food system.

1. Introduction

Ice cream has always been the most popular frozen dairy dessert, packed with calories and nutrients. Its demand has risen not only in India but across the globe. The Business

Department of Food and Nutritional Sciences, Sri Sathya Sai Institute of Higher Learning (Deemed to be University), Anantapur 515002, Andhra Pradesh, India. E-mail: deepikas@sssihl.edu.in; alishapradhan@sssihl.edu.in; sharanyapalleti98@gmail.com; swetha.bala97@gmail.com; msrijaya@sssihl.edu.in; Tel: +91-924742399

Research Company projects that the global ice cream market will grow from $42.07 billion in 2024 to $44.69 billion in 2025, reflecting a steady annual growth rate of 6.2%.[1] According to Expert Market Research, the Indian ice cream market was valued at about USD 3.46 billion in 2024. The market is expected to expand at a compound annual growth rate of 15.00% from 2025 to 2034, potentially reaching a value of approximately USD 14.00 billion by 2034.[2]

At the same time, several factors affect this upward trend, including the seasonal appeal of ice cream, more effective marketing and advertising, innovative packaging solutions, and increasing health concerns such as calorie issues, endocrine disorders, cow milk allergies and lactose intolerance, lactase enzyme malabsorption, and hypercholesterolemia. Other factors include a growing preference for alternatives to bovine milk for ethical and environmental reasons, along with changing needs and urbanization.[1,3–7]

In response to these trends, many people use plant-based milk substitutes for their ice cream, meeting today's sustainability demands. Oat-based milk substitute has a significantly lower climate footprint than dairy milk because it avoids emissions linked to livestock, manure, and the cultivation of animal feed. Research by Mäkinen *et al.* (2015), as stated by Röös *et al.* (2016), shows that direct emissions from sources like animals, fertilizers, and energy use are 16–41% lower in oat milk substitute production compared to traditional dairy farming.[8] Supporting this, a study by Riofrio & Baykara (2022) found that oat beverages perform much better environmentally—producing over 80% fewer greenhouse gas emissions than cow's milk.[9] Moreover, the study by Aydar *et al.* (2020) reports that oats are often cultivated alongside crops like grass-clover and legumes. These plants improve soil health by enhancing nitrogen fixation and structure, supporting beneficial organisms that control pests naturally, reducing reliance on chemical pesticides, and benefiting the environment by protecting water quality and pollinators.[10] Additionally, the land saved by shifting away from dairy farming could be repurposed for bioenergy production with lower nitrogen losses, wetland restoration, or more sustainable crop cultivation—all of which can help reduce problems like acidification and water pollution.[11]

In addition to these advantages, OMS—like other plant-based milk alternatives—also provides valuable nutritional components and functional properties that make it a suitable dairy substitute. Whole oat (*Avena sativa*) milk substitute was first developed by Swedish scientists in the 1990s, named OATLY as a sustainable, lactose-free alternative to dairy milk.[12] A health claim was also permitted by the FDA in 1997 based on extensive clinical evidence that links oat β-glucan to a lowered chance of coronary heart disease.[13] Due to their high nutritional value, various products have been developed from wholesome oats, like bread, biscuits, cookies, probiotic drinks, breakfast cereals, flakes, and infant food.[14]

Similarly, the addition of herbs in food delivers multifunctional properties, not only enhancing nutritional quality but also acting as additives, improving the organoleptic properties, and extending shelf stability.[15] Moreover, the herbs have demonstrated several health benefits on consumption, like anti-mutagenic, anti-inflammatory, and antioxidant properties, and immune modulatory properties.[16] Therefore, incorporating herbs in dairy products can be one of the techniques to improve health conditions through the intake of nutritious food.[17]

Basil (*Ocimum basilicum*) has been widely used as a flavouring ingredient because of its distinctive flavour, which is due to the presence of major compounds like linalool, estragole, methyl cinnamate, eugenol, and cineole.[18]

Although considerable amount of research has focused on the nutritional profile, physico-chemical properties, texture, and taste of dairy-based ice cream, limited scientific literature has explored the integration of plant-based milk substitutes for sustainable ice cream development. Hence, to address this gap, the present study explored the feasibility of developing new dessert formulations by replacing dairy milk with OMS, thereby reducing reliance on dairy milk and promoting the utilization of plant-based milk substitutes. Furthermore, the incorporation of basil leaf extract as a flavouring agent in the plant-based ice cream can be an innovative technique to combine various medicinal, organoleptic, and nutritional characteristics in a single yet unique functional product, deriving the holistic idea about the value addition of the natural herb basil into ice cream. Overall, the study highlights a novel approach towards the development of functional, plant-based value-added frozen desserts that respond to consumer demands for healthier and more sustainable food alternatives.

2. Materials and methods

2.1 Materials

Whole oat groats (Urban Platter store), spray-dried milk powder (Sagar Company), vanilla flavor (Ossoro Company), sodium alginate (Tripathi Products), glycerol monostearate (Tripathi Products), calcium chloride (AksharChem India Ltd), amylase enzyme (AksharChem India Ltd), and citric acid (AksharChem India Ltd) were procured from various online sources, including Urban Platter and Amazon. All these ingredients were food grade.

Pasteurized and UHT-treated full-cream milk (Arokya–Hatsun Brand Product Ltd), low-fat fresh cream (AmulFed Dairy), commercial food-grade sucrose, and fresh basil leaf (used for basil flavor) were sourced from the local market in Anantapur, Andhra Pradesh, India.

2.2 Formulation and optimization of basil-flavoured oat-based milk substitute (BF-OMS) ice cream

2.2.1 Extraction of oat-based milk substitute (OMS). OMS was extracted for the formulation of Basil-Flavoured Oat-based Milk Substitute (BF-OMS) ice creams using a modified method that combined both acid and enzymatic extraction techniques consecutively among the different extraction techniques, as summarized in Table 1.[19] These methods were chosen based on their effectiveness in maximizing yield and producing sensory attributes resembling to FCDM.

2.2.2 Optimization of full cream dairy milk substitution with oat-based milk substitute (OMS). To determine the

Table 1 Methods of extraction of the oat-based milk substitute[12,42]

Hydrolytic treatment	Acid-hydrolytic treatment	Enzyme hydrolytic treatment	Acid and enzyme hydrolytic treatment
25 g Whole oat groats ↓ Blending with 7 times dilution with distilled water (w/w) ↓ Slurry ↓ Filtration ↓ OMS	25 g Whole oat groats ↓ Blending with 7 times dilution with distilled water (w/w) ↓ Slurry ↙ ↘ 0.5% citric acid (5 ml) / 1% citric acid (5 ml) ↓ OMS	25 g Whole oat groats ↓ Blending with 7 times dilution with distilled water (w/w) ↓ Slurry ↓ Heat treatment (65 °C) ↓ 0.04% $CaCl_2$ (catalyst) at 50 °C ↓ 0.00025 g (α amylase enzyme) at 75 °C ↓ 45 min of liquefaction at 75 °C along with continuous agitation ↓ OMS ↓ Inactivation of enzyme at 95 °C for 5 minutes	25 g Whole oat groats ↓ Blending with 7 times dilution with distilled water (w/w) ↓ Slurry ↓ Heat treatment (45 °C) ↓ 1% citric acid (5 ml) ↓ 0.04% $CaCl_2$ (catalyst) at 50 °C ↓ 0.00025 g (α amylase enzyme) ↓ 40/60 min of liquefaction at 75 °C (continuous agitation) ↓ OMS ↓ Inactivation of enzyme at 95 °C for 5 minutes

optimal level of full cream dairy milk substitution with OMS in BF-OMS ice cream, initially the substitutions were made at – 20% (O2), 25% (O3), 50% (O4), 75% (O5), 80% (O6), and 100% (O7) and compared against a reference sample with 100% FCDM (O1) in terms of organoleptic characteristics.

2.2.3 Extraction and optimization of basil leaf extract infusion percentage. Fresh basil leaf extract was used to enhance the flavor of the OMS-based ice creams. Fresh basil leaves were thoroughly washed, blended with an equal amount of water, and gently blanched at 50 °C for 3 minutes. After cooling to room temperature, the leaves were ground into a smooth paste and strained through a muslin cloth to obtain a fine extract.[20]

The percentage of basil leaf extract infusion was optimized by evaluating concentrations of 5%, 10%, and 15% on OMS blends. Based on sensory evaluation by 18 semi-trained panellists using a 9-point hedonic scale, the best infusion concentration was selected for the BF-OMS ice cream formulation. The basil leaf extract-infused OMS blends were further analysed by the same sensory panel to determine the most suitable substitution levels of FCDM with OMS for ice cream formulation and to facilitate subsequent characterization.

2.2.4 Preparation of ice creams. In the preparation of BF-OMS ice cream, the selected OMS blend/100% OMS was heated in a double boiler at 63 °C for 30 min and then cooled to 50 °C.[21] Reconstituted skimmed milk powder (in hot water) and cream were added to the OMS at 60 °C and sugar at 70 °C with constant stirring. Furthermore, the emulsifier (glycerol monostearate) and stabilizer (sodium alginate), each previously dissolved separately in hot water, were added to the mix. The mix was then pasteurized at 80 °C for 30 minutes to eradicate harmful microorganisms as well as improve emulsification.[22] Next, the pasteurized mix was cooled and blended for 10–20 minutes using a manual blender (Philips mixer, HR 1453, 175 watts). The blended mix was then allowed to hydrate by aging at 4 °C for 12 hours.[22] Following the ageing process, the mix was flavoured with 10% basil leaf extract. The mix was then processed in the ice-cream maker (Skyline Model No: VI-1919), frozen, and stored at −18 °C for further analysis.[22] The same procedure was used for the control, except that the flavour used was 0.25% vanilla instead of basil leaf extract.

The two formulated BF-OMS ice cream samples were designated as IO1 (50% substitution) and IO2 (100% substitution), while the control sample was IC (0% substitution, 100% FCDM ice cream). These samples were further subjected to detailed characterization analyses.

3. Characterization of basil flavoured oat-based milk substitute ice-creams

3.1 Physicochemical analysis

The FCDM, OMS, and formulated ice creams were subjected to physicochemical and nutritional analysis to assess parameters such as pH, titratable acidity, total solids, fat content, protein content, total carbohydrates, total ash content, and viscosity. Furthermore, the ice cream samples were tested for specific gravity, weight per gallon, overrun, and melting resistance.

The pH of the FCDM, OMS, and ice cream samples was measured using a calibrated pH meter (L1 120ELICO, India) at 25 °C by dipping the glass electrode in 50 ml of the samples with constant stirring. The titratable acidity (as lactic acid) was determined by titrating the samples with 0.1 N NaOH using phenolphthalein as an indicator.[23] A gravimetric assay was adopted to measure the total solids.[24] The specific gravities of the ice cream samples were determined using the method described by Winton (1958) as cited in Veer *et al.* (2019).[25,26] The weight per gallon (in kilograms) was calculated according to Burke (1947) by multiplying the specific gravity of the ice cream samples by the factor 4.5461.[27] Overrun was calculated using the equation given by Jimenez-Flores *et al.* (1992) as cited in Batista *et al.* (2019) with a standard measuring cup.[28] The melting resistance was evaluated according to the experimental design developed by Muse and Hartel (2004).[29]

3.2 Rheological and textural analysis

A digital Brookfield Viscometer model DV-II (Brookfield Engineering Laboratories, Stoughton, MA, USA) was used to determine the apparent viscosity of the FCDM, OMS, and the ice cream mixes of IC, IO1, and IO2 after ageing for 24 hours at 4 °C, and the melted ice cream. All measurements of viscosity were obtained at 15 ± 2 °C using an LV2-6 set at 100–200 rpm (manual of Brookfield Viscometer).

The flow behavior of the melted ice cream samples was examined by measuring shear stress over a range of 0.5 to 200 s^{-1} within 120 seconds at 20 °C. This analysis was performed using an Anton Paar MCR-302e rheometer equipped with a cone-plate setup. The cone had a radius of 55 mm, and the gap between the cone and plate was set to 0.103 mm. Before measurement, the melted ice cream samples—IC, IO1, and IO2—were rested for five minutes. Additionally, the Power Law model was applied to assess the non-Newtonian properties of the ice cream samples,

$$\alpha = K\dot{\gamma}^n$$

Here, σ represents the shear stress, K is the consistency index, $\dot{\gamma}$ denotes the shear rate, and n is a dimensionless value indicating how closely the flow behavior resembles that of a Newtonian fluid. The values of K and n were determined through non-linear regression analysis using Microsoft Excel 2021.[30]

A texture analyzer (TA-XT Plus, Stable Microsystems) was used to measure key properties of the ice cream samples, including hardness, adhesiveness, cohesiveness, gumminess, springiness, and chewiness. The tests were performed at 25 °C using a 2 mm stainless steel cylindrical probe (P2) with a trigger force of 5 g. The probe penetrated 20 mm into the center of the ice cream samples at a speed of 5 mm per second.[30]

3.3 Nutritional analysis

The total ash content in the FCDM, OMS, and ice cream samples was analysed using the AOAC Official Method.[31] Fat and protein contents were estimated using the Gerber method and the Lowry method, respectively.[24,32] The total carbohydrate content was determined by difference using the following equation:

$$\begin{aligned}\text{Total carbohydrate content }\% = 100 &- \text{moisture content }(\%)\\ &- \text{total protein content }(\%) - \text{total fat content }(\%)\\ &- \text{total ash content }(\%).\end{aligned}$$

$$^{*}\text{Moisture content }\% = 100 - \text{total solids }\%$$

This method is approved by the FAO (2003) and the Food Safety and Standards Authority of India (2015).[24,33]

3.4 Storage stability

To evaluate the impact of storage on the stability and quality of the formulated basil-flavoured ice cream samples, key parameters such as fat destabilization index, color, total polyphenol content, DPPH antioxidant activity, organoleptic properties, and microbial stability were assessed on day 0 and after 15 days of storage.

The fat destabilization index was determined by the spectrophotometry method, according to the Bolliger *et al.* (2000) method.[34] Color was measured using a Minolta colorimeter CR-200 (Minolta Camera Co., Osaka, Japan). The color of the samples was obtained by measuring L^* (brightness; 0: black, 100: white), a^* (+: red; −: green), and b^* (+: yellow; −: blue) values by reflection of light.[35] Total polyphenol content was determined using the Folin–Ciocalteu colorimetric method according to Hwang *et al*. (2009).[36] The phytochemical and antioxidant properties were measured using the DPPH assay, *i.e.*, free radical scavenging method developed by Kedare S. B. (2011).[37]

In addition, an organoleptic evaluation was carried out for the ice cream samples to assess their overall acceptability using a modified ice cream scorecard from the American Dairy Science Association[38] (see SI, Table S1 and Fig. S1 and S2 for reference). Around 30 grams of ice cream were taken from the freezer and placed in odourless cups. The quality of the ice creams was assessed by following the maximum score for each category – flavouring system, body and texture, color and appearance, melting quality, and overall acceptability, with deductions made for any defects. The maximum score was given to each category if the sample met the standard of the ideal ice cream and exhibited no noticeable defects. Panellists were trained to recognize quality attributes and defects in ice cream.[38]

Furthermore, to ensure the microbial safety and quality of the ice cream samples during storage, the total bacterial count was determined by using the standard plate count (SPC) method with Plate Count Agar (PCA - Himedia) as described by Aneja K. R. (2007).[39]

Biochemical tests (indole test, methyl red test, and Voges–Proskauer test) were also carried out to identify bacteria, especially *E. coli*, based on their biochemical properties and enzymatic reactions following the method described by Aneja K. R. (2007).[39,40]

3.5 Statistical analysis

The mean and standard deviation were calculated for each parameter measured in the ice cream samples. To examine significant differences between full cream dairy milk and OMS, the Student's *t*-test was applied. Additionally, ANOVA followed by Duncan's multiple range test (DMRT) was used to analyze differences among treatments and storage durations, all performed using SPSS 30 software.

4. Results and discussion

4.1 Yield % and sensory characteristics of OMS

The combined method of acid (citric acid) and enzymatic (α-amylase) hydrolytic extraction, followed by 60 minutes of liquefaction, resulted in OMS with a yield of 78.5%, along with a smooth, mildly sweet taste free from raw or starchy notes, as recorded in Table 2. A consistency similar to full-cream dairy milk was attained by limiting starch gelatinization *via* controlled enzymatic hydrolysis of starch using alpha-amylase, in combination with acidic treatment, which modifies starch structure and reduces excessive viscosity development. Furthermore, the production of dextrins from the starch hydrolysis might have developed mild sweetness, improving the overall mouthfeel of the OMS.[12,41,42]

4.2 Analysis of full cream dairy milk (FCDM) and oat-based milk substitute (OMS)

The significant compositional differences between dairy milk and oat-based milk substitute (OMS) were revealed through the independent sample *t*-test results across all the measured physicochemical parameters (Table 3). The independent sample *t*-test revealed significant compositional differences ($p < 0.05$) between dairy milk and OMS across all measured parameters. Dairy milk exhibited a significantly higher pH compared to OMS. OMS showed significantly higher titratable acidity than dairy milk. Viscosity was also significantly greater in OMS (7.32 ± 0.11 cps) than in dairy milk (3.98 ± 0.83 cps). In contrast, dairy milk had significantly higher total solids (11.65 ± 0.85% *vs.* 6.83 ± 0.22%), fat (6.00 ± 0.20% *vs.* 0.96 ± 0.04%), and protein content (3.71 ± 0.66% *vs.* 0.76 ± 0.04%). Conversely, OMS contained significantly higher carbohydrate levels (5.36 ± 0.05%) than dairy milk (3.81 ± 0.47%), as well as higher ash content (0.80 ± 0.05% *vs.* 0.65 ± 0.03%). These findings were similar to the discoveries of Sangami & Radhai (2018).[43]

It can be inferred from the above results that OMS is mildly acidic in nature and also exhibits high viscosity, which could be due to the higher β-gluten content and its good water-binding capacity. Moreover, a higher percentage of total solids was observed, which could be due to the higher molecular weight of OMS. The fat and protein content in the sample was found to be considerable compared to other cereals. Carbohydrate was found to be high, which may be due to its composition, consisting of 50–60% starch.[44] The finding showed an optimum amount of ash content in the OMS, which may be due to the higher mineral content. Overall, the results suggest that replacing dairy milk with OMS introduces statistically significant ($p < 0.05$) and nutritionally relevant variations in composition.

Table 2 Yield % of the oat-based milk substitute obtained by different extraction methods[a]

Extraction process	Yield/25 g sample	Observation
Hydrolytic extraction	60%	Off-white in color, raw starchy flavour, thin consistency
Acid hydrolysis treatment	86.5%	Off-white, thinner consistency, raw starchy flavour
	63%	Off-white, thinner consistency, raw starchy flavour
Enzymatic hydrolysis	70%	Light brown, moderately viscous consistency, cooked starchy flavour
Acid and enzyme hydrolysis	63.5% (40 min liquefaction) 78.5% (60 min liquefaction)	Light brown in appearance, optimum consistency resembling that of milk, cooked starchy flavour

[a] The yield % of the OMS was calculated after the enzymatic treatment and filtration of the slurry. The yield was calculated in w/w % of the oat slurry.[80]

Table 3 Physicochemical and rheological characteristics of Full Cream Dairy Milk (FCDM) and Oat-based Milk Substitute (OMS)[a]

	Types of milk	
Parameter	Full cream dairy milk (FCDM)	Oat-based milk substitute (OMS)
pH	6.43 ± 0.23	4.35 ± 0.04*
Titrable acidity (%)	0.22 ± 0.05	0.38 ± 0.07*
Viscosity (cP)	3.98 ± 0.83	7.32 ± 0.11*
Total solids (%)	11.65 ± 0.85	6.83 ± 0.22*
Fat (%)	6 ± 0.20	0.96 ± 0.04*
Protein (%)	3.71 ± 0.66	0.76 ± 0.04*
Carbohydrate (%)	3.81 ± 0.47	5.36 ± 0.05*
Ash (%)	0.65 ± 0.03	0.80 ± 0.05*

[a] * indicates a significant difference between samples ($p < 0.05$; Student's t-test). Values are presented as mean ± S.D, with $n = 3$.

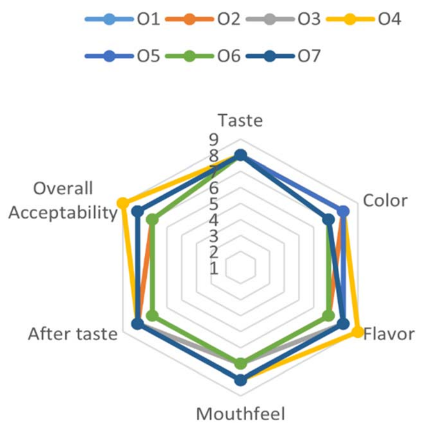

Fig. 1 Mean sensory scores of Oat-based Milk Substitute O1 (0%), control, O2 (20%), O3 (25%), O4 (50%), O5 (75%), O6 (80%), O7 (100%) formulations for taste, color, flavor, mouthfeel, aftertaste, and overall acceptability. Scores are based on a 9-point hedonic scale.

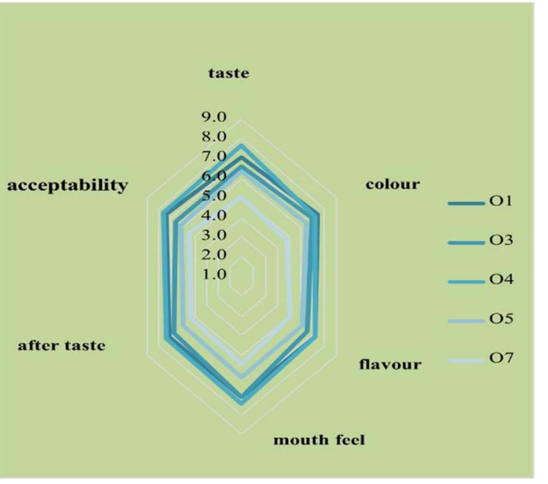

Fig. 2 Sensory evaluation scores of ice cream samples formulated with different levels of oat-based milk substitute (OMS) and 10% basil leaf extract. Mean sensory scores for taste, colour, flavour, mouth feel, aftertaste, and overall acceptability of ice cream samples—O1 (0%, control), O3 (25%), O4 (50%), O5 (75%), and O7 (100%)—containing varying OMS levels and 10% basil leaf extract. Sensory scores are based on a 9-point hedonic scale.

4.3 Basil flavoured oat-based milk substitute ice cream formulation

Based on sensory evaluation, 18 semi-trained sensory panel members preferred the milk samples with 25% (O3), 50% (O4), 75% (O5), and 100% (O7) substitution of FCDM with OMS over other substitution levels, as shown in Fig. 1. Similarly, sensory evaluation for different basil infusion concentrations in milk blends showed that 10% infusion of basil leaf extract in the OMS achieved the highest score for maintaining a good balance of flavor with OMS flavor, as given in Table 4. Considering the sensory acceptability of these milk formulations, two substitution levels—50% (O4) and 100% (O7) replacement of FCDM with OMS and 10% infusion of basil leaf extract were selected for subsequent ice cream development for a detailed study (Fig. 2). A 50% substitution was chosen to evaluate partial replacement of dairy milk while retaining sensory quality and a 100% substitution, to explore the feasibility of complete dairy milk replacement.

4.4 Physicochemical properties of formulated basil flavoured oat-based milk substitute (BF-OMS) ice creams

Table 5 presents the physicochemical composition of the BF-OMS ice creams (IO1 and IO2) along with the control, IC. The mean pH value in the control ice cream, IC, was 6.96, and in the developed BF-OMS ice creams, IO1 and IO2, ranged from 6.91 to 6.94. Statistically, no significant difference in pH between the control (IC) and IO1 was present, while IO2 exhibited a significant ($p < 0.05$) difference compared to both the control, IC, and IO1. This indicates that incorporating OMS, which is naturally slightly acidic, helps in maintaining the pH of the ice cream within an optimal range. These observations are consistent with

Table 4 Sensory characterization of basil leaf infusion in Oat-based Milk Substitute (OMS)

	Percentage of basil extract infusion		
Sensory attributes	5% Extract	10% Extract	15% Extract
Color	Very pale	Light green	Light green
Flavour	Dominant oats' starchy flavor	Mild basil	Strong basil
Taste	Dominant oats' starchy taste	Distinct basil	Pronounced basil
After taste	Retention of oats' starchy aftertaste	Refreshing and smooth mouthfeel	Astringent aftertaste
Acceptance	Very low	Very high	Moderate

Table 5 Physicochemical and nutritional properties of Basil Flavoured Oat-based Milk Substitute (BF-OMS) ice creams[a,b]

	Sample		
Parameter	IC (0%)	IO1 (50%)	IO2 (100%)
pH	6.96 ± 0.01^b	6.94 ± 0.01^b	6.91 ± 0.01^a
Titrable acidity (%)	0.38 ± 0.1^b	0.27 ± 0.1^a	0.25 ± 0.1^a
Total solids (%)	45.50 ± 1.2^a	48.70 ± 0.4^b	55.95 ± 2.3^b
Overrun%	30.03 ± 1.45^b	25.23 ± 0.23^a	23.29 ± 0.35^b
Specific gravity	1.05 ± 0.01^b	1.03 ± 0.01^a	1.08 ± 0.01^b
wt/gallon (kg)	4.77 ± 0.03^a	4.67 ± 0.16^a	4.93 ± 0.04^b
Total ash%	0.55 ± 0.01^a	1.05 ± 0.05^b	1.15 ± 0.05^b
Total carbohydrate (%)	35.56 ± 1.44^a	40.7 ± 1.41^b	51.76 ± 0.96^c
Protein (%)	5.39 ± 0.51^b	4.69 ± 0.63^a	2.04 ± 0.16^a
Fat (%)	4.1 ± 0.1^b	2.25 ± 0.05^a	1.1 ± 0.1^a

[a] Values are mean ± S.D, $n = 3$. [b] Means within treatments in a column having different superscripts are significantly different ($p < 0.05$).

previous studies (El-Kholy, Amira M, 2005).[45] The free fatty acids and phenolic acids (avenalumic acid) in OMS and the combined acid and enzymatic extraction methods promote the release of organic acids, which support the maintenance of optimum pH and acidity in BF-OMS ice creams.[43,45,46] Maintaining optimum acidity in ice cream has been reported to enhance protein stability, improve flavour, whipping rate, viscosity, and inhibit microbial growth.[38,47]

In this study, total solids significantly ($p < 0.05$) increased with higher levels of OMS substitution in BF-OMS ice creams, *i.e.*, from 48.70% (IO1) to 58.95% (IO2) compared to the control, IC, *i.e.*, 45.50%. The experimental samples henceforth fulfil the requirement of at least 36% total solids as per the Indian regulation for ice cream.[38] Also, the observation is in line with the findings of Cody *et al.* (2007), who reported increased total solids with increasing starch concentration.[48] The increase could be due to the oat's high starch content (approximately 60% of total dry weight), along with 14% protein, 7% lipids, and 4% β-glucan present in the oat.[49] Additionally, the enzymatic hydrolysis of the starch by alpha amylases leads to the production of maltodextrins, thereby increasing the total content of the dissolved solids.[50]

Similarly, the overrun values in the BF-OMS ice creams, IO1 and IO2, were reduced (25.23% and 23.29% respectively) compared to the control (30.03%). Statistical analysis revealed a significant difference ($p < 0.05$) between the control and IO1, but no significant difference between the control and IO2. The lower overrun values suggest that the reduced fat content and increased viscosity from the OMS blending might have impeded the air incorporation in the experimental ice cream samples and resulted in a denser, creamier texture with a richer flavour. This result is consistent with the findings reported by the studies by Sangami and Radhai Sri (2018) and Adapa *et al.* (2000).[43,51]

Regarding the specific gravity, the resultant data in Table 5 show that the specific gravity of IO1 (1.03) was significantly ($p < 0.05$) lower than that of the control ice cream mix, IC (1.05), and IO2 (1.08), while IO2 showed the highest specific gravity among all the samples. The results obtained could be supported by the findings reported by Thomas *et al.* (2019), stating that the high water binding capacity of the β-glucan in OMS might have increased the specific gravity, which is advantageous in the formation of denser and richer products.[52]

Melting property is one of the important parameters that can influence the overall quality of ice cream. In this study, IO2 (100% OMS substitution) demonstrated better melting resistance with the first dripping at 270 s, quite close to the control at 277.5 s, showing no significant difference, while the complete meltdown time of IO1 and IO2 was comparable to that of the control sample, as demonstrated in Fig. 3 and 4, respectively. This similarity to the control's melting behavior demonstrates the formation of a stable structure attributed to the β-glucan in OMS, which might have enhanced the viscosity through its gelling properties, which in turn decreases the melting rate.[48,53] The significant ($p < 0.05$) increased viscosity observed in IO1 (27.30 cP) and IO2 (146 cP) after 12 hours of ageing likely

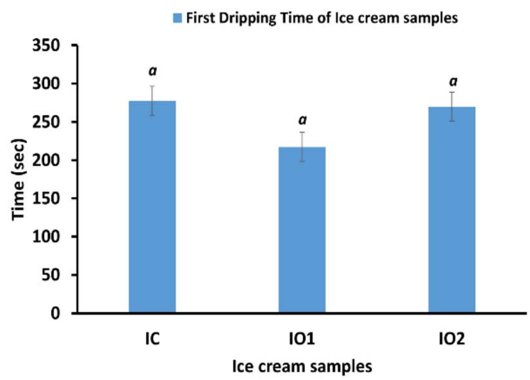

Fig. 3 The first dripping time (seconds) of ice cream samples with different levels of oat-based milk substitution; control (IC, 100% full cream dairy milk), IO1 (50% dairy substitution by Oat-based Milk Substitute), and IO2 (100% dairy substitution by oat-based milk substitute). Values are presented as mean ± standard error; bars with different superscript letters indicate significant differences at $p < 0.05$ (DMRT).

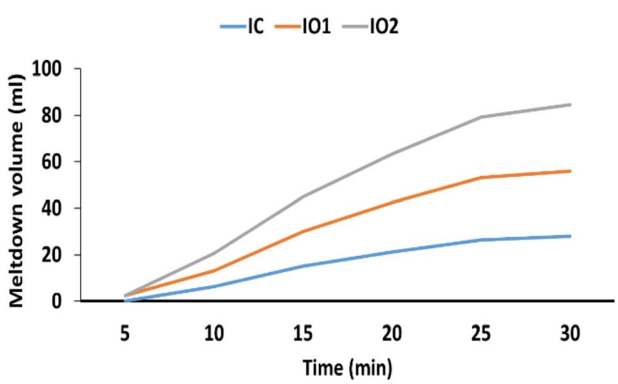

Fig. 4 Complete meltdown volume *versus* time for ice cream formulations: control (IC, 100% full cream dairy milk), IO1 (50% dairy substitution by oat-based milk substitute), and IO2 (100% dairy substitution by oat-based milk substitute).

Table 6 Rheological properties of control and Basil Flavoured Oat-based Milk Substitute (BF-OMS) ice cream mix and ice cream samples[a,b]

	Ice cream (mix)		Ice cream (melted)		
	Viscosity (cP)				
Sample	Before ageing	After ageing	Viscosity (cP)	Flow behavior index (n)	Consistency index (K, Pa s^n)
IC	37.70 ± 0.62[a]	23.8 ± 1.00[b]	218.13 ± 4.04[a]	0.41 ± 0.03[a]	4.5 ± 0.02[a]
IO1	27.30 ± 0.76[b]	35.13 ± 4.51[a]	316.90 ± 4.33[b]	0.42 ± 0.02[a]	6.23 ± 0.03[b]
IO2	32.50 ± 0.81[b]	146 ± 3.95[a]	321.93 ± 3.84[b]	0.39 ± 0.03[a]	7.79 ± 0.03[c]

[a] Values are mean ± S.D, $n = 3$. [b] Means within treatments in a column that have different superscripts are significantly different ($p < 0.05$).

contributed to their improved melting resistance by reducing the amount of free water, which resulted in significantly lower melting rates and penetration values. This, in turn, led to the development of a harder, more compact body and smoother texture compared to the control (IC).[52] These findings are further supported by Marshall (2003), who reported similar results.[38] Also, the bioactive compounds present in OMS (β-glucan, avenanthramides, polyphenols) might have improved the melting properties by increasing the induction time for the first dripping and slowing down the 50% melting time.[54,55] These compounds help in the formation of more stable hydrogen bonds and gel with the protein–polyphenolic network. This gel helps in improving the BF-OMS ice cream's resistance to melting and also retains a better shape.[56,57]

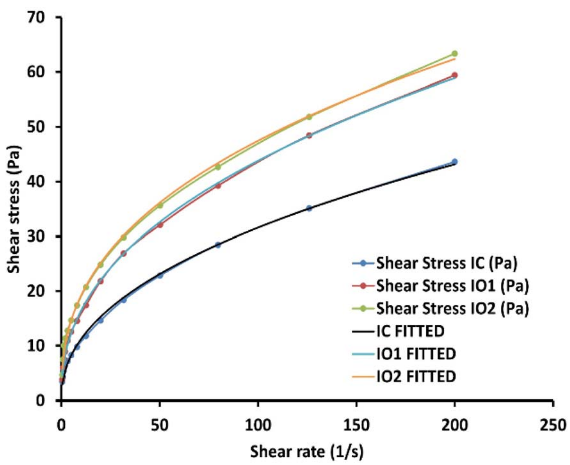

Fig. 5 Shear stress *versus* shear rate curves for ice cream formulations: control (IC, 100% full cream dairy milk), IO1 (50% dairy substitution by oat-based milk substitute), and IO2 (100% dairy substitution by oat-based milk substitute).

4.5 Rheological and textural analysis

Statistical analysis (Table 6) of the viscosity in ice cream mixes showed that as the level of OMS substitution increased in the BF-OMS ice creams, the viscosity rose significantly ($p < 0.05$) compared to the control during the ageing process. A similar trend was also seen in the melted ice cream. The increased β-glucan content from the oat-based milk substitute and stabilizer (sodium alginate) binds free water in the mix, which might have limited water molecule movement, leading to higher bulk viscosity and a more stable ice cream structure with a slower melting rate.[33,53,58,59] Supporting these findings, Thomas *et al.* (2019) revealed that increasing the oat flour content from 0% to 6% raises fibre levels, which in turn binds more water and thus increases the viscosity.[52]

The relationship between shear stress and shear rate for the BF-OMS ice-cream samples is illustrated in Fig. 5. The power law model was used to determine the consistency index, K, and flow behaviour index, n (Table 6). The control, IC, and BF-OMS ice cream samples, IO1, and IO2 showed flow behaviour index (n) values 0.41 ± 0.03, 0.42 ± 0.02, and 0.39 ± 0.03, respectively, showing no statistically significant difference. All the values are typically below 1, indicating a typical shear-thinning fluid and pseudoplastic behaviour. This means the viscosity decreases upon increasing shear rate, confirming a non-Newtonian fluid.[60] The consistency index (K) values for the ice cream samples—control, IC, IO1, and IO2 were 4.5 ± 0.02 Pa s^n, 6.23 ± 0.03 Pa s^n, and 7.79 ± 0.03 Pa s^n, respectively, demonstrating a statistically significant ($p < 0.05$) increase in viscosity with greater OMS content. The increase in viscosity could be correlated with the higher molecular weight and inherent gel-forming property of β-glucan present in OMS.[59]

The substitution of FCDM with OMS at different levels in the BF-OMS ice cream formulation has shown significant differences ($p < 0.05$) in textural properties such as hardness,

Table 7 Textural properties of control and Basil Flavoured Oat-based Milk Substitute (BF-OMS) ice creams[a,b]

Sample	Hardness (g force^2)	Adhesiveness (g s)	Cohesiveness	Gumminess	Springiness	Chewiness
IC	749.85 ± 0.03[b]	−29.08 ± 0.02[b]	0.17 ± 0.02[a]	124.02 ± 0.02[b]	0.75 ± 0.02[b]	92.09 ± 0.02[a]
IO1	1679.31 ± 0.03[c]	−15.99 ± 0.02[c]	0.13 ± 0.03[a]	207.56 ± 0.02[c]	0.70 ± 0.02[b]	145.90 ± 0.03[b]
IO2	1857.17 ± 0.03[a]	−83.40 ± 0.02[a]	0.18 ± 0.03[a]	333.98 ± 0.02[a]	0.79 ± 0.02[a]	267.01 ± 0.02[c]

[a] Values are mean ± S.D, $n = 3$. [b] Means within treatments in a column that have different superscripts are significantly different ($p < 0.05$).

adhesiveness, gumminess, springiness, and chewiness – while cohesiveness remained statistically similar across samples (Table 7). IO2 exhibited the highest hardness (1857.17 g) and gumminess (333.98), followed by IO1 whereas the control, IC, showed the lowest values in accordance with the study by Goff (2013) as mentioned by Ng *et al.*, 2023, which highlighted that low fat content and higher viscosity in ice cream can lead to a harder texture due to its increased resistance to deformation. Furthermore, the study also reveals that ice cream with a higher overrun is softer, as the increased volume of the dispersed phase of the ice cream reduces its hardness.[61] The sustained cohesiveness in oat-based formulations indicates that oat β-glucans, along with the added stabilizer, might have successfully compensated for the weakened protein–fat network that is typical in reduced-fat systems, thereby maintaining internal bonding strength comparable to that of the control (dairy-based ice cream). This observation is consistent with reports by Buniowska-Olejnik *et al.* (2023) that oat β-glucan improves the structural integrity of ice cream by promoting additional bonding and limiting ice crystal growth more effectively than conventional stabilizers.[62] The notably higher gumminess and springiness, especially in the 100% BF-OMS formulation, highlight the gel-like resilience developed through increased total solids and polysaccharide interactions. Similar findings have been reported, where β-glucan was shown to enhance consistency, viscosity, cohesiveness, and firmness in low-fat ice creams.[63] Taken together, these results suggest that BF-OMS ice creams are not only capable of matching but, in key textural aspects such as firmness and body, they even surpass traditional full-fat formulations, while also offering the added advantages of reduced fat content.

4.6 Nutritional characterization

The percentage of total ash, protein, fat, and total carbohydrate was evaluated, and the obtained results are demonstrated in Table 5. There is a significant ($p < 0.05$) rise in the total ash content of the BF-OMS ice creams with the substitution level of 50% (IO1) and 100% (IO2) compared to the control due to the higher mineral content present in the OMS as reported in previous studies.[50,64]

Higher carbohydrate content was observed in BF-OMS ice creams, IO1 and IO2, ranging from 40.7 to 51.76% compared to the control sample, IC (35.56%). This difference showed statistical significance ($p < 0.05$). These findings align with the study by Antunes *et al.* (2025), who found that OMS contains more carbohydrates (9.7 g/100 ml) than regular dairy milk (4.9 g/100 ml).[33] Additionally, another study supports these findings by demonstrating that the oat contains approximately 60% starch (dry weight basis) and 2.3–8.5% dietary fibre, contributing to the improvement of the ice cream's creaminess, structure, and mouthfeel.[14]

The protein content in OMS-substituted ice-cream samples (IO1 and IO2) was lower, ranging from 2.04% to 4.69%, compared to the control, IC, at 5.39%, with a significant difference ($p < 0.05$). This statistical difference shows the impact on the protein level while substituting the FCDM with OMS at 50% and 100%. However, OMS still offers a well-balanced amino acid profile, containing about 36% essential amino acids, which makes it a good source of high-quality protein.[65] In addition, OMS is naturally gluten-free and has low allergenicity, making it a great option for people who are lactose intolerant or sensitive to milk allergens.[66]

Furthermore, a study by Martínez-Padilla *et al.* (2020) states that OMS's total *in vitro* digestibility is similar to that of cow's milk, with no significant difference observed, emphasizing that OMS and dairy milk show similar protein digestion efficiency.[67]

Likewise, the fat content was also highest in the control sample (4.1 ± 0.1) and lowest in IO2 (1.1 ± 0.1), as shown in Table 5. The low-fat percentage observed in the OMS-based ice cream samples could be supported by the findings of Kouřimská *et al.* (2018), who reported that OMS generally contains less fat than dairy milk but stands out for its high proportion of healthy unsaturated fatty acids (78–81.5%), including linoleic acid (34.6–38.2%).[68]

4.7 Storage stability of basil flavoured OMS ice creams

In this section, fat destabilization, water activity, color stability, phytochemical and antioxidant retention (DPPH assay), organoleptic evaluation, microbial stability, and biochemical properties were assessed on the 0th and 15th day. These parameters were analyzed using a two-way ANOVA to understand the influence of both sample type and storage duration, thereby providing a comprehensive evaluation of storage-related changes in BF-OMS ice creams.

4.7.1 Fat destabilization. The results showed in (Fig. 6) significant influences of both formulation and storage time ($p < 0.05$) on fat destabilization values.

IO1 and IO2 showed significantly higher fat destabilization (30.9 ± 0.8 and 39 ± 0.7, respectively), unlike IC, which exhibited the lowest fat destabilization (17.1 ± 0.4). On day 15, fat destabilization values increased across all samples, with IO1

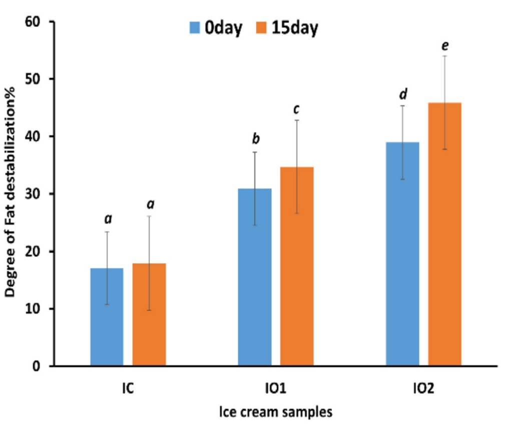

Fig. 6 Effect of storage on fat destabilization (%) in control ice cream (IC, 100% full cream dairy milk) and formulated ice cream samples—IO1 (50% dairy substitution with oat-based milk substitute) and IO2 (100% dairy substitution with oat-based milk substitute)—at 0 and 15 days. Values represent mean ± SD ($n = 3$). Values are mean ± SD ($n = 3$). Different superscript letters indicate significant differences at $p < 0.05$ (DMRT).

(34.7 ± 0.4) and IO2 (45.9 ± 0.4) experiencing further significant increases while IC remained relatively stable (17.9 ± 0.7). This observation reveals that higher substitution of OMS for FCDM results in higher fat destabilization and increases markedly upon extended storage. According to the studies by Rezaei *et al.* (2015) and Marshall RT (2003), the high content of complex carbohydrates (starch and β-glucan) present in OMS helps in the foam stability, controlling fat destabilization in the ice cream mix, which in turn, helps in producing a smooth texture and more melting resistance in the developed ice creams.[38,69]

4.7.2 **Water activity.** The results in Table 8, revealed that there is a significant effect of sample type on water activity ($p < 0.05$) at both time points. At day 0, a significant difference was observed among samples, with IO1 (0.94 ± 0.01) and IO2 (0.94 ± 0.01) exhibiting slightly higher aw compared to IC (0.93 ± 0.01). This slightly higher water activity observed in the BF-OMS ice creams could be due to the presence of β-glucan from OMS, which binds free water and makes it less available for microbial growth. This explanation is supported by the findings of M. Wootton and A. Bamunuarachchi (1978).[70]

However, after 15 days of storage, aw values in IO1 decreased to 0.93 ± 0.01, similar to the IC sample, while IO2 maintained the aw (0.94 ± 0.01). These differences were statistically significant ($p < 0.05$), suggesting that the level of OMS substitution influences water activity retention during frozen storage. This observation is consistent with the findings of Buniowska-Olejnik *et al.* (2023), who noted that the interaction between milk protein and β-glucan leads to enhanced water-holding capacity, reducing the amount of free water over time.[62] Moreover, storage of these ice cream samples at low temperature (−18 °C) also acts as an effective barrier to microbial growth.

4.7.3 **Color stability.** The results in Table 8 revealed a significant effect of sample type ($p < 0.05$), with the highest initial lightness in the control (IC) and a reduction in lightness in BF-OMS ice cream samples.

On day 0, the L^* value (lightness) was highest for IC at 72.6 ± 0.1, followed by IO1 (69.5 ± 0.1) and IO2 (65.6 ± 0.1). This variation may be due to the higher fat content in the control sample. In contrast, the BF-OMS ice creams showed slightly lower lightness because of the 10% basil leaf extract, with the chlorophyll adding a distinct green color that gave them a more natural and refreshing appearance.[71] The 100% OMS (IO2) sample retained significantly higher lightness (62.5 ± 0.6) after 15 days compared to IC and IO1, indicating superior color stability. This could be due to the potential of OMS, which helps in slowing down the rate of ice crystal formation during frozen storage, contributed by the oat's high viscosity property. This further reduces light scattering and maintains uniform color throughout frozen storage.[62]

Across all treatments and storage periods, no significant differences ($p > 0.05$) were detected in a^* values, indicating that the red–green balance remained stable.

On day 0, the presence of chlorophyll in the BF-OMS formulations (IO1 and IO2) resulted in a slight but non-significant reduction in a^* values (−1.3 ± 0.1 and −1.8 ± 0.1, respectively) compared with the control (IC), *i.e.*, 0.5 ± 0.1, reflecting a minor shift toward greener tones. On the 15th day of storage, the storage effect on IO1 and IO2 was subtle and did not compromise overall color stability, corroborating previous findings that chlorophyll from botanical extracts can impart mild green hues while maintaining the integrity of the red–green chromatic axis in dairy alternative systems, as described by Roland *et al.* (1999).[72]

Significant effects of both treatment and storage time ($p < 0.05$) were observed for b^* values. On day 0, IO2 showed higher b^* values (8.7 ± 0.06), indicating greater yellowness and comparable to the control (9.7 ± 0.06). By the 15th day of storage, b^* values declined across all samples, but still IO2 retained more yellowness (7.9 ± 0.01). This can be attributed to carotenoids and phenolic compounds in oat and basil extracts, which help stabilize pigments and slow oxidative degradation during storage.[73] This aligns with emerging consumer preferences for plant-based dairy alternatives without compromising sensory and visual attributes.

4.7.4 **Phytochemical and antioxidant retention.** The total polyphenol content as shown in Fig. 7 varied significantly among samples (IC, IO1, IO2; $p < 0.05$), increased significantly from 0 to 15 days ($p < 0.05$), and the extent of this increase significantly ($p < 0.05$) varies by formulation.

On day 0 of the storage period, IO1 and IO2 had similar content of total polyphenols, *i.e.*, 46.68 mg GAE/100 g and 45.44 mg GAE/100 g, respectively, while the least was observed in the control, IC (28.62 mg GAE/100 g). This high content of polyphenol in OMS ice cream, IO1, and IO2 may be attributed to

Table 8 Storage studies of Basil Flavoured Oat-based Milk Substitute (BF-OMS) ice-creams at 0th and 15th days of storage[a,b]

Parameter	Days of storage	Sample IC (0%)	IO1 (50%)	IO2 (100%)
Color	L^* (0th day)	72.6 ± 0.1^a	69.5 ± 0.1^b	65.6 ± 0.1^b
	L^* (15th day)	60 ± 0.5^b	55.9 ± 0.7^b	62.5 ± 0.6^a
	a^* (0th day)	0.5 ± 0.1^a	-1.3 ± 0.1^a	-1.8 ± 0.1^a
	a^* (15th day)	1.2 ± 0.3^a	0.2 ± 0.9^a	0.8 ± 3.6^a
	b^* (0th day)	9.7 ± 0.06^a	6.5 ± 0.3^b	8.7 ± 0.06^a
	b^* (15th day)	8.7 ± 0.5^b	6.275 ± 0.3^b	7.9 ± 0.01^c
Water activity (aw)	0th day	0.93 ± 0.01^a	0.94 ± 0.01^b	0.94 ± 0.01^b
	15th day	0.93 ± 0.01^a	0.93 ± 0.01^b	0.94 ± 0.01^a

[a] Values are mean ± S.D, $n = 3$. [b] Means within treatments in a column that have different superscripts are significantly different ($p < 0.05$).

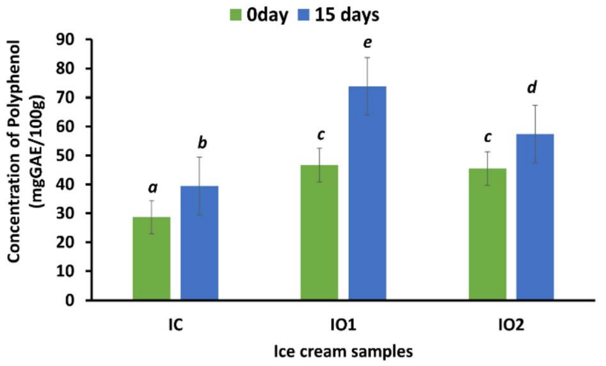

Fig. 7 Effect of storage on total polyphenol concentration (mg GAE/100 g) in control ice cream (IC, 100% full cream dairy milk) and formulated ice cream samples—IO1 (50% dairy substitution with oat-based milk substitute) and IO2 (100% dairy substitution with oat-based milk substitute)—at 0 and 15 days. Values are mean ± SD ($n = 3$). Different superscript letters indicate significant differences at $p < 0.05$ (DMRT).

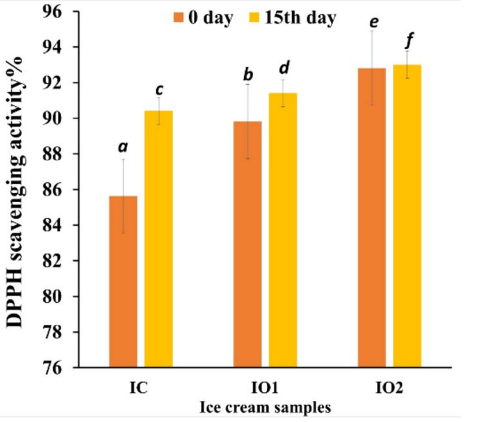

Fig. 8 Effect of storage (0 and 15 days) on DPPH radical scavenging activity (%) of ice cream samples: IC (100% full-cream dairy milk, control), IO1 (50% substitution with oat-based milk substitute), and IO2 (100% substitution with oat-based milk substitute). Values are mean ± SD ($n = 3$). Different superscript letters indicate significant differences at $p < 0.05$ (DMRT).

the inherent phenolic profile of oats, particularly avenanthramides (49.6 ± 8.3 μg g^{-1}, fresh weight in bran), known for their strong antioxidant activity.[54] Additionally, the incorporation of basil leaf extract provided further bioactive compounds, notably vanillic acid (140 μg g^{-1}, dry weight), thereby enriching the overall phenolic content of the formulations.[55]

Furthermore, on the 15th day of storage, the total polyphenol content increased to 73.78 mg GAE/100 g in IO1 and 57.41 mg GAE/100 g in IO2. This significant ($p < 0.05$) increased total polyphenol content in the formulated OMS ice cream, especially the IO1 sample, might have been contributed by the synergistic interaction of dairy and oat components, which may have supported greater polyphenol stability or enhancement during storage, whereas the slight increase in IC (39.78 mg GAE/100 g) highlights the limited accumulation potential of dairy-only formulations. These bioactive compounds are reported to provide cardiovascular health benefits.[62]

Similarly, there was a significant major effect of sample type and storage time ($p < 0.05$) on antioxidant activity, as well as a significant interaction between these factors ($p < 0.05$) (Fig. 8). At day 0, the control, IC, exhibited the least antioxidant capacity, *i.e.*, 85.63% while IO1 (89.92%) and IO2 (92.81%) exhibited better antioxidant capacity. After 15 days, antioxidant activity increased significantly, IO1 reached 91.42% and IO2 reached 93.01%, highlighting that 100% oat-based milk substitution maximally enhances antioxidant potential (Fig. 8). The studies suggest that polyphenols, avenanthramides, *etc.*, present in OMS and basil extracts might have contributed to this achievement, contributing beneficial health benefits to the consumers.[54]

4.7.5 Organoleptic properties of basil flavoured OMS ice-creams. Sensory evaluation of ice cream samples (IC, IO1, IO2) was conducted on the 0th and 15th day using the modified ADSA score card. The sensory scores in Tables 9 and 10 depict significant effects of formulation and storage ($p < 0.05$), indicating differences in the organoleptic characteristics of the formulated ice creams with those of the control. The flavour evaluation was investigated for defects like too high flavour, high starchy flavor, and a lack of fine flavour, with their intensity.

IO1 scored comparably to the dairy control (7.19 ± 0.72 for 'too high flavor' and 7.13 ± 0.66 for 'high starchy flavor'), indicating that partial substitution with the oat-based milk substitute can successfully retain the desirable flavor profile of traditional dairy ice cream. The result shows strong consumer appeal for IO1, which exhibited a well-balanced flavor profile offering a novel taste that included subtle starch notes. Interestingly, IO2 received favorable scores for "too high flavor" (6.5 ± 0.1) and "high starchy flavor" (6.2 ± 0.78), remaining within the acceptable range of the 9-point scale, though marginally lower than the dairy control. These scores reflect subtle sensory differences attributed to oat-based milk substitutes' natural flavor and starch properties, complemented by a slight creamy note perceived by the panelists.[45]

No significant differences were observed for the "lacks fine flavor" attribute ($p > 0.05$), suggesting that while OMS alters certain flavor notes, it does not compromise the overall flavor integrity of the product. Additionally, the flavor scores in OMS samples showed a similar pattern even on the 15th day of storage, also indicating that these ice creams retain their good sensory quality over time.

Furthermore, different textural characteristic defects like gumminess, mouth coating, sandiness, and coarseness were also evaluated along with their intensity at the 0th day and 15th day of storage on a 10-point scale. Based on sensory scores for gummy texture, IO1 and IO2 were significantly different ($p < 0.05$) from the control (IC) due to a slight perception of gumminess; however, both remained within an acceptable score range. The gumminess could be due to higher solid content or lower overrun.[38] Upon storage of 15 days, a slight increase in the defect was perceived by the sensory panellist in

Table 9 Organoleptic characterization of Basil Flavoured Oat-based Milk Substitute (BF-OMS) ice-creams at 0th day storage[a,b]

	Flavor-10			Texture-5				Appearance and color-5		Melting quality-3		
Sample	Too high flavor	High starchy flavor	Lacks fine flavor	Gummy	Mouth coating	Sandy	Coarse icy	Dull color	Non-uniform color	Foamy melting	Delayed melting	Overall acceptability-10
IC	7.25 ± 0.8^{ab}	9.67 ± 0.5^{d}	8.07 ± 0.72^{a}	4.6 ± 0.7^{d}	$4.\pm 86^{d}$	4.40 ± 0.51^{c}	3.67 ± 0.60^{d}	4.666 ± 0.48^{c}	4.83 ± 0.41^{c}	2.8 ± 0.5^{a}	2.8 ± 0.4^{b}	8.625 ± 0.79^{c}
IO1	7.19 ± 0.72^{ab}	7.13 ± 0.66^{bc}	7.6 ± 0.78^{a}	3.7 ± 0.87^{bc}	3.67 ± 0.77^{bc}	3.93 ± 0.82^{c}	3.80 ± 0.69^{cd}	4.25 ± 0.63^{c}	4.67 ± 0.45^{bc}	2.2 ± 0.5^{ab}	2.2 ± 0.4^{ab}	8.437 ± 0.82^{c}
IO2	6.5 ± 0.1^{a}	6.2 ± 0.78^{ab}	7.8 ± 0.5^{a}	3.1 ± 0.6^{a}	3.33 ± 0.77^{ab}	3.73 ± 0.7^{bc}	3.40 ± 0.66^{bc}	3 ± 0.53^{ab}	4 ± 0.86^{ab}	2.8 ± 0.58^{bc}	2.6 ± 0.5^{ab}	$7.437 \pm 0.52b^{c}$

[a] Values are mean ± S.D, $n = 3$. [b] Means within treatments in a column that have different superscripts are significantly different ($p < 0.05$).

Table 10 Organoleptic characterization of Basil Flavoured Oat-based Milk Substitute (BF-OMS) ice-creams at 15th day storage[a,b]

	Flavor-10			Texture-5				Appearance and color-5		Melting quality-3		
Sample	Too high flavor	High starchy flavor-	Lacks fine flavor	Gummy	Mouth coating	Sandy	Coarse icy	Dull color	Non-uniform color	Foamy melting	Delayed melting	Overall acceptability-10
IC	7.7 ± 0.9^{b}	7.9 ± 0.5^{c}	7.5 ± 0.8^{a}	4.47 ± 0.51^{cd}	3.8 ± 0.8^{c}	3 ± 0.8^{abc}	2 ± 0.5^{a}	3.9 ± 0.3^{bc}	3.9 ± 0.4^{ab}	2.2 ± 0.6^{a}	2.6 ± 0.57^{ab}	6.9 ± 0.8^{ab}
IO1	6.8 ± 0.7^{ab}	7.1 ± 0.7^{bc}	7.2 ± 0.8^{a}	3.03 ± 0.64^{ab}	2.8 ± 0.7^{ab}	3.1 ± 0.8^{ab}	2.7 ± 0.9^{ab}	3.1 ± 0.7^{ab}	3.6 ± 0.5^{a}	$2.\pm 0.9^{a}$	2 ± 0.5^{a}	6.7 ± 0.6^{ab}
IO2	6.4 ± 0.74^{a}	6 ± 0.8^{a}	7.2 ± 0.8^{a}	2.7 ± 0.8^{a}	2.4 ± 0.9^{a}	2.6 ± 0.5^{a}	2 ± 0.64^{a}	2.6 ± 0.6^{a}	3.5 ± 0.7^{ab}	2.4 ± 0.5^{a}	2.4 ± 0.5^{ab}	6.2 ± 0.8^{a}

[a] Values are mean ± S.D, $n = 3$. [b] Means within treatments in a column that have different superscripts are significantly different ($p < 0.05$).

IO2. This defect can be normalized by lowering the percentage of substitution of the OMS in the ice cream formulation.

Mouth coating scores of IO1 and IO2 were significantly different between the control, IC, and BF-OMS ice creams, reflecting a slightly higher mouth coating perception. This observation aligns with the findings of Cody *et al.* (2007), who reported a significant increase in the mouth coating associated with higher viscosity at increased starch concentrations.[48] However, a creamier and smoother mouthfeel was perceived in BF-OMS ice creams. By day 15, all samples exhibited similar mouth coating scores, indicating that BF-OMS ice creams maintain comparable texture quality over time.

These results indicate that both the ice cream formulation and storage time significantly influenced the perception of sandy texture, with the effect of time being consistent across treatments. On day 0, the scores of IO1 and IO2 were slightly lower than IC, exhibiting low sandiness and showing a smoother and creamier mouthfeel.[74] This could be due to the significant effect of OMS (β-glucan), owing to its stable colloidal properties, reducing ice crystal formation, and higher total solids developed in the ice cream.[62] This phenomenon, in turn, increases viscosity and stabilizes air bubbles.[22] On the 15th day, the sensory score decreased in IO2 and IO1, indicating an increase in the sandiness. One of the reasons could be probably because the aggregation of the fibres in the ice cream mixes over time didn't fully dissolve in the mixture. A similar observation was reported by Tolve *et al.* (2024), who found that fortifying ice cream with oat fiber resulted in pronounced sandiness.[75]

For evaluating the coarseness defect in ice creams, BF-OMS ice creams (IO1 and IO2) at 0 and 15th day, demonstrated a significant difference by treatment and day ($p < 0.05$) in comparison to IC, reflecting the least coarse iciness and even smoother texture in comparison to the control (IC). IO1 achieved the highest score of 3.80 ± 0.69, followed by IO2, *i.e.*, 3.4 ± 0.66, while the control IC scored 3.67 ± 0.6 on day 0. This observation aligns with the findings of Buniowska-Olejnik *et al.* (2023), who noted that the interaction between milk protein and β-glucan leads to a favourable structure with enhanced water-holding capacity.[62] This results in improved crystal formation at a slower rate, producing smaller ice crystals—typically not exceeding 50 μm and often around 20 μm in diameter—which contributes to the desired smoothness and prevents the development of a coarse crystalline texture.[62]

Furthermore, the presence and intensity of dull color and non-uniform defects in the formulated BF-OMS ice creams were evaluated. Significant effects for Treatment and Storage day were observed. On day 0, the sensory score obtained for the parameter by IO1 and IO2 was significantly different ($p < 0.05$) from that of the control, IC. On a 5-point scale, IO1 scored 4.25 ± 0.63 and IO2 scored 3 ± 0.53, both indicating low levels of defect. The rich color of OMS and the light green shade of the basil extract complemented each other, achieving a comparable score to that of the control, IC. On the evaluation of the 15th day of storage, the sensory scores for both IO1 and IO2 slightly decreased but were not significantly different ($p < 0.05$) from IC and maintained acceptable color quality during storage.

The sensory evaluation scores for melting properties showed significant effects of treatment and day ($p < 0.05$) between the control and OMS ice cream samples. Notably, on day 0, IO2 scored the highest for having the fewest defects related to foamy and delayed melting, performing comparably to the control (IC), which suggests it had better structural stability and melted more slowly. Even on 15 days of storage, IO2 maintained similar scores for foamy melting (2.4 ± 0.5) and delayed melting (2.4 ± 0.5) compared to the control, highlighting improved melting resistance and stability with increased OMS substitution. This improvement could be due to higher total solids and the viscosity benefits from the β-glucan in OMS, which are known to help plant-based ice creams achieve better melting stability and texture.[48]

Although the fresh and stored control (IC) scored the highest for overall acceptability, it is evident that OMS ice creams, both IO1 and IO2, demonstrated superior performance across several key parameters.

4.7.6 Microbial quality and safety.

The results for total bacterial count from ice cream samples are tabulated in Table 11. All ice-creams initially tested negative for bacterial presence, highlighting their excellent initial quality. After storing the ice cream samples for 15 days, the total plate count (TPC) measured 6.9×10^2 cfu g^{-1} for the control, IC, 8×10^2 cfu g^{-1} for IO1 (50% substitution) (IO1), and 4.1×10^2 cfu g^{-1} for IO2 (100% OMS substitution). All samples showed some microbial growth on plate count agar, indicating the presence of psychrophilic microorganisms. However, the counts were below the maximum permissible limit of 250 000 cfu g^{-1} set by the Food Safety and Standards Authority of India (FSSAI).[76] This confirms that all the ice cream samples remained microbiologically safe during storage. The reason for the low total bacterial counts observed in all samples could be attributed to effective pasteurization, good hygienic manufacturing practices during preparation, preservation, or serving of ice cream.[64,77] Additionally, the OMS's ability to lower the pH of the ice cream mix, along with the presence of phytochemicals like polyphenols in OMS and basil leaf extract, could suppress the growth of bacteria such as *E. coli.*, as supported by the study of Cueva *et al.* (2010).[78]

Furthermore, biochemical tests, *i.e.*, indole production, methyl red, and Voges–Proskauer, were performed to characterize any microorganisms present in the ice cream. All tests showed negative results at both the 0th and 15th day of storage, as shown in Table 12.

Table 11 Microbiological analysis of Basil Flavoured Oat-based Milk Substitute (BF-OMS) ice creams[a]

Test	Day	Samples IC	IO1	IO2
Total plate count (10^2 cfu g^{-1})	0th day	ND	ND	ND
	15th day	6.9	8	4.1

[a] ND: not detected, showing no viable bacteria forming colonies.

Table 12 Biochemical test of Basil Flavoured Oat-based Milk Substitute (BF-OMS) ice creams[a]

		Samples		
Qualitative test	Day	IC	IO_1	IO_2
Indole test	0 day	Negative (−)	Negative (−)	Negative (−)
	15th day	Negative (−)	Negative (−)	Negative (−)
Methyl red test	0 day	Negative (−)	Negative (−)	Negative (−)
	15th day	Negative (−)	Negative (−)	Negative (−)
Voges–Proskauer test	0 day	Negative (−)	Negative (−)	Negative (−)
	15th day	Negative (−)	Negative (−)	Negative (−)

[a] Negative (−) results showing no presence of coliforms, *E. coli*, or other harmful bacteria usually found in dairy products.

A negative indole test was confirmed by the absence of a red ring at the top of the medium, indicating no production of indole and hence, the absence of bacteria such as *Escherichia coli* and other indole-positive species.[39] The methyl red test also showed a negative result when methyl red indicator was added to the medium; no red color developed. Instead, the medium turned yellow, indicating low acid production and the absence of strong acid-producing bacteria like *E. coli*. Similarly, the Voges–Proskauer test showed a negative result since no red color developed after adding V–P reagent I and V–P reagent II to the medium. This observation indicates no acetoin production and the absence of Enterobacter and Klebsiella.[39,79]

The negative results for all biochemical tests at both 0 day and 15th day indicated that the ice cream samples remained microbiologically safe and hygienically sound throughout the storage period.

5. Conclusion

The present study demonstrated that replacing dairy milk with oat-based milk substitutes (OMS), partially or fully, had a significant impact on the physicochemical, nutritional, rheological, textural, antioxidant, microbial, and sensory qualities of traditional ice creams. A 50% substitution level delivered ice cream with protein quality comparable to the dairy control, while also improving sensory acceptability and offering better texture and melting properties. In contrast, full replacement with OMS provided additional functional advantages, including higher antioxidant activity, greater storage stability, and improved melting resistance. The addition of basil leaf extract further enriched the phenolic content and introduced distinctive flavour notes that complemented the traditional sensory appeal of ice cream. Beyond nutritional and functional benefits, the substitution of dairy milk with OMS may also contribute to reducing the environmental impact of frozen dessert production, supporting more sustainable manufacturing practices. Altogether, these findings demonstrate that basil-flavoured oat-based milk substitute ice creams can be developed as sustainable, nutritious, and consumer-friendly alternatives to conventional dairy-based frozen desserts. With plant-based products gaining momentum for both health and environmental reasons, such formulations hold significant promise for driving innovation and supporting a more sustainable future in the frozen dessert industry.

Conflicts of interest

The authors declare that they have no financial or non-financial interests, either directly or indirectly, that could have influenced the work submitted for publication.

Data availability

Any relevant data sourced from the literature have been properly cited and acknowledged where applicable.

All essential data supporting the findings, statements, and conclusions have been included in the manuscript as well as in the supplementary information (SI). Supplementary information: a modified scorecard for ice cream evaluation based on ADSA ice cream scorecard (Table S1), ADSA ice cream score card (Fig. S1) and Score guide for Melting Rate of Ice cream (Fig. S2). These materials were adapted and sourced from Marshall *et al.* (2003).[38] See DOI: https://doi.org/10.1039/d5fb00232j.

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