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Research Article

Impact of Psyllium (*Plantago ovata*) Husk as a Natural Fat Replacer on Quality Attributes of Low-Fat Camel Milk Ice Cream

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Abstract

Background and Objective: The growing consumer demand for healthier frozen dairy desserts has increased interest in low-fat ice cream made with natural ingredients. However, reducing fat content can negatively impact the texture, creaminess and overall quality of the product. This study aims to evaluate psyllium husk powder (PSHP) as a multifunctional ingredient capable of acting simultaneously as a fat replacer and stabilizing agent in low-fat camel milk ice cream (CMIC), focusing on its effects on physicochemical properties, rheological behavior, melting characteristics and sensory acceptance of psyllium husk ice cream (SHIC) samples. **Materials and Methods:** Four formulations were prepared by substituting fat with PSHP at 0% (SHIC-0), 0.5% (SHIC-0.5), 1.0% (SHIC-1) and 1.5% (SHIC-1.5). The PSHP was dry-blended and hydrated in preheated camel milk (50°C), followed by pasteurization and a 24-hour aging period at 4°C. The aged mixes and hardened ice creams were systematically analyzed for their physicochemical, rheological, structural, bioactive and sensory properties. **Results:** The increasing PSHP significantly improved mix viscosity, density and weight per gallon, while reducing overrun. Ice cream hardness, cohesiveness, gumminess and adhesiveness increased with PSHP incorporation, whereas springiness showed a moderate decline at higher levels. Melting resistance was significantly enhanced, with a delayed first drop and extended complete melting time in PSHP-enriched samples, indicating improved structural stability. Color measurements revealed decreased lightness (L*) and increased redness (a*) and yellowness (b*), reflecting the natural color contribution of psyllium. Antioxidant activity (DPPH and ABTS) and total phenolic content increased significantly with PSHP addition, confirming its functional bioactive potential. Sensory evaluation indicated acceptable scores for all treatments, although overall acceptability slightly decreased at higher PSHP levels (SHIC-1.5: far replacement by 1.5%). **Conclusion:** Accordingly, PSHP was evaluated as a combined fat-replacing and stabilizing agent and the observed effects represent the overall contribution of these dual functionalities. In general, the PSHP improved both nutritional and functional characteristics while maintaining satisfactory sensory quality. This highlights its potential as a natural fat replacer in low-fat CMIC, especially for 1% fat replacement.

Key words: Camel milk, low-fat ice cream, psyllium husk, antioxidant activity

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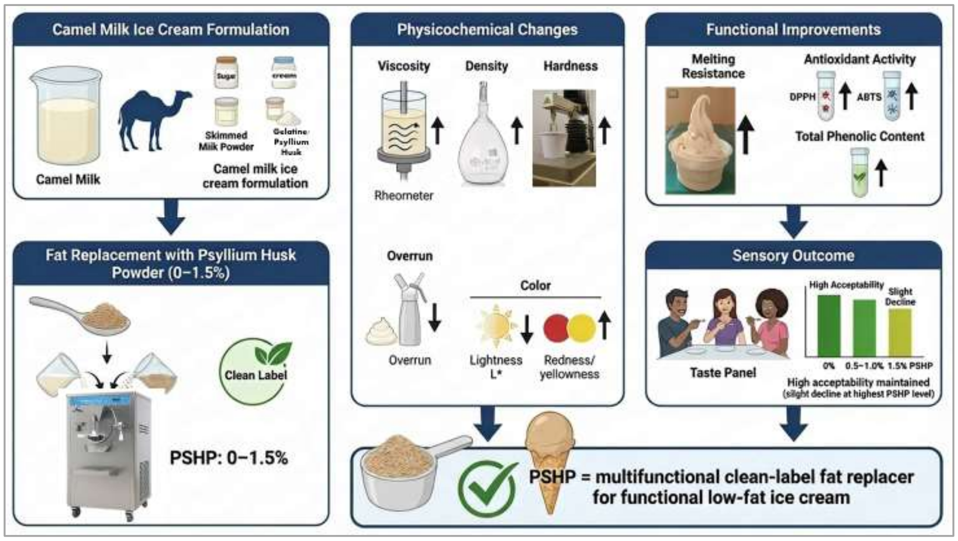
Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

GRAPHICAL ABSTRACT

Schematic representation of the effects of psyllium husk powder (PSHP) as a natural fat replacer in low-fat camel milk ice cream.



INTRODUCTION

There is a growing consumer demand for cost-effective functional dairy products, particularly within the realm of low-fat ice cream. Recent research has focused on the formulation of low-fat ice creams exhibiting enhanced functional and rheological properties. These studies have explored the incorporation of plant-based substances and techno-functional ingredients that are rich in natural antioxidants and high in unsaturated fatty acids. Such innovations aim to improve the nutritional profile and sensory characteristics of ice cream while maintaining desirable textural attributes[1]. Fat replacers (carbohydrate-, protein-, or lipid-based) are designed to mimic fat's texture and mouthfeel but provide fewer calories (0-9 kcal/g vs. 9 kcal/g for fat), directly reducing product energy density[2].

Recent studies have confirmed psyllium husk's effectiveness as a fat replacer in frozen dairy products. This perennial plant originates from the Mediterranean region, specifically Southern Europe, North Africa and Western Asia[3]. Psyllium is a natural fiber derived from the husks of the psyllium plant, while psyllium gum is a water-soluble colloid found within the husk of the plant. Traditionally, psyllium husk has been utilized in Chinese and Indian medicine as a safe laxative and to help reduce the risk of chronic diarrhea, dysentery and other intestinal disorders. Consuming psyllium has been shown to provide various nutritional benefits, including lowering the glycemic index, reducing the risk of cardiovascular disease and alleviating issues related to cholesterol and constipation[4].

With a long history as a dietary supplement, psyllium is a rich source of soluble fiber, with the seeds being the commercially valuable part of the plant. Research supports the safety of psyllium husks for use in functional and nutritional foods. Psyllium offers a range of nutritional and health benefits and its colloidal properties allow it to serve as a substitute for other hydrolyzed colloids in food products. It is commonly used in gluten-free bread as a gluten replacement and can also be added to wheat bread to improve water absorption.

Additionally, psyllium's high water absorption capacity makes it useful in specialized formulations aimed at reducing fat content or enhancing water retention. Its fibers, which have properties similar to xanthan gum, demonstrate strong crystallization and emulsifying abilities when used as a fat substitute[4]. For instance, the incorporation of psyllium husk powder in low-fat ice cream formulations significantly improved physicochemical, rheological and sensory properties, while enhancing antioxidant activity and total phenolic content[5]. Similarly, psyllium has been shown to enhance viscosity, reduce melting rate and improve texture and acceptability in ice milk and plant-based frozen desserts. These findings highlight its multifunctional role as both a fat replacer and stabilizer in dairy products[6].

Table 1: Ingredients of different low-fat CMIC formulations incorporating PSHP as a fat replacer

	Ingredients (g 100/g)			
Ingredients	SHIC-0	SHIC-0.5	SHIC-1	SHIC-1.5
Camel milk	55.4	64.72	73.474	76.59
Camel milk cream	25.83	16.66	7.478	-
Camel milk powder	6.27	6.12	6.048	5.97
Camel skim milk	-	-	-	3.94
Sugar	12	12	12	12
Gelatin	0.5	-	-	-
PSHP	-	0.5	1	1.5
Total	100	100	100	100

Also, camel milk contains higher concentrations of vitamin C, several B vitamins and essential minerals such as iron, zinc and magnesium compared to cow's milk. Additionally, it is enriched with bioactive proteins like lactoferrin, immunoglobulins and Lactoperoxidase. Notably, camel milk also has a lower cholesterol content and exhibits a distinct fatty acid composition[7]. Camel milk ice cream is often marketed as a functional dessert due to its association with various beneficial properties, including antidiabetic and antihypertensive effects, as well as its antioxidant, antimicrobial and hypoallergenic potential. These attributes make it a compelling option in the realm of health-oriented food products[8].

Despite these advances, limited research has focused on the application of psyllium husk in camel milk ice cream, particularly in low-fat formulations. Given the unique compositional characteristics of camel milk and the functional properties of psyllium, there is a need to investigate their combined effects on the quality attributes of ice cream. Understanding these interactions is essential for optimizing formulation strategies and developing innovative functional dairy products that meet consumer expectations for both health and sensory quality. Therefore, the present study aims to evaluate the effectiveness of psyllium (*Plantago ovata*) husk as a natural fat replacer in low-fat camel milk ice cream and to assess its impact on key quality attributes, including physicochemical properties, rheological behavior, melting characteristics and sensory acceptance.

MATERIALS AND METHODS

Study area and duration: This study was conducted at the processing unit of the Department of Food Science and Human Nutrition, College of Agriculture and Food, Qassim University, Qassim Region, Kingdom of Saudi Arabia between May and July 2025.

Materials: Whole fresh camel milk (4.5% fat) was obtained from local farms, Buraydah, Qassim Region, Kingdom of Saudi Arabia. Fresh bulk milk was separated into cream (15% fat) and skim milk (0% fat). Full-fat camel milk powder (94% TS and 26% fat) was obtained from Sawani, the first camel dairy company launched in Saudi Arabia. Camel milk powder was rehydrated according to the manufacturer's instructions and immediately cooled to 5±1°C and kept refrigerated until use. The PSHP was procured from National Foods, Unaizah, Qassim Region, Kingdom of Saudi Arabia. Sugar, gelatin and vanilla were purchased from Local Market, Unaizah, Qassim Region, Kingdom of Saudi Arabia.

All chemicals used in the study were of analytical grade. Chemicals for each experimental method are mentioned in detail under its method of analysis, described subsequently.

Preparation of different low-fat CMIC mixes and ice-cream production: Low-fat Ice cream mixes were standardized to contain 11% solids-not-fat (SNF), 8% fat, 12% sucrose and 0.5% gelatine, according to Samakradhamrongthai *et al.*[9]. Four formulations were prepared using the ingredients listed in Table 1. PSHP was used as a fat replacer at different levels: SHIC-0 (control, 0% PSHP, 0.5 % gelatine, 8% fat), SHIC-0.5 (0.5% PSHP replacing 1% fat), SHIC-1 (1% PSHP replacing 2% fat) and SHIC-1.5 (1.5% PSHP replacing 3% fat). Thus, PSHP was incorporated as a multifunctional ingredient designed to replace both milk fat and gelatine in low-fat CMIC formulations. As a result, the observed effects in the treated samples reflect the combined functionalities of fat replacement and stabilization provided by PSHP, rather than the effect of fat substitution alone. Liquid ingredients were heated to 60°C, followed by the addition of dry ingredients and solubilized gelatine was added to SHIC-0 only. The mixes were pasteurized at 85°C for 15 min under continuous agitation and then rapidly cooled. Aging was carried out at 4±1°C for 24 hrs. After aging, the mixes were whipped at -7°C for 5-6 min at speed level 6 using an automated ice cream machine (Finamac Pro 16, Santo André, Brazil). The resulting ice cream samples were hardened and stored at -18°C until analysis.

Methods of analysis

Proximate analysis: Standard AOAC (2012) methodologies[10] were employed to assess total solids, crude protein, fat, ash content and available carbohydrates in the ice cream samples. Titratable acidity was quantified and expressed as grams of lactic acid per 100 mL. The pH measurements of various samples were conducted using a Jenway 3505 pH meter (Staffordshire, UK).

Specific gravity (g/mL) and weight per gallon (lbs/gallon) of ice cream mix: The specific gravity of ice cream was determined using the pycnometer method as outlined by AOAC (2000), as explained by Miano *et al.*[11]. The following formula was employed to calculate specific gravity (g/mL):

$$\text{Specific gravity} = \frac{\text{Weight of ice cream mix}}{\text{Weight of distilled water}}$$

The specific gravity was then used for calculating weight per gallon (lbs/gallon) as mentioned by Goff *et al.*[12] using the following equation:

$$\text{Weight per gallon} = \text{Specific gravity} \times 8.34$$

where, 8.34 is the weight per gallon of water in pounds.

Viscosity determination of ice cream mix: The viscosity of different low-fat CMIC mixtures with varying proportions of PSHP was evaluated at different shear rates using spindle 4 on a digital viscometer (model MFDVIS). Viscosity measurements, reported in centipoise (cP), were taken directly from the instrument after a one-minute equilibration period at 25ºC[13].

Overrun determination: The overrun of different low-fat CMIC samples and their melting rate over 120 min at room temperature were monitored[14]. To measure the overrun %, the weight of freshly prepared and unfrozen ice cream mix was compared with the weight of the ice cream using the following formula:

$$\text{Overrun (\%)} = \frac{\text{Weight of ice cream mix} - \text{Weight of ice cream}}{\text{Weight of ice cream}} \times 100$$

Melting behavior: The melting point and melting resistance of ice cream samples were measured by melting 50 g at 22°C. Drippings from the samples were collected in a beaker after they had been set on a fine wire screen over a glass funnel. The time at which the first drop fell and the complete melting time were recorded. Drainage weight was measured periodically for a total of 120 min. Melting resistance was determined by calculating the percentage of relative melted amount for each time interval[15].

Instrumental color measurements: The color of each low-fat CMIC sample was evaluated using a chroma meter (Color Flex, Reston, VA, USA) based on the CIELAB scale (L*, a* and b*), with adjustments made using standard tiles in white, green and black.

Determination of total phenolic content (TPC) and antioxidant scavenging activity (AA): The TPC was determined using the Folin-Ciocalteu assay with minor modifications to a previously described method[16]. Freeze-ried ice cream samples were extracted with 10 mL of 70% (v/v) methanol and the extracts were clarified by centrifugation. The final volume was adjusted to 10 mL with the extraction solvent. An aliquot of the extract was mixed with diluted Folin-Ciocalteu reagent (1:10, v/v) and incubated for 5 min prior to the addition of 7.5% (w/v) sodium carbonate. After incubation for 60 min at room temperature, absorbance was recorded at 765 nm. Results were expressed as mg gallic acid equivalents per g dry weight (mg GAE/g DW) using a gallic acid calibration curve ($R^2 = 0.99$).

Antioxidant activity was evaluated using the DPPH radical scavenging assay[17]. Freeze-dried samples (1 g) were extracted with 10 mL of 70% (v/v) methanol and the volume was adjusted to 10 mL. A 0.1 mL aliquot of the extract was added to 2.9 mL of DPPH solution and incubated in the dark for 60 min at room temperature. Absorbance was measured at 517 nm. Antioxidant activity was expressed as mg Trolox equivalents per g dry weight (mg TE/g DW) based on a Trolox standard curve.

The activity of radical scavenging against the stable ABTS (2,2'-azino-bis3-ethylbenzothiazoline-6-sulfonic acid) radical cation was carried out as described by Moolwong *et al.*[18]. A graph was created using the Trolox standard and the results were reported in terms of µmoL TE/g DW.

Rheological properties measurement: The hardness of the samples was assessed using a Texture Analyzer (TA-TX plus, Stable Micro Systems, UK). Identical volume samples were prepared with plastic rings, each measuring 25 mm in height and 60 mm in diameter. They were stored in a freezer at -20°C for at least 24 hrs. Prior to testing, a climate chamber was set up with the Texture Analyzer to maintain a temperature of -20°C. The samples were removed from the plastic rings using a cylindrical cutting tool and immediately placed in the

Table 2: Changes in specific gravity, weight per gallon and apparent viscosity of low-fat CMIC mixes incorporating PSHP as a fat replacer. (Mean±SE), n = 3

	Parameter		
Low-fat CMIC	Specific gravity (g/mL)	Weight per gallon (lbs/gallon)	Apparent viscosity (cP)
SHIC-0	1.061±0.000[d]	8.851±0.001[d]	44.667±0.333[d]
SHIC-0.5	1.071±0.000[c]	8.931±0.000[c]	48.333±0.333[c]
SHIC-1	1.090±0.000[b]	9.092±0.001[b]	66.333±0.882[b]
SHIC-1.5	1.094±0.000[a]	9.122±0.000[a]	84.333±0.333[a]

[a-d]There is no significant difference (p>0.05) between any two means, within the same column have the same superscript letter

climate chamber. The measurements were taken using an aluminum cylinder probe (10 mm in diameter) connected to a 50 kg load cell, penetrating to a strain of 50% at a rate of 2 mm/s. The instrumental hardness was determined as the maximum peak force recorded during the penetration of each sample, as previously described[19].

Air cell size distribution: Air cell size distribution was analyzed using an Olympus CX41 microscope (Japan) equipped with a built-in camera, following the procedure outlined by El-Hadad *et al.*[20]. Measurements were conducted in a temperature-controlled refrigerated container set to -6°C. A small volume of ice cream (0.2-0.5 mL) was carefully placed in the slide's depression and covered with a coverslip, leading to the visibility of air bubbles at the coverslip's surface, with no dispersing liquid required. At least two slides were prepared for each sample, capturing approximately four images to analyze air cells. The number of air cells and their average area in μm^2 were calculated using ImageJ and analyzed by Origin 2026 software, respectively.

Sensory evaluation: Different low-fat CMIC samples were sensory evaluated according to Kamjijam *et al.*[21]. 15 untrained participants, selected based on their habitual ice cream consumption and availability for the study. The evaluation focused on various sensory attributes, including color, odor, taste, texture and overall acceptability. A 9-point hedonic scale was utilized, where 1 denoted "extreme dislike" and 9 indicated "extreme liking". Ice cream samples weighing 50 g each were taken from storage at -18°C before sensory analysis. Each sample was assigned a random three-digit code and presented to the participants under controlled lighting conditions to minimize bias. Participants were instructed to rinse their mouths with water between samples to avoid any carryover effects.

Statistical analysis: The data is presented as the Mean± Standard Error (SE). A randomized complete block design along with factorial analysis of variance was performed using SPSS software (SPSS Ver. 23, IBM, USA). Each parameter was analyzed in triplicate, adhering to the methodology outlined by Steel *et al.*[22]. Tukey's multiple-range test facilitated the one-way ANOVA for the experimental design and comparisons, with results regarded as statistically significant at $p \leq 0.05$.

RESULTS AND DISCUSSION

Specific gravity, weight per gallon and viscosity: The incorporation of PSHP powder significantly ($p \leq 0.05$) influenced the physical properties of the ice cream mix, including specific gravity, weight per gallon and apparent viscosity, as presented in Table 2. A gradual and significant increase in mix density was observed with increasing PSHP levels, rising from 1.061 g/cm^3 in the control (SHIC-0) to 1.094 g/cm^3 in SHIC-1.5. This increase can be attributed to the incorporation of soluble fiber components, which enhance the solid content and reduce the proportion of free. Additionally, the hydration of psyllium mucilage contributes to a more compact and structured system, leading to higher density values, where the addition of dietary fibers and hydrocolloids increased mix density due to improved water immobilization and matrix structuring[23]. Consistent with density results, the weight per gallon of the mix increased significantly across treatments. This parameter is directly related to the mass-to-volume ratio and is influenced by both total solids and air incorporation capacity. The increase in weight per gallon suggests that PSHP enhances the mix's ability to retain water and dissolved solids, resulting in a heavier and more concentrated system. Recent research on fiber-enriched ice cream mixes confirms that hydrocolloid addition increases mix weight due to enhanced hydration and reduced free water mobility[23,24]. The most pronounced effect of PSHP addition was observed in apparent viscosity, which increased sharply from 44.67 cP in the control to 84.33 cP in SHIC-1.5. This significant rise is primarily due to the high swelling capacity and gel-forming behavior of psyllium husk polysaccharides. Upon hydration, psyllium forms a viscous network that entraps water and interacts with milk proteins, leading to increased resistance to flow[6]. Such behavior is characteristic of soluble fibers, where psyllium and similar hydrocolloids significantly

Table 3: Proximate chemical composition of different low-fat CMIC formulations incorporating PSHP as a fat replacer. (Mean±SE), n = 3

	Chemical composition (g 100/g)					
Low-fat CMI	TS	Fat	Protein	Ash	Fibers	Total carbohydrates
SHIC-0	33.47±0.03[a]	8.10±0.06[a]	4.33±0.01[d]	0.91±0.00[d]	0±0[d]	20.12±0.03[d]
SHIC-0.5	32.80±0.06[b]	7.10±0.06[b]	4.44±0.01[c]	0.93±0.01[c]	0.37±0.02[c]	20.33±0.01[c]
SHIC-1	32.13±0.00[c]	6.00±0.06[c]	4.53±0.01[b]	1.13±0.01[b]	0.94±0.01[b]	20.47±0.03[b]
SHIC-1.5	31.77±0.03[c]	5.03±0.07[d]	4.61±0.01[a]	1.22±0.01[a]	1.12±0.01[a]	20.91±0.09[a]

[a-c]There is no significant difference (p>0.05) between any two means for each parameter, within the same column have the same superscript letter

enhance viscosity and improve the stability of dairy emulsions[25]. However, excessively high viscosity at higher PSHP levels (e.g., SHIC-1.5) may negatively affect processability and pumping during industrial production as previously reported by Soukoulis *et al.*[26]. They mentioned that the addition of dietary fiber influenced the rheological behavior of ice cream mixes by enhancing viscosity development and strengthening the shear-thinning behaviour, along with the decrease in the flow behavior index. Therefore, optimization of PSHP concentration is critical to balance functional benefits and processing feasibility.

Proximate analysis and acidity: The compositional analysis of low-fat CMIC formulated with increasing levels of PSHP is presented in Table 3. The presented data revealed significant ($p\leq0.05$) changes across all measured components. These variations reflect both the direct contribution of PSHP and its indirect effects on the ice cream matrix. A progressive increase in total carbohydrates was observed from SHIC-0 to SHIC-1.5. The incorporation of PSHP therefore contributes additional carbohydrate fractions, particularly non-digestible components, leading to a measurable increase in total carbohydrate content. As expected, fiber content showed a marked and significant increase with higher PSHP substitution levels, rising from 0% in the control to 1.12% in SHIC-1.5. The Ash content also increased significantly with PSHP addition, indicating a higher mineral contribution from the plant material. Psyllium husk contains about 4.07% ash that contributes to the overall ash content, which explains the gradual rise observed across low-fat CMIC samples. Protein content exhibited a slight but significant increase with increasing PSHP levels. While psyllium is not a major protein source[27], this rise may be due to concentration effects resulting from fat reduction and total solids redistribution as PSHP added as a fat replacer.

In contrast, fat content decreased significantly from 8.10% in the control (SHIC-0) to 5.03% in SHIC-1.5, confirming the successful partial replacement of milk fat with PSHP. This reduction aligns with the formulation objective of producing low-fat ice cream while maintaining acceptable compositional balance. Total solids (TS) content showed a decreasing trend with increasing PSHP levels. This reduction may be attributed to the lower solid contribution of fat compared to the water-binding nature of psyllium, which can increase moisture retention in the system[5,28]. Consequently, although PSHP adds dry matter, its high water-holding capacity may lead to an overall dilution effect on total solids.

The pH and TA% of different low-fat CMIC samples containing PSHP as a fat replacer are presented in Fig. 1a significant ($p\leq0.05$) increase in TA% as well as a significant decrease ($p\leq0.05$) in pH value were recorded with the increase in the replacement percent of fat with PSHP. The same trend was also reported when Psyllium husk powder[5,28] was added to replace fat in dairy products. The observed decrease in pH value and increase in TA% can be attributed to the relatively low pH of PSHP (5.5) compared to the other components in the formulation. Nevertheless, the inclusion of the PSHP component not only contributes to the overall natural acidity of the ice milk mix but also enhances the protein content within the formulations. This elevated protein presence further exacerbates the acidity, leading to a reduction in the overall pH level[28].

Physical properties: The physical properties of the resultant low-fat CMIC samples are tabulated in Table 4 and a significant ($p\leq0.05$) differences by the incorporation of PSHP as a fat replacer, particularly in terms of density, weight per gallon and overrun are presented. These changes reflect the impact of PSHP on air incorporation, structural stability and the overall matrix of the frozen product. A significant increase in ice cream density was observed with increasing PSHP levels, rising from 0.803 g/cm^3 in the control (SHIC-0) to 0.913 g/cm^3 in SHIC-1.5. This trend is primarily attributed to the reduced incorporation of air and the enhanced water-binding capacity of psyllium[28]. As a hydrocolloid, PSHP increases mix viscosity[5,29], which in turn limits air incorporation during the freezing process, resulting in a denser final product. Consistent with density results, the weight per gallon increased significantly with increasing PSHP concentration. This parameter is inversely related to overrun and reflects the reduced air phase in the ice cream structure. The higher weight per gallon values observed in PSHP-enriched samples

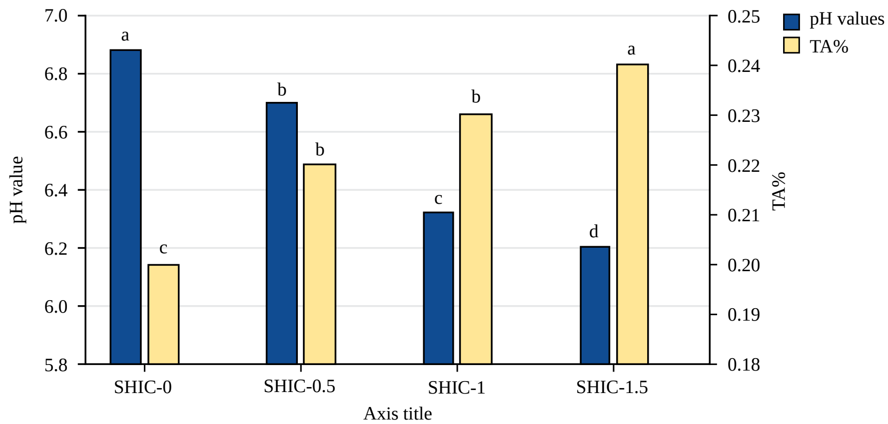


Fig. 1: Effect of fat replacement with PSHP on pH value and TA% of the low-fat CMIC

SHIC-0 (control, 0% PSHP, 0.5 % gelatine, 8% fat), SHIC-0.5 (0.5% PSHP replacing 1% fat), SHIC-1 (1% PSHP replacing 2% fat) and SHIC-1.5 (1.5% PSHP replacing 3% fat

Table 4: Changes in specific gravity, weight per gallon and overrun of low-fat CMIC samples incorporating PSHP as a fat replacer. (Mean±SE), n = 3

	Parameter		
Low-fat CMIC	Specific gravity (g/mL)	Weight per gallon (lbs/gallon)	Overrun (%)
SHIC-0	0.803±0.001[d]	6.697±0.01[d]	59.11±0.012[a]
SHIC-0.5	0.817±0.001[c]	6.811±0.007[c]	51.2±0.012[b]
SHIC-1	0.843±0.001[b]	7.033±0.007[b]	41.993±0.007[c]
SHIC-1.5	0.913±0.001[a]	7.612±0.007[a]	36.553±0.257[d]

[a-d]There is no significant difference (p>0.05) between any two means for each parameter, within the same column have the same superscript letter

Table 5: Changes in melting behavior of low-fat CMIC samples incorporating PSHP as a fat replacer, (Mean±SE), n = 3

	Melting resistance (loss %)						Melting behavior (min.)	
Low-fat CMIC	10	20	30	40	50	60	First drop	Complete melting
SHIC-0	8	21.99	70	91.2	-	-	5:33	41:00:00
SHIC-0.5	7.11	19.98	68.7	84.45	-	-	6:11	46:45:00
SHIC-1	5.4	16.12	64.1	82.55	98.12	-	7:08	51:17:00
SHIC-1.5	-	13.09	62.23	80.19	90.11	-	10:07	58:09:00

confirm that these formulations contained less incorporated air and more solid-liquid mass per unit volume. This behavior aligns with previous research indicating that hydrocolloids enhance phase viscosity and limit air incorporation, thereby increasing product weight[30].

In contrast, overrun decreased significantly from 59.11% in the control to 36.55% in SHIC-1.5. Overrun is a critical quality parameter that reflects the amount of air incorporated during freezing and contributes to texture, lightness and sensory perception. The observed reduction in overrun can be directly linked to the substantial increase in apparent viscosity of the mix with PSHP addition. High-viscosity systems resist air incorporation and hinder bubble formation and stabilization. Additionally, the formation of a thick polysaccharide network may restrict air cell expansion and distribution.

Melting resistance and thermal stability: The melting behavior of the low-fat CMIC samples containing PSHP as a fat replacer was significantly influenced by the incorporation of PSHP, as evidenced by differences in melting resistance, first drop time and complete melting time (Table 5). These parameters are critical indicators of product stability, structural integrity and consumer acceptability[31]. A clear improvement in melting resistance was observed with increasing PSHP levels. The control sample (SHIC-0) exhibited the highest melting loss at early time intervals (e.g., 8% at 10 min and 21.99% at 20 min). In contrast, PSHP-enriched samples, particularly SHIC-1 and SHIC-1.5, showed reduced melting loss over the same periods. Notably, SHIC-1.5 exhibited negligible or delayed melting during the initial stages, indicating superior resistance to heat-induced structural breakdown. At

Table 6: Changes in instrumental color parameters of low-fat CMIC samples incorporating PSHP as a fat replacer. (Mean±SE), n = 3

	Parameter		
Low-fat CMIC	L*	a*	b*
SHIC-0	42.95 ± 0.006^{a}	7.25 ± 0.006^{d}	11.08 ± 0.003^{d}
SHIC-0.5	30.09 ± 0.009^{b}	10.48 ± 0.006^{c}	17.17 ± 0.02^{c}
SHIC-1	28.50 ± 0.007^{c}	12.25 ± 0.006^{b}	21.03 ± 0.037^{b}
SHIC-1.5	25.18 ± 0.006^{d}	14.78 ± 0.025^{a}	22.87 ± 0.07^{a}

a-dThere is no significant difference ($p>0.05$) between any two means for each parameter, within the same column have the same superscript letter

later stages (30-60 min), the control sample melted more rapidly and reached complete melting earlier than PSHP-containing treatments.

In contrast, SHIC-1 and SHIC-1.5 maintained structural integrity for longer periods, with lower cumulative melting losses and delayed transition to complete melting. This enhanced stability is likely due to the formation of a viscous polysaccharide network that entraps water and stabilizes the fat-protein matrix, thereby reducing serum phase separation during melting. The first drop time increased progressively with PSHP concentration, from 5:33 min in the control to 10:07 min in SHIC-1.5. This indicates a delay in the onset of melting, which is a desirable quality attribute associated with improved product stability. Likewise, complete melting time was significantly extended from 41:00 min in SHIC-0 to 58:09 min in SHIC-1.5, further confirming the role of PSHP in enhancing thermal resistance. These results are in line with several recent studies that studied the effect of the addition of psyllium husk as a fat replacer in ice-cream[5,28,29]. They reported that the interaction between psyllium polysaccharides and milk proteins may enhance emulsion stability and limit phase separation, which is a key factor in controlling melting behavior. From a technological standpoint, enhanced melting resistance is advantageous for improving product shelf stability, especially under fluctuating temperature conditions during distribution and storage. However, excessive resistance to melting, particularly at higher PSHP levels, may lead to a gummy or overly stable structure that could negatively affect sensory perception as previously reported when rigid Polysaccharides were used[31]. Therefore, optimization of PSHP concentration is essential to balance melting stability with desirable texture and mouthfeel.

Instrumental color parameters: The incorporation of PSHP significantly ($p\leq0.05$) affected all color parameters (L*, a* and b*), indicating noticeable visual changes in the final product as presented in Table 6. A significant decrease in lightness (L*) was observed with increasing PSHP levels, declining from 42.95 in the control (SHIC-0) to 25.18 in SHIC-1.5. This reduction in brightness can be attributed to the intrinsic dark beige to brownish color of psyllium husk, which imparts a darker tone to the ice cream matrix[29]. Additionally, the presence of insoluble fiber particles may increase light absorption and reduce reflectance, contributing to the observed decrease in L* values[28]. Similar reductions in lightness have been reported in fiber-enriched dairy systems, where plant-based additives introduce pigmentation and reduce product whiteness[28]. Conversely, redness (a*) values increased significantly from 7.25 in the control to 14.78 in SHIC-1.5. This shift toward the red region may be associated with the natural color compounds present in PSHP, as well as possible interactions between polysaccharides and milk components during processing, which can influence color development[29]. The yellowness (b*) values showed a marked increase with PSHP addition, rising from 11.08 in the SHIC-0 sample to 22.87 in the SHIC-1.5 sample. This indicates a progressive shift toward a more yellowish hue, which is consistent with the color characteristics of psyllium. The combined decrease in L* and increase in a* and b* values indicate a transition from a bright, creamy-white appearance in the control to a darker, more yellowish appearance.

Texture profile analysis: Texture profile analysis (Table 7) revealed that the incorporation of PSHP significantly ($p\leq0.05$) modified the mechanical and structural attributes of the ice cream, reflecting its strong functionality as a hydrocolloid and fat replacer. Hardness increased markedly with increasing PSHP concentration, rising from 0.99 N in the control (SHIC-0) to 3.23 N in SHIC-1.5. This trend is primarily attributed to the reduction in fat content and the formation of a more rigid network due to the high water-binding capacity of psyllium[4,5]. Fat typically contributes to softness and lubrication in ice cream[20]; thus, its replacement with PSHP leads to a firmer structure. Additionally, the increased viscosity of the mix and reduced overrun contribute to a denser matrix with greater resistance to deformation[29]. Adhesiveness also increased significantly across treatments, indicating a greater tendency of the product to stick to surfaces. This behavior is closely associated with the gel-forming ability of psyllium mucilage, which enhances intermolecular interactions and

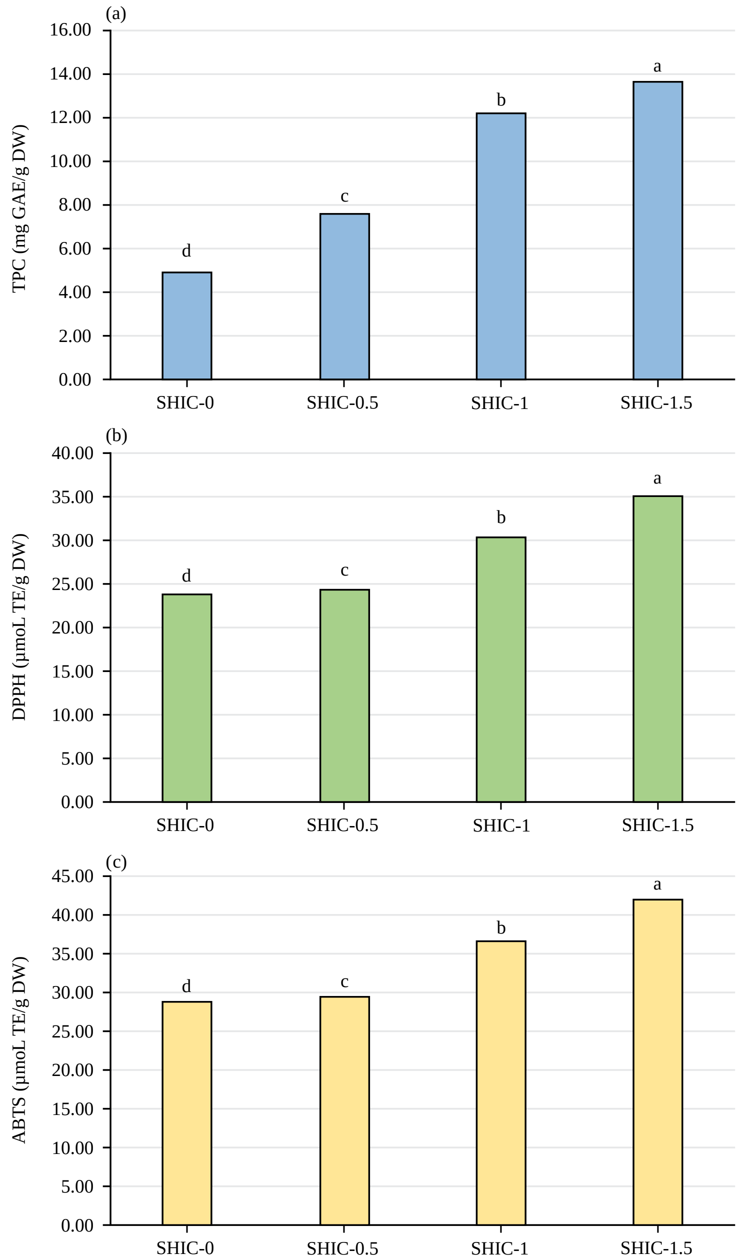


Fig. 2(a-c): Effect of fat substitution with PSHP on total phenolic content, DPPH and ABTS of PSHPIC

SHIC-0 (control, 0% PSHP, 0.5 % gelatine, 8% fat), SHIC-0.5 (0.5% PSHP replacing 1% fat), SHIC-1 (1% PSHP replacing 2% fat) and SHIC-1.5 (1.5% PSHP replacing 3% fat)

Table 7: Texture profile parameters of low-fat CMIC samples incorporating PSHP as a fat replacer. (Mean±SE), n = 3

	Parameter			
Low-fat CMIC	SHIC-0	SHIC-0.5	SHIC-1	SHIC-1.5
Hardness (N)	0.99[b]	1.61[b]	2.50[a]	3.23[a]
Adhesiveness (N)	5.99[d]	6.64[c]	7.95[b]	8.63[a]
Springiness (mm)	6.87[c]	9.11[a]	8.15[b]	7.01[c]
Cohesiveness	1.16[b]	1.65[a]	1.56[a]	1.42[a]
Chewiness (N*mm)	1.11[c]	4.89[a]	4.01[a]	2.99[b]
Gumminess (N)	0.15[b]	0.46[ab]	0.52[a]	0.58[a]

[a-c]There is no significant difference (p>0.05) between any two means for each parameter, within the same row have the same superscript letter

water retention within the matrix[4]. Springiness showed a different trend, with SHIC-0.5 exhibiting the highest value, followed by a gradual decline at higher PSHP levels. This suggests that moderate incorporation of PSHP improves the elastic recovery of the ice cream structure, likely due to optimal network formation between proteins and polysaccharides[5]. However, excessive PSHP (as in SHIC-1.5) may lead to an overly rigid matrix that limits structural recovery after deformation. This highlights the importance of optimizing hydrocolloid concentration to achieve desirable textural balance[29]. Cohesiveness increased significantly with PSHP addition, particularly in SHIC-0.5 and SHIC-1 treatments, indicating stronger internal bonding within the ice cream structure. This can be attributed to enhanced interactions between psyllium polysaccharides and milk proteins, resulting in a more integrated and stable network[4]. However, a slight decrease at the highest level (SHIC-1.5) suggests that excessive fiber may disrupt uniform matrix formation. Chewiness and gumminess followed trends similar to hardness and cohesiveness. Chewiness increased significantly in PSHP-containing samples, peaking at intermediate levels (SHIC-0.5 and SHIC-1), before decreasing at the highest concentration. This behavior reflects the combined effect of increased hardness, cohesiveness and springiness. From a technological perspective, the observed changes in texture parameters are closely linked to the increased viscosity, reduced overrun and enhanced water immobilization induced by PSHP[5]. While improvements in firmness, cohesiveness and structural stability are desirable for low-fat ice cream, excessive hardness and adhesiveness at higher PSHP levels may negatively affect sensory acceptance[29].

Antioxidant properties: The antioxidant capacity of low-fat CMIC that incorporates PSHP as a fat replacer is shown in Fig. 2a-c, demonstrating a progressive increase in DPPH radical scavenging activity (Fig. 2a), total phenolic content (TPC) (Fig. 2b) and ABTS values (Fig. 2c). These findings highlight the functional role of PSHP as a natural source of bioactive compounds with antioxidant potential. DPPH radical scavenging activity increased markedly from 23.85 µmoL TE/100 g in the control (SHIC-0) to 35.02 µmoL TE/100 g in SHIC-1.5. This improvement can be attributed to the presence of phenolic compounds and associated phytochemicals in psyllium husk, which act as hydrogen donors to neutralize free radicals[4,26]. The dose-dependent increase suggests that higher levels of PSHP contribute greater amounts of antioxidant-active constituents. Similar trends have been reported in recent studies on fiber-enriched dairy products, where plant-derived ingredients significantly enhanced radical scavenging capacity[32]. A parallel trend was observed for TPC, which increased from 4.94 to 13.67 mg GAE/g with increasing PSHP levels. This substantial rise confirms that psyllium husk is an effective contributor of phenolic compounds to the ice cream matrix. The strong correlation between TPC and antioxidant activity (DPPH and ABTS) further supports the role of phenolics as primary contributors to the observed antioxidant effects in food matrix[28]. In addition, interactions between phenolic compounds and milk proteins may improve their stability and retention within the frozen system[33]. Similarly, ABTS radical scavenging activity showed a significant increase from 28.62 to 42.02 µmoL TE/100 g across treatments. The higher ABTS values compared to DPPH may be related to the broader sensitivity of the ABTS assay to both hydrophilic and lipophilic antioxidant compounds[32]. In parallel with our findings, the results indicated by Akbari *et al.*[5] represent that the consistent increase across all assays indicates that PSHP provides a wide spectrum of antioxidant activity within the product.

Air cells size distribution: Table 8 and Fig. 3a-d show the effect of PSHP incorporation on the air cell characteristics of ice cream, expressed as air cell area (µm^2) and average number of air cells. Air cell size and distribution are important indicators of ice cream microstructure because they directly influence texture, overrun, melting behavior and sensory quality[23,27]. The control sample (SHIC-0) exhibited the highest number of air cells (53) with a relatively low average cell area (195.47 µm^2), indicating the presence of numerous small and well-dispersed air bubbles. This microstructure is generally associated with a smoother texture and more stable foam system[30]. When fat was replaced with 0.5% PSHP (SHIC-0.5), the average number of air cells decreased to 44, while the average cell area increased to 244.68 µm^2. At higher psyllium levels (SHIC-1 and SHIC-1.5), a more pronounced increase in air cell size was observed. The average air cell area increased significantly to 302.17 and 478.68 µm^2, respectively, while the number of air cells declined to 32 in both treatments. In addition, the maximum cell area rose markedly from 1540.00 µm^2 in the control to 5977.81 µm^2 in SHIC-1.5, indicating the formation of much larger air pockets. This behavior may be attributed to excessive mix viscosity at higher psyllium concentrations, which can hinder efficient air incorporation during freezing and promote bubble aggregation[34]. The progressive reduction in air cell number combined with enlargement of cell size suggests that increasing psyllium husk concentration altered the aeration mechanism and destabilized the uniform foam structure, as previously reported for fiber-enriched dairy ice creams[31]. Larger but fewer air cells may result in a coarser texture and lower overrun, although they may also

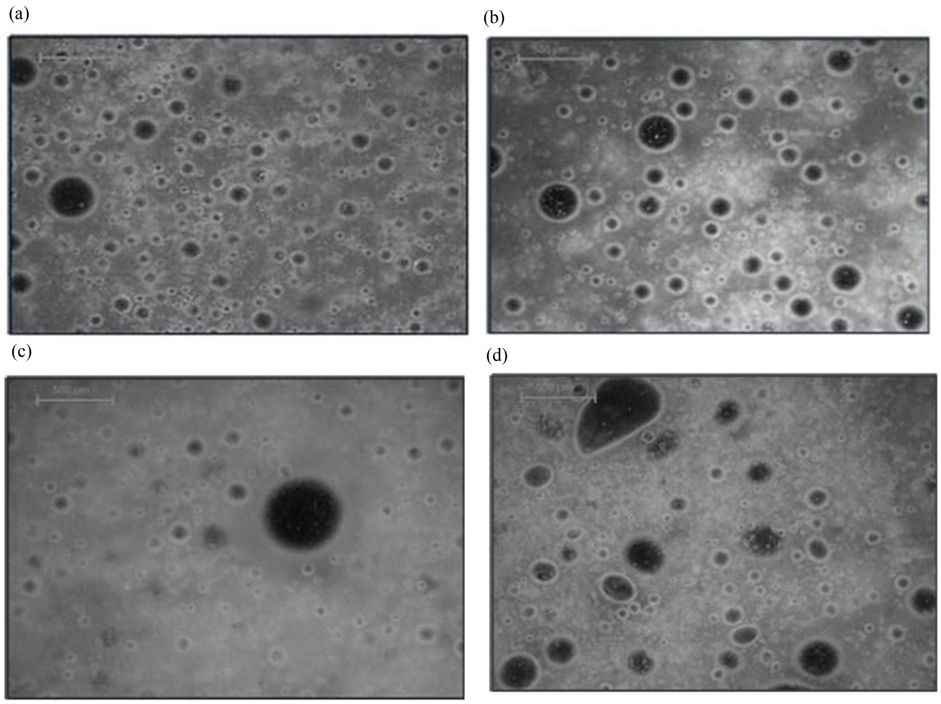


Fig. 3(a-d): Air cell size distribution in low-fat CMIC samples with different fat-replacement levels with PSHP, (a) SHIC-0 (control, 0% PSHP, 0.5 % gelatine, 8% fat), (b) SHIC-0.5 (0.5% PSHP replacing 1% fat), (c) SHIC-1 (1% PSHP replacing 2% fat) and (d) SHIC-1.5 (1.5% PSHP replacing 3% fat)

Table 8: Air cell size distribution after agitation in low-fat CMIC samples contained PSHP as a fat replacer

		Air cell area (µm^2)		
	Average number of air cells	Average	Minimum area	Maximum area
SHIC-0	53	195.47	22.83	1540
SHIC-0.5	44	244.68	34.24	1526.55
SHIC-1	32	302.17	37.62	4678.85
SHIC-1.5	32	478.68	27.19	5977.81

Table 9: Organoleptic properties of low-fat CMIC samples incorporating PSHP as a fat replacer. (Mean±SE), n = 3

	Sensory attribute				
Low-fat CMIC	Color	Odor	Taste	Texture	Overall acceptability
SHIC-0	8.56±0.18^a	7.89±0.35^a	7.89±0.26^a	8.11±0.26^a	8.22±0.28^a
SHIC-0.5	8.67±0.17^a	7.67±0.33^a	7.67±0.29^a	8.22±0.15^a	8.33±0.24^a
SHIC-1	8.67±0.24^a	7.67±0.33^a	7.22±0.22^b	7.89±0.31^a	7.67±0.29^b
SHIC-1.5	8.78±0.15^a	7.67±0.33^a	7.22±0.22^b	7.89±0.26^a	7.44±0.24^b

^{a,b}There is no significant difference (p>0.05) between any two means for each parameter, within the same column have the same superscript letter

contribute to slower melting by reinforcing the structural matrix through water-binding and viscosity enhancement[19]. Overall, moderate psyllium addition (0.5%) maintained a relatively balanced air cell structure, whereas higher concentrations (1.0-1.5%) caused substantial changes in air cell morphology. These findings indicate that the psyllium husk level should be carefully optimized to improve functional properties without adversely affecting the desirable microstructure and texture of ice cream.

Organoleptic properties: The sensory evaluation of low-fat CMIC with PSHP-replaced fat revealed that the incorporation of PSHP had a variable but generally moderate effect on consumer acceptability parameters, including color, odor, taste, texture and overall acceptability (Table 9). Overall acceptability showed a slight decline with increasing PSHP concentration, decreasing from 8.22 in the control (SHIC-0) to 7.44 in SHIC-1.5. Although all formulations remained within an acceptable range (scores>7), the reduction at higher PSHP levels may be associated with textural and flavor modifications induced by the hydrocolloid. At elevated concentrations, PSHP increases viscosity and firmness, which may lead to a heavier mouthfeel that is less preferred by panellists[4,29]. Texture scores remained relatively stable across treatments, with no significant differences observed among SHIC-0, SHIC-0.5, SHIC-1 and SHIC-1.5. This could be because the ability of PSHP to mimic fat-like creaminess through water binding and network formation likely helped maintain desirable textural perception even in low-fat formulations[5]. Taste scores showed a slight but significant decline in SHIC-1 and SHIC-1.5 compared to the control. This reduction may be attributed to the dilution effect of fat replacement and the potential presence of mild plant-like notes from psyllium husk. Fat plays a key role in flavor release and perception in ice cream and its reduction can lead to a less rich taste profile[35]. Odor scores remained statistically unchanged across all treatments, indicating that PSHP incorporation did not introduce any strong off-odors or negatively affect aroma perception. This suggests that psyllium husk is relatively neutral in terms of volatile compounds at the tested concentrations. Color scores showed a slight but non-significant improvement with increasing PSHP levels, rising from 8.56 in the control to 8.78 in SHIC-1.5. The relatively high scores suggest that the color modifications remained within an acceptable range for consumers. The sensory evaluation indicates that PSHP can be effectively integrated into low-fat CMIC without significantly compromising sensory attributes, especially at lower inclusion rates (0.5-1.0%). However, at higher concentrations (1.5%), there may be a slight decline in overall acceptability, likely due to the adverse effects on both taste and mouthfeel attributes. In agreement with our results, Salama *et al*.[6] indicated that ice milk formulated with psyllium husk exhibited a desirable creamy color and received high sensory attribute ratings, particularly with fat replacement levels of up to 1%. This suggests that psyllium husk can effectively enhance the texture and overall sensory qualities of ice milk while maintaining acceptable organoleptic properties.

CONCLUSION

Psyllium husk powder is an effective fat replacer in low-fat camel milk ice cream, enhancing nutritional quality through increased dietary fiber and reduced fat content. Beyond its nutritional contribution, it acts as a structure-forming hydrocolloid, significantly improving mix viscosity, density and flow behavior, while modifying the physicochemical and sensory properties of the final product. Its incorporation reduced overrun and improved melting resistance, indicating enhanced structural stability of the ice cream matrix. These findings align with current trends in clean-label formulation, where plant-derived hydrocolloids are increasingly used to improve functionality and stability in frozen dairy systems. At higher inclusion levels (>1%), psyllium husk powder induced darker coloration, likely due to fiber-related light scattering effects, which may influence product appearance and consumer perception. It also contributed to a firmer and more cohesive texture; however, optimization is required to balance structural benefits with sensory acceptability. Notably, psyllium husk powder enhanced antioxidant capacity, adding functional value beyond its role as a fat replacer. Overall, psyllium husk powder shows strong potential as a multifunctional ingredient in low-fat camel milk ice cream, offering simultaneous improvements in nutritional profile, structural integrity and functional properties while maintaining technological feasibility. A limitation of the current study is that camel milk cream and gelatine were replaced simultaneously with PSHP. As a result, the individual effects of fat reduction and stabilizer replacement could not be distinguished. Future studies should include additional control formulations to separately assess the impacts of fat replacement and the stabilizing effects of PSHP.

SIGNIFICANCE STATEMENT

This study demonstrates the potential of psyllium husk powder (PSHP) as a natural, clean-label multifunctional ingredient for low-fat camel milk ice cream. The PSHP simultaneously enhanced structural stability, rheological properties, melting resistance and antioxidant potential while maintaining acceptable sensory quality. The findings indicate that approximately 1% PSHP may provide an effective balance between technological functionality and consumer acceptability, supporting the development of healthier and functionally enriched camel milk ice cream.

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