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Debittered pomelo (*Citrus maxima*) seed powder as a functional ingredient in low-fat ice cream

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By-product valorisation is a hallmark of sustainable processing and resource efficiency. Repurposing wastes into functional entities fosters environmentally responsible and viable industrial practices. In this study, pomelo (*Citrus maxima*) seed powder was explored as a functional ingredient in low-fat ice cream. Both raw (OSP) and de-oiled seed powders (DSPs) were first debittered using appropriate methods, achieving over 90% reduction in limonin and naringin. The processes also remarkably eliminated tannins, phytic acid and trypsin inhibitors. DSP exhibited >200% enhancement in functional properties over OSP. Improved melting resistance (0.32 g min^{-1} to 0.64 g min^{-1}) and reduced overrun (51.49% to 29.74%), indicating enhanced ice cream matrix stability, were attained. Hardness, adhesiveness, and gumminess increased with rising concentrations (1–5%) of the powder, indicating the roles of seed polysaccharides and proteins in inducing structural integrity in the pseudoplastic emulsions. This was supported by steady and dynamic rheometry, revealing significant enhancements in apparent viscosity (1.52 Pa s to 9.33 Pa s), consistency index (7.36 Pa s to 47.92 Pa s), yield stress (23.83 Pa to 398.74 Pa) and viscoelastic moduli (G' and G''), with decreases in the flow behaviour index (0.66 to 0.17) and loss tangent (0.251 to 0.137). However, prominent color differences, as affirmed by spectrophotometric analysis of lightness (L^*), whiteness (WI) and yellowness (b^*) occurred. Fuzzy logic-based sensory evaluation identified the formulation with 4% DSP as the most acceptable in terms of taste, creaminess, mouthfeel and appearance. Nutritional analysis re-confirmed the low-caloric nature of the final product. Hence, the processed seed powder served a dual-function as a fat mimetic and stabilizer in the low-fat dairy system.

Sustainability spotlight

Citrus industries annually generate approximately 3–8 million tonnes of seeds, representing a largely untapped source of high-value bioresource. Technological valorisation of these seeds supports sustainable waste-management and aligns with the sustainability goals of responsible production and consumption. Citrus seeds are rich in proteins, oils and bioactive compounds, offering potential for improving nutri-functional profiles of food products, advancing circular economy practices. Their utilization can reduce the environmental burden of incineration or landfill disposal, creating value-added employment opportunities and contributing to climate action and poverty alleviation. In this study, *Citrus maxima* seeds were successfully applied as a fat-reducing functional ingredient in ice cream. De-oiled seed powder demonstrated favourable fat-mimicking, stabilizing and texturizing properties, enabling the development of a reduced-fat ice cream formulation.

1. Introduction

Rapid population growth and urbanization are placing intense pressure on natural resources, prompting the need for alternatives that reduce strain and curb food loss. Fresh fruit processing alone generates approximately 1.3 billion tonnes of waste annually, including peels, seeds, pomace and cores, often comprising 25–40% of the original mass.[1–3] Traditionally discarded or underused, these by-products are now recognized for their high nutritional value and concentration of bioactive compounds. Valorising fruit waste not only addresses environmental concerns but also introduces functional ingredients into food systems (SDG 9 and 13). Their incorporation into bakery, dairy, beverage and snack products supports clean-label formulation, nutritional enhancement, and product innovation (SDG 3, 9 and 12). This strategy aligns with circular economy principles by transforming waste into value-added goods, lowering disposal costs and generating new economic opportunities (SDG 1 and 10). Fruit by-product utilization thus represents a sustainable pathway for industrial practices and agri-food system resilience.[1–3]

Ice cream is a complex, aerated, frozen dairy dessert composed primarily of milk, cream, sugars, emulsifiers, stabilizers and flavouring agents. It is produced by homogenizing and pasteurizing a liquid mixture, followed by dynamic freezing

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under continuous agitation to incorporate air and inhibit the formation of large ice crystals. The result is a semi-solid product with a smooth texture and desirable mouthfeel.[4] Milk fat, typically comprising 10–16% of traditional ice cream formulations, plays a central role in the product's structure and sensory appeal. It traps flavours and gradually releases them in the mouth. Fat globules contribute to creaminess, lubricity and the overall viscoelastic quality of ice cream. They also participate in partial coalescence during freezing, stabilizing air cells and improving body and resistance to melting.[4,5]

Excessive intake of saturated fats has been linked to obesity, cardiovascular disease and other metabolic disorders. This has driven consumer demand and industrial innovation toward low-fat and reduced-fat ice cream alternatives.[6] Low-fat ice creams, generally containing less than 3% fat, present formulation challenges. To address this, polysaccharide- or protein-based hydrocolloids are incorporated as fat replacers.[7] These hydrocolloids mimic the mouthfeel and physical behaviour of fat, and enhance product stability.[8,9]

However, unlike fat, these additives interact differently within frozen matrices, requiring careful formulation for optimal performance.[10] A variety of polysaccharides are commonly incorporated into low-fat ice creams to compensate for the loss of structural and sensory attributes typically provided by fat. These include galactomannans such as guar gum and locust bean gum, microbial exopolysaccharides like xanthan gum, seaweed-derived kappa and iota carrageenans, pectin and fructans such as inulin.[9] These hydrocolloids function individually or synergistically to stabilize the ice cream matrix by minimizing phase separation, reducing ice recrystallization and promoting uniform fat dispersion. Their presence enhances the creaminess, smoothness and melt-down properties, thereby improving overall texture and mouthfeel.[4,5] These hydrocolloids exhibit high water-holding and oil-binding capacities, which reduce the availability of free water within the colloidal system in ice cream. This improves freeze–thaw stability by limiting syneresis and inhibiting ice crystal growth during frozen storage. Moreover, their ability to interact with fat molecules prevents fat agglomeration, thereby reducing the formation of dense micro-zones and improving the homogeneity of the matrix. Their gel-forming capabilities also play a critical role in maintaining the structural integrity of the product, helping to retain the colloidal network structures and modulate melting behaviour for a more desirable sensory experience.[9,11,12] Proteins such as globulin, casein and albumin, due to their amphiphilic nature, adsorb at oil–water and air–water interfaces, reducing interfacial tension and improving emulsion stability. This prevents fat coalescence and contributes to smaller and more stable ice crystals, enhancing texture and storage stability.[8,11] The combined use of polysaccharides and proteins thus provides a robust strategy to mimic the physical, rheological and sensory properties of traditional full-fat ice cream in reduced-fat formulations.

Currently, the rising demand for natural and sustainable ingredients has intensified interest in citrus fruit processing wastes. These wastes, particularly due to their high carbohydrate content, are prone to rapid fermentability, contributing to increased biological load and eutrophication.[2,3] Citrus seeds constitute a significant fraction of this waste stream.[13,14] Rich in structural polysaccharides such as cellulose, hemicellulose and pectin, as well as protein fractions like globulins, citrus seed meals exhibit valuable functional properties.[13–15] These include high water and oil holding capacities, swelling power and gel-forming ability. Studies on seed meals from *Citrus limon*, *C. sinensis*, and *C. paradisi* highlight their effective emulsifying and stabilizing functions, making them promising candidates for use in aqueous and oil-in-water food systems.[15–17]

Citrus maxima (pomelo) is the largest species in the Citrus genus, with fruits weighing 550–2000 g and measuring 97–192 mm in length and 115–205 mm in diameter. Each fruit contains approximately 50–60 seeds, averaging 8.15 mm (length), 6.19 mm (breadth) and 3.07 mm (width).[18] Pomelo seeds are rich in biopolymers and proteins, including high-methoxy pectin, hydrophilic amino acids and functional globulins, making them suitable for colloidal food applications such as low-fat ice creams.[18–21] The seed oil content, reaching up to 40%, is notable for its high saturation, offering potential as a stable frying oil.[3] Notably, full-fat and de-oiled pomelo seed flours exhibit markedly different functional profiles with defatting enhancing certain techno-functional properties.[15,22]

Despite such functional potential, pomelo seeds have seen limited application due to high concentrations of bitter compounds. Chief among them is limonin, a triterpenoid lactone responsible for delayed bitterness and naringin, a flavanone glycoside that imparts immediate bitterness.[18,23] These compounds negatively affect taste and are particularly problematic in dairy matrices where bitterness is easily perceived. Application of pomelo seeds in foods remains promising if the bitterness can be mitigated. Various debittering strategies have been explored, including alkaline treatments to degrade limonoids, non-polar solvent extraction, mechanical oil extraction to remove fat-soluble bitter constituents and enzymatic treatments to hydrolyse bitter compounds into tasteless derivatives.[24–28]

This study explores the application of debittered oil-rich and de-oiled pomelo seed powders as functional ingredients in the formulation of low-fat milk-based ice creams. It aims to assess their influence on key product characteristics including texture, functionality, viscoelasticity and sensory quality. By doing so, the study highlights the potential of these underutilized seed derivatives as an alternative to conventional stabilizers in frozen dairy desserts.

2. Materials and methods

2.1. Materials

Mature, healthy and unbruised pomelo fruits were harvested on the 210th day after initial fruiting. The pomelo tree used for fruit collection was 14 years old and measured approximately 9 meter in height, with distinctly drooping branches. The leaves were elliptic, dark green and leathery, ranging from 7 to 20 cm in length and arranged alternately along the branches. The harvested fruits, characterized by a yellow exocarp, had a mean length of 17–19 cm, a mean width of 19–20 cm and an average

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weight ranging from 1500 to 1700 g. Ultra-high-temperature treated defatted milk containing 1.5% milk fat was purchased form market. Food-grade additives and analytical-grade chemicals (SRL, Hi-Media and Merck) were procured.

2.2. Preparation of seed powder

The harvested fruits were first washed to remove any surface contaminant. The seeds were manually extracted using a knife and soaked in distilled water (DW) for 24 h. The seeds were then rubbed to eliminate surface mucilage and hot air-dried at 35 ± 2 °C for 24 h followed by 50 °C for 20–24 h until moisture content was below 1%. The dried seeds were manually dehulled and the kernels were ground. An oily seed powder (OSP, Fig. 1a) of paste-like consistency was obtained, which was not suitable for sieving. De-oiled seed powder (DSP, Fig. 1c) was obtained by treating OSP with petroleum ether (boiling point = 40–60 °C) at 50 °C for 8 h in a Soxhlet apparatus. The obtained residue was gently macerated and sieved. The obtained particle sizes ranged between 100 μm to 150 μm.

2.3. De-bittering

Debittering of OSP and DSP was carried out using two separate approaches. Debittering of OSP was performed by thermal treatment in an alkaline medium.[24] Two hundred fifty grams OSP was suspended in a 5% (w/v) $NaHCO_3$ solution and heated at 85 °C for 1 h. The treated suspension was filtered using muslin cloth, and the residue was rinsed with 1% citric acid followed by DW and then dried at 50 °C for 24–30 h to less than 1% moisture content (Fig. 1b). Debittering of DSP was conducted using a two-step solvent extraction process. First, 250 g DSP was suspended in acetone and incubated at room

Table 1 Coding of the samples based on the seed powder type and different ice cream formulations

S.No	Code	Description
1	OSP	Oil rich seed powder
2	DSP	De-oiled seed powder
3	DOSP	Debittered oil rich seed powder
4	DDSP	Debittered de-oiled seed powder
5	DOSP1	Ice cream prepared from 1% DOSP
6	DOSP2	Ice cream prepared from 2% DOSP
7	DOSP3	Ice cream prepared from 3% DOSP
8	DOSP4	Ice cream prepared from 4% DOSP
9	DOSP5	Ice cream prepared from 5% DOSP
10	DDSP1	Ice cream prepared from 1% DDSP
11	DDSP2	Ice cream prepared from 2% DDSP
12	DDSP3	Ice cream prepared from 3% DDSP
13	DDSP4	Ice cream prepared from 4% DDSP
14	DDSP5	Ice cream prepared from 5% DDSP
15	NC	Negative control; ice cream prepared without any additive
16	PC	Positive control; ice cream prepared with 0.3% GG

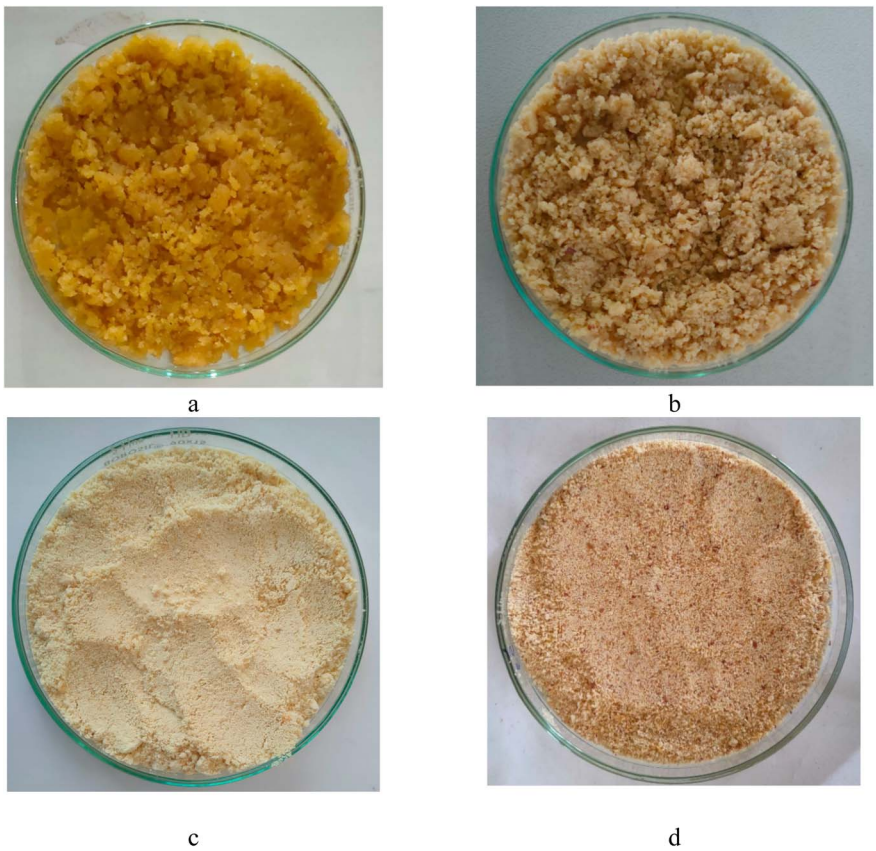

Fig. 1 Fractions of pomelo (*Citrus maxima*) seed powders. (a) OSP, (b) DOSP, (c) DSP and (d) DDSP.

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temperature (RT, 25 ± 2 °C) with shaking for 24 h to extract limonoids.[29] The mixture was then filtered through Whatman no. 41 filter paper and the solid residue was collected. The residue was then suspended in ethanol and incubated at 55 °C for 24 h to remove the flavonoid-derived bitter compounds.[26] After filtration, the final solid residue was dried (Fig. 1d).

Solvent extraction was not applied to OSP as acetone and ethanol could dissolve the oil constituents in the seed powder. The debittered dry OSP and DSP (DOSP and DDSP, respectively) were stored in airtight containers at 4 °C for further use. All sample codes are presented in Table 1.

2.4. Physicochemical analysis of seed powders

2.4.1. Water absorption and oil absorption indices. The water absorption index (WAI) of seed powder samples was determined by vortexing 1 g sample with 30 g of DW, incubating at 50 °C for 24 h, followed by centrifugation at 3000*g* for 20 minutes. The free water was decanted and the residue was weighed. For the oil absorption index (OAI), the same process was followed using sunflower oil instead of DW.[30] The WAI and OAI were calculated using the following equations.

$$\text{WAI (or) OAI(g/g)} = \frac{M_2 - M_1}{M_1} \tag{1}$$

where, M_1 and M_2 represent the initial weight and the residue containing water and oil, respectively.

2.4.2. Swelling index. 0.5 g sample and 5 ml DW were mixed in a measuring cylinder, followed by stirring gently to eliminate any trapped air bubble. The mixture was then kept at RT for 24 h and the final volume was recorded. The value of SI was calculated using the following equation:

$$\text{SI}\ (\text{ml g}^{-1}) = \frac{(V_2 - V_1)}{W} \tag{2}$$

where V_1 and V_2 represent the volumes of the sample before and after swelling, respectively, and W represents the weight of the sample before swelling.

2.4.3. Emulsion activity and stability. The emulsion activity (EA) of the seed powders was measured by mixing the sample with DW and sunflower oil in a 10 : 100 : 100 (w : v : v) ratio. After vigorous vortexing for 15 minutes and centrifugation (3000*g*, 5 minutes), the height of the emulsified layer was recorded and emulsion activity was calculated.[31]

$$\text{EA}(\%) = \frac{H_1}{H_2} \times 100 \tag{3}$$

where H_1 and H_2 represent the height of the emulsion layer and the total height of the mixture, respectively.

Emulsion stability (ES) was determined by incubating the emulsion obtained from the previous step at 80 °C for 30 minutes, followed by rapid cooling in an ice bath. After centrifugation at 3000*g* for 5 minutes, ES was calculated.

$$\text{ES}(\%) = \frac{H_1}{H_2} \times 100 \tag{4}$$

where H_1 and H_2 represent the height of the remaining emulsion layer and the total height of the mixture, respectively.

2.4.4. Foaming capacity and foam stability. 5 g sample was mixed with 100 ml DW in a measuring cylinder. The pH of the mixture was adjusted at 7.0, followed by vortexing vigorously for 10 minutes at RT and foaming capacity (FC) was calculated.[32]

$$\text{FC}(\%) = \frac{V_2 - V_1}{V_1} \times 100 \tag{5}$$

where, V_1 and V_2 are the mixer volumes before and after vortexing, respectively.

Foam stability (FS) was assessed by allowing the foamed samples from the previous step to stand for 30 minutes at RT.[32] The remaining foam volume was recorded and FS was calculated.

$$\text{FS}(\%) = \frac{V_2}{V_1} \times 100 \tag{6}$$

where V_1 and V_2 represent the initial foam volume and residual foam volume, respectively.

2.4.5. Least gelation concentration. Least gelation concentration (LGC) was determined by first preparing a 30% (w/v) stock dispersion of seed powders in DW (pH = 7.0). This stock dispersion was serially diluted to obtain concentrations ranging from 2% to 30% (w/v) in test tubes. Each dispersion was boiled (100 °C, 1 h), cooled under running tap water and visually inspected for gel formation. The resultant samples were classified as solid gel when the sample firmly adhered to the test tube walls, a semi-solid gel when a runny gel remained suspended in a liquid phase and a liquid state when no gel formation occurred.[33]

2.4.6. Proximate composition. Moisture content on a wet basis and protein, fat, and ash contents on a dry basis were analysed for the seed powder samples using standard protocols.[34] Moisture content (MC) was determined gravimetrically by drying samples in a hot-air oven at 105 °C for 3 h, followed by weighing. The percentage moisture was calculated using eqn (7).

$$\text{MC}(\%) = \frac{W_1 - W_2}{W_1} \times 100 \tag{7}$$

where, W_1 is the initial weight of the sample and W_2 is the weight after drying.

Fat content (FC) was measured using a Soxhlet apparatus. Dried seed samples were extracted with petroleum ether (boiling point = 50 °C) for 8 h, and the recovered oil was weighed to estimate the fat percentage (eqn (8)).

$$\text{FC}(\%) = \frac{W_\text{f}}{W_\text{s}} \times 100, \tag{8}$$

where W_f is the weight of extracted fat and W_s is the weight of the dried sample respectively.

Protein content (PC) was determined by the Kjeldahl method. Dried and defatted powders were digested in a mixture of K_2SO_4, $CuSO_4$ and concentrated H_2SO_4 at 400 °C. The digest was diluted with distilled water, neutralized with 35% NaOH and distilled to release ammonia. The released ammonia was captured in 4% H_3BO_3 and titrated against 0.02 N H_2SO_4. Nitrogen content was calculated (eqn (9)), and PC was obtained

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by multiplying the nitrogen percentage by the conversion factor 6.25.

$$\text{Nitrogen content (\%)} = \frac{(V_1 - V_0) \times N \times 1.4}{W_s} \quad (9)$$

where, V_1 is the titration volume for the sample, V_0 is the blank, N is the normality of H_2SO_4 and W_s is the sample weight (g).

Ash content (AC) was analyzed by incinerating dried and defatted seed powders in a muffle furnace at 600 °C for 6 h, after which the ash residue was weighed and expressed as a percentage (eqn (10)).

$$\text{AC (\%)} = \frac{W_a}{W_s} \times 100 \quad (10)$$

where W_a is the weight of ash and W_s is the weight of the dried sample.

Carbohydrate content (CC) was determined by difference, as follows:

$$\text{Carbohydrate content (\%)} = 100 - \{\text{MC (\%)} + \text{PC (\%)} + \text{FC (\%)} + \text{AC (\%)}\} \quad (11)$$

where, MC, PC, FC and AC represent moisture, protein, fat and ash content, respectively.

2.4.7. Naringin content. OSP, DSP, DOSP, and DDSP were initially defatted with petroleum ether. Each defatted powder (10 g) was suspended in 100 ml ethanol and incubated at 55 °C for 3 h with continuous agitation. After centrifuging (3000*g*, 10 minutes), the solid residue was re-extracted with fresh ethanol for 1 h and centrifuged. The combined supernatants were then concentrated under reduced pressure at 45 °C using a rotary evaporator (Evator, Equitron Medica). The extract concentrate was reconstituted in 10 ml ethanol. For naringin quantification, 0.1 ml of the extract was mixed with 0.1 ml of 4 N NaOH and 10 ml ethylene glycol, vortexed and incubated at RT for 15 minutes. Once yellow coloration developed, absorbance was measured at 420 nm using a UV-Vis spectrophotometer (Orion AquaMate 8100, Thermo Fisher Scientific). A standard curve was constructed using naringin solutions (10–200 μg) and the concentration in the sample solution was determined from it. Naringin content was expressed as μg naringin per g of sample.[26]

2.4.8. Limonin content. Defatted seed powder was suspended in acetone and shaker-incubated for 4 h. Insoluble residues were removed by centrifugation and filtration. The obtained extracts were vacuum concentrated at 40 °C and reconstituted in 10 ml of acetonitrile. Limonin quantification was performed by reacting 1 ml of extract with 1.5 ml of Burham's reagent prepared by combining 0.1 g 4-(dimethylamino) benzaldehyde, 3 ml glacial acetic acid and 2.4 ml perchloric acid. Incubation at RT for 30 minutes resulted in full colour development. Absorbance was measured at 503 nm. A standard curve was generated using limonin solutions (10–100 μg ml^{-1} in acetonitrile) and sample concentration was calculated accordingly. The results were expressed as μg limonin per g of sample.[29]

2.4.9. Phytic acid content. Phytate content was determined using an iron precipitation method.[35] One gram sample was extracted with 50 ml trichloroacetic acid (TCA) for 30 minutes under agitation and centrifuged at 3000*g* for 10 minutes. A 10 ml aliquot of the supernatant was combined with 4 ml ferric chloride and heated in a boiling water bath for 45 minutes before centrifuging again. The precipitate was washed with 3% TCA and subsequently with DW for 10 minutes each. The residue obtained by centrifugation was then dissolved in 3 ml of 1.5 N sodium hydroxide, diluted to 30 ml, heated for 30 minutes, filtered and washed with boiling water. The final precipitate was dissolved in 40 ml hot HNO_3 and made up to 100 ml. One hundred microlitres of this solution was diluted to 1 ml, mixed with 2 ml of 1.5 N potassium thiocyanate and made up to 10 ml. Absorbance was read at 480 nm and iron (Fe) content was calculated from a standard curve obtained using ferric nitrate (100–1000 μg ml^{-1}). Phytate content was computed using the following equation:

$$\text{Phytate (mg/100mg)} = \frac{\mu\text{g Fe} \times 15}{\text{Sample weight(g)}} \quad (12)$$

2.4.10. Tannin content. Tannin content was estimated using the vanillin–hydrochloride method.[35] One gram sample was extracted with 50 ml methanol for 24 h, followed by centrifugation (3000*g*, 10 minutes). A one millilitre aliquot of the supernatant was mixed with 5 ml of freshly prepared vanillin–hydrochloride reagent (1 : 1, 8% hydrochloric acid in methanol: 4% vanillin in methanol). The reaction mixture was incubated at RT for 20 minutes and absorbance was recorded at 500 nm. Tannin content was expressed as mg catechin equivalents, calculated from a standard curve prepared using catechin (10–100 μg ml^{-1}).

2.4.11. Trypsin inhibitor content. 0.5 g of sample was macerated in 25 ml chilled distilled water using a pre-chilled mortar and pestle. The homogenate was kept at 4 °C for 3 h with occasional maceration and centrifuged at 10 000*g* for 20 minutes. The supernatant was diluted tenfold with DW to serve as the trypsin inhibitor (TI) source. For the assay, 0–1 ml of the diluted extract was transferred into separate test tubes. A tube without extract served as the endogenous control. Tubes containing extract were designated as samples. Each sample tube received 1 ml of trypsin solution prepared by dissolving 6.25 mg trypsin in 25 ml of 0.001 M HCl and diluting 2 ml of it to 25 ml. The endogenous control received 2 ml of Tris–HCl buffer (pH 8.2). Another tube designated as the standard received 1 ml buffer and 1 ml trypsin solution. All tubes were incubated at 37 °C for 10 minutes. Then reaction was initiated by adding 2.5 ml of BAPNA substrate prepared by dissolving 40 mg benzoyl-DL-arginine-*p*-nitroanilide in 0.5 ml dimethyl sulfoxide and diluting to 100 ml with Tris–HCl buffer. After 60 minutes at 37 °C, the reaction was stopped by adding 0.5 ml of 30% glacial acetic acid. Absorbance was measured at 410 nm. The absorbance values of the standard, endogenous and sample tubes were compared. One unit of TI activity was defined as the volume of extract required to inhibit 50% of trypsin activity, as indicated by a reduction in absorbance. Protein content of the

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corresponding aliquot was determined by Lowry's method and TI activity was expressed as trypsin inhibitor units (TIU) per mg protein of sample.[35]

2.5. Preparation of ice cream

A traditionally used base mix of 20% sucrose and 80% low-fat milk was used to prepare ice cream.[36] This mix was aggressively homogenized (10 000 rpm for 5 minutes at 85 °C) using a homogenizer (Ultra-Turrax, IKA T25, Germany). This was followed by blending at the same temperature (85 °C) for an additional 15 minutes. The mix was then cooled to 4 °C and held for 24 h to allow aging. After aging, the mix was whipped for 20 minutes without external aeration and then frozen at −18 °C to obtain the final ice cream product (Fig. 2). To formulate samples, the base mix was supplemented with DOSP and DDSP at varying concentrations ranging from 1% to 5%. A mix containing 0.3% guar gum (GG) was used as the positive control. A formulation without any added stabilizer served as the negative control. Each formulation was prepared in triplicate to perform further analyses.

2.6. Melting behaviour

The melting behaviour of ice cream samples was evaluated based on initial drip time, melting rate and complete melting

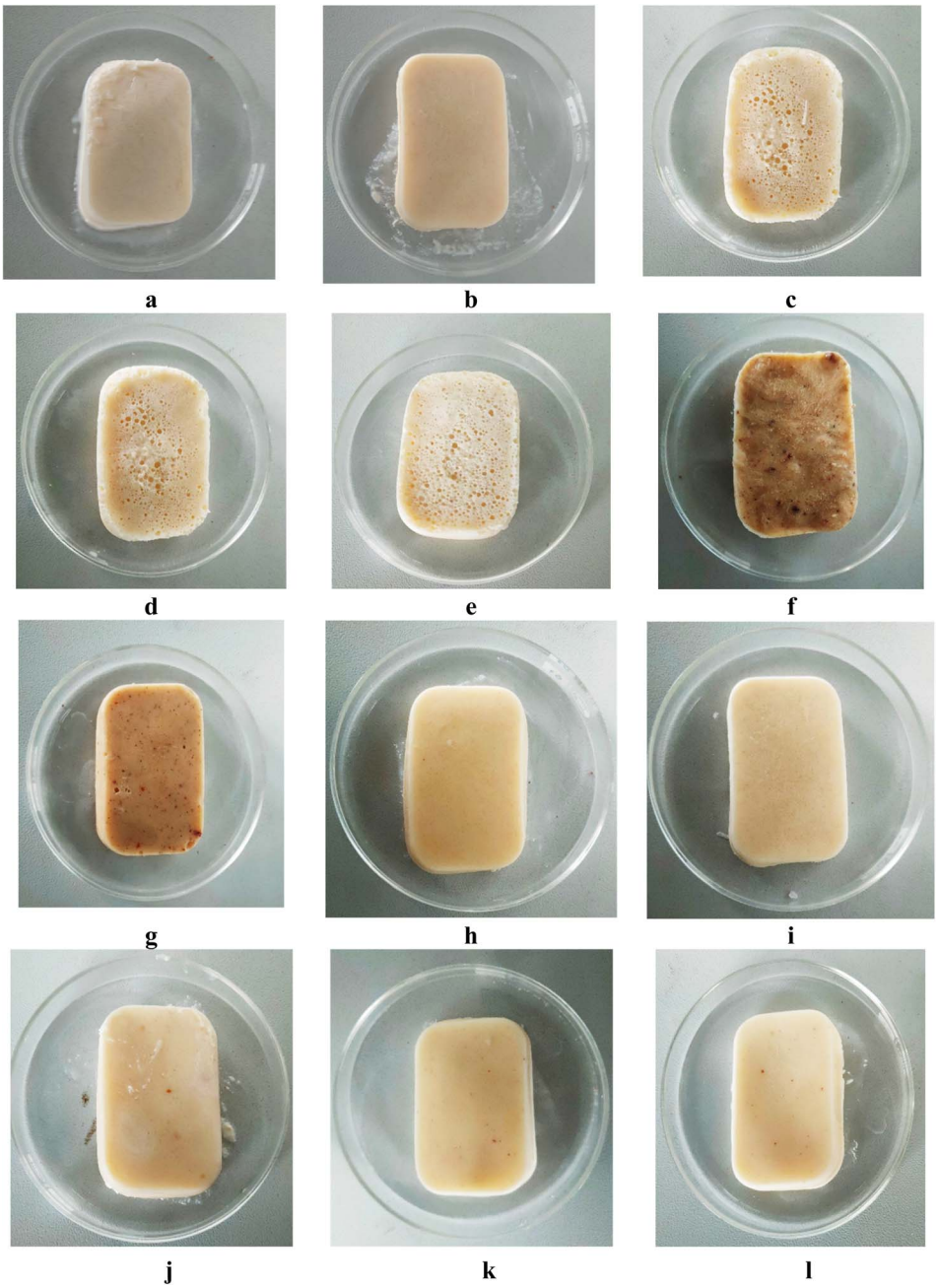

Fig. 2 Ice creams prepared using different concentrations of pomelo (*Citrus maxima*) seed fractions. (a) NC, (b) PC, (c) DOSP1, (d) DOSP2, (e) DOSP3, (f) DOSP4, (g) DOSP5, (h) DDSP1, (i) DDSP2, (j) DDSP3, (k) DDSP4, and (l) DDSP15. Samples are coded as mentioned in Table 1.

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time. A 25 g block of ice cream was placed on a wire mesh positioned over a pre-weighed collection vessel and allowed to melt at RT. The time at which the first drop of melt appeared was recorded as the initial drip time. The melting rate (g min^{-1}) was determined by collecting and weighing the melt every 2 minutes for 60 minutes. The rate was calculated from the slope of the linear portion of the drained mass *versus* time plot. Complete melting time was the duration required for the entire sample to melt and drain into the collection vessel.[31]

2.7. Overrun

Overrun was calculated by comparing the weights of equal volumes of ice cream mix and frozen ice cream and expressed as a percentage.[31]

$$\text{Overrun (\%)} = \left(\frac{\text{Weight of mix} - \text{Weight of ice cream}}{\text{Weight of ice cream}}\right) \times 100 \tag{13}$$

2.8. Colour

The CIE L^* (lightness), a^* (redness–greenness) and b^* (yellowness–blueness) colour values of the ice cream samples were recorded using a HunterLab ColorQuest UltraScan VIS spectrophotometer (Hunter Associates Laboratory, USA). The total colour difference (ΔE^*) was calculated using the following equation:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{14}$$

The whiteness index (WI), an indicator of the visual whiteness of ice cream, was determined using the following formula:

$$\text{WI} = 100 - \sqrt{(100 - L^*)^2 + (a^*)^2 + (b^*)^2} \tag{15}$$

2.9. Texture profile

Texture profile analysis (TPA) of the ice cream samples was conducted using a TA.XT Plus Texture Analyzer (Stable Micro Systems, UK) equipped with a 50 kg load cell and a 35 mm diameter cylindrical probe. Samples measuring 62 × 42 × 20 mm (length × width × height) were tested. The probe penetrated 10 mm into the centre of each sample at a constant speed of 1.0 mm s^{-1}, with a trigger force of 5 g. Each sample was analysed in triplicate and parameters including hardness, adhesiveness and gumminess were recorded.

2.10. Rheological properties

Rheological measurements of the ice cream sample were conducted using a Physica MCR 101 rheometer (Anton Paar, Austria) equipped with a cone-and-plate geometry (50 mm diameter, 1° cone angle, 0.1 mm gap). Samples were brought to 4 °C and kept for 60 minutes to allow temperature equilibration prior to testing. Steady shear, time-dependent and viscoelastic properties were evaluated, with all measurements performed in triplicate.[31,37]

2.10.1. Steady shear. Steady shear tests were performed under a controlled shear rate from 0 to 100 s^{-1} over 2 minutes, followed by a reversal over the next 2 minutes. Apparent viscosity was measured across the shear rate range, with particular emphasis on the value at 50 s^{-1}, which approximates oral shear conditions for low-viscosity foods.[36] Flow behaviour was characterized using the Herschel–Bulkley (H–B) model

$$\tau = \tau_0 + K\dot{\gamma}^n \tag{16}$$

where, τ represents the shear stress (Pa), τ_0 represents the yield stress (Pa), K is the consistency coefficient (Pa s^n), $\dot{\gamma}$ represents the shear rate (s^{-1}) and n is the flow behaviour index (dimensionless).

2.10.2. Dynamic shear. Dynamic frequency sweep tests were carried out within a frequency range of 0.1–10 rad s^{-1} at a constant strain of 0.1%, confirmed to lie within the linear viscoelastic region. The storage modulus (G') representing elastic behaviour and the loss modulus (G'') representing viscous behaviour, were recorded as functions of angular frequency (ω). The loss tangent ($\tan\delta$), indicative of the relative dominance of viscous or elastic behaviour, was calculated as:

$$\tan\delta = \frac{G''}{G'} \tag{17}$$

The overall viscoelastic response to oscillatory strain was further characterized using the complex modulus (G^*) and complex viscosity (η^*).

$$G^* = \sqrt{(G')^2 + (G'')^2} \tag{18}$$

$$\eta^* = \frac{G^*}{\omega} \tag{19}$$

Plots of ω *versus* G' and G'' were analysed using nonlinear regression to determine the intercepts (K' and K''), slopes (n' and n'') and corresponding coefficients of determination (R^2), based on the power-law model.

$$G' = K'(\omega)^{n'} \tag{20}$$

$$G'' = K''(\omega)^{n''} \tag{21}$$

2.11. Sensory evaluation using fuzzy logic

Sensory evaluation was performed in accordance with the declaration of Helsinki and the Indian Council of Medical Research (ICMR) National Ethical Guidelines for Biomedical and Health Research Involving Human Participants, 2017. The evaluation protocol involving human participants was carried out as per the guidelines approved by Mizoram University's Institutional Human Ethical Committee (Ref. No. MZU/HEC/2024/011, dated 17/06/2024). Informed consent was obtained from each panellist prior to participation in the analyses. An

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initial pool of forty individuals (20 males and 20 females), aged 22–38 years, representing demographic diversity and having prior experience in sensory analysis, was pre-screened using a consent and survey form. Individuals with underlying medical conditions and regular tobacco consumers were excluded. A final sensory panel of 21 members (13 females and 8 males) was constituted. Two orientation sessions were conducted to standardize the evaluation protocol and train panellists in the use of the scoring system.

Testing was carried out in a single session comprising seven coded and randomized ice cream samples. Panellists were instructed to refrain from consuming food or beverages, other than water, for at least 30 minutes prior to testing. Each panellist was seated individually in a neutral-coloured cubicle and samples weighing 10 g were provided in randomly coded white paper cups directly from the freezer (−18 °C). Each sample was evaluated independently by placing a small scoop of ice cream in the mouth, allowing it to melt for 5 seconds and then spreading it across the oral cavity with a backward tongue movement before swallowing. A five-point hedonic scale was used to rate four key sensory attributes: appearance, taste, creaminess and mouthfeel. The scale descriptors were: not satisfactory, fair, medium, good and excellent. After evaluating each sample, panellists rinsed their mouths with water and waited for two minutes before testing the next sample. No discomfort or allergic reactions were reported by any panellist during or after the evaluation sessions.

Subsequently, the relative importance of each sensory attribute was categorized into five levels: not at all important, somewhat important, important, highly important and extremely important. Fuzzy logic analysis was employed to rank the ice cream samples based on sensory performance. The evaluation followed a structured, stepwise process: assignment of triplet values corresponding to both hedonic scores and attribute importance levels, determination of relative weightings for each sensory parameter, calculation of overall sensory scores and their associated membership function values, estimation of similarity indices for each sample and final ranking based on sensory desirability. This method enabled a more nuanced characterization of each sample's sensory profile, minimizing subjective bias and enhancing interpretive resolution.[38]

2.12. Nutritional properties of optimized ice cream

The sensorially optimized ice cream sample was analysed for total protein, fat and carbohydrate contents.[34,35] Protein content was estimated using the Kjeldahl method, as described earlier in Section 2.4.6. Fat content was determined directly using a calibrated butyrometer. Samples were digested in concentrated H_2SO_4 and isoamyl alcohol at 65 °C for 10 min, followed by centrifugation at 350 g for 5 min. The fat layer was read directly from the butyrometer scale. Fat percentage was measured using eqn (22).

$$\mathrm{FC}(\%) = \frac{V_f}{W_s} \times 100 \tag{22}$$

where V_f is the volume reading from the butyrometer and W_s is the sample weight (g).

Carbohydrate content was estimated by the anthrone method. Samples were digested with 2.5 N HCl, neutralized and then reacted with anthrone reagent. Absorbance was measured spectrophotometrically and glucose concentration was determined using a standard calibration curve (0.01–0.1 mg ml^{-1}). Total carbohydrate percentage was estimated using eqn (23).

$$\mathrm{CC}(\%) = \frac{C_g \times V_t}{W_s \times 1000} \times 100 \tag{23}$$

where, C_g is the glucose concentration (mg ml^{-1}) obtained from the standard curve, V_t is the total volume of the extract (ml) and W_s is the sample weight (g).

Its energy value was calculated using the following formula:

$$\text{Energy (kcal/100 g)} = (4 \times \mathrm{PC}\ (\%)) + (9 \times \mathrm{FC}\ (\%)) + (4 \times \mathrm{CC}\ (\%)) \tag{24}$$

where, PC represents the protein content, FC represents the fat content and CC represents the carbohydrate content.

2.13. Statistical analysis

All analyses were conducted in triplicate and the results were expressed as mean ± standard deviation. Statistical significance among treatments was evaluated using one-way analysis of variance (ANOVA), followed by Duncan's multiple range test at a 95% confidence level ($p \leq 0.05$), using IBM SPSS Statistics 21 (IBM Corporation, USA). Graphs were plotted and model fitting was performed using Origin 9.0 (OriginLab Corporation, USA). Fuzzy logic analysis was carried out in Microsoft Excel 2021 (Microsoft, WA, USA).

3. Results and discussion

3.1. WAI, OAI and SI

The WAI and OAI of DSP and DDSP were significantly higher than those of their oil-rich counterparts (OSP and DOSP) (Table 2). Notably, the WAI of DSP and DDSP was approximately 2.4 times greater, while the OAI was about 4.3 times higher compared to OSP and DOSP. This sharp increase is attributed to the removal of inherent fat. The presence of oil in OSP and DOSP reduces both water and oil uptake due to two primary factors, physical blockage of absorption sites by lipids and the hydrophobic barrier they create. Water's inherent lipophobicity further prevents effective hydration of these fat-laden matrices. In contrast, oil extraction from DSP and DDSP increases the porosity and surface area of the seed powder, enhancing its ability to interact with water and oil.[39,40] Values of SI also followed a similar trend, being markedly higher (>2.8×) in DSP and DDSP. Effective swelling requires water to penetrate and rehydrate the internal components of the powder, which is more feasible when lipid content is reduced.[39,40] High WAI, OAI and SI values are critical indicators of a material's potential to enhance the textural properties and reduce syneresis in colloidal food systems. These observations align with similar functional behaviour reported in defatted seed flours derived

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Table 2 Physicochemical parameters of the different variations of *Citrus maxima* seed powder[a]

S.No	Parameters	Samples			
		OSP	DSP	DOSP	DDSP
1	Water absorption index (g g^{-1})	1.95 ± 0.09^a	6.71 ± 0.08^b	1.78 ± 0.06^a	6.79 ± 0.13^b
2	Oil absorption index (g g^{-1})	0.62 ± 0.21^a	3.38 ± 0.51^b	0.53 ± 0.23^a	3.44 ± 0.69^b
3	Swelling index (ml g^{-1})	0.59 ± 0.03^b	2.31 ± 0.28^c	0.47 ± 0.09^a	2.46 ± 0.19^c
4	Emulsion activity (%)	21.21 ± 1.55^a	51.78 ± 1.69^c	26.09 ± 1.48^b	53.26 ± 2.33^c
5	Emulsion stability (%)	8.19 ± 2.09^a	28.21 ± 1.39^c	12.23 ± 1.16^b	32.45 ± 1.21^d
6	Foaming capacity (%)	32.17 ± 0.10^a	86.48 ± 0.20^c	36.89 ± 0.13^b	89.24 ± 0.30^d
7	Foam stability (%)	3.76 ± 0.08^b	14.62 ± 0.10^d	1.53 ± 0.10^a	11.48 ± 0.15^c
8	Moisture content (g/100 g)	0.37 ± 0.03^a	0.46 ± 0.02^a	0.39 ± 0.03^a	0.48 ± 0.04^a
9	Carbohydrate content (g/100 g)	39.58 ± 1.66^a	46.94 ± 1.07^b	40.17 ± 2.06^a	47.13 ± 1.14^b
10	Protein content (g/100 g)	13.69 ± 2.45^a	43.78 ± 1.33^c	15.19 ± 0.67^b	43.69 ± 2.54^c
11	Fat content (g/100 g)	43.59 ± 3.25^a	0.68 ± 0.21^c	41.09 ± 0.98^b	0.71 ± 0.16^c
12	Ash content (g/100g)	3.49 ± 0.46^a	7.19 ± 0.72^b	3.55 ± 0.31^a	7.23 ± 1.13^b
13	Naringin content (μg g^{-1})	135.43 ± 6.88^d	109.28 ± 4.41^c	2.71 ± 0.78^b	0.07 ± 0.03^a
14	Limonin content (μg g^{-1})	379.41 ± 5.21^d	257.13 ± 2.81^c	4.32 ± 1.76^b	0.69 ± 0.15^a
15	Phytic acid (%)	0.56 ± 0.02^b	0.17 ± 0.01^a	ND	ND
16	Tannin (μg g^{-1})	0.07 ± 0.01	ND	ND	ND
17	Trypsin inhibitor (TIU/mg protein)	7.26 ± 0.17^b	1.69 ± 0.08^a	ND	ND

[a] Mean with different subscripts across the columns are significantly different ($p \leq 0.05$) as indicated through Duncan's multiple range test and independent *t*-test. ND: not detected.

from *Citrus sinensis* and oilseed press cakes such as groundnut and soybean, which also exhibit more than a two-fold increase in hydration and absorption characteristics following oil removal.[15,22,40,41] No significant differences in WAI, OAI or SI values were observed between OSP and DOSP or between DSP and DDSP, indicating that the debittering process did not substantially alter these functional properties.

3.2. EA, ES, FC and FS

Oil extraction had a pronounced effect on the emulsifying and foaming properties of pomelo seed powders. De-oiled samples (DSP and DDSP) exhibited significantly higher EA and ES than OSP and DOSP (Table 2). Approximately 2.5 times increase in EA was observed following oil removal, while ES rose upto 5 times. This enhanced emulsification capacity is particularly valuable in applications such as in salad dressings, sauces and plant-based creams, where uniform dispersion of fat within aqueous systems is essential for stability and mouthfeel.[42]

The foaming properties were similarly influenced. DSP and DDSP showed a threefold increase in foaming capacity compared to OSP and DOSP. Foam stability also improved, reflecting the better ability of de-oiled proteins to form cohesive films at the air–water interface.[40] These properties are relevant for aerated food products like whipped toppings, mousses and bakery batters that rely on stable foams for structure and volume.[42]

The role of debittering was also evident in modifying these properties. In OSP and DOSP, debittering led to ~23% and ~49% increases in ES, respectively. In DSP and DDSP, EA increased by ~2.5% and ES increased by ~15% following debittering. The FC values of DOSP and DDSP were ~14% and ~3% higher than those of their non-debittered counterparts. These observations are in line with the results from defatted seed flours of *Citrus sinensis*, *Citrus limon* and *Citrus paradisi*, where emulsion and foam properties increased by 10–15% upon oil removal.[15,43,44] However, FS showed an opposite trend. DOSP and DDSP exhibited reductions of ~59% and ~21%, which was likely due to protein denaturation.

The improved EA and ES are attributed to more effective dispersion of proteins in aqueous systems once oil is removed. The absence of lipid barriers allows protein and carbohydrate molecules to interact more freely with the surrounding medium and adsorb efficiently at the oil–water interface. In addition, the concentration of functional biopolymers per gram increased post-defatting, further enhancing interfacial performance.[40,44] The heat involved in oil extraction may partially unfold proteins, exposing hydrophobic regions that improve emulsifying behaviour.[40,44] While higher protein levels improve foam formation, excessive heat from debittering likely caused denaturation, weakening the protein films necessary for foam stability.[15] The low FS in OSP could be due to limited protein–water interaction caused by the presence of surface lipids.

3.3. LGC

LGC was significantly lower in DSP and DDSP compared to OSP (Table 3). The improvement in DSP is primarily attributed to

Table 3 Least gelation concentration of different *Citrus maxima* seed powders[a]

Sample	Powder concentration (%)														
	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
OSP	L	L	L	L	L	SS	SS	S	S	S	S	S	S	S	S
DSP	L	L	SS	SS	S	S	S	S	S	S	S	S	S	S	S
DOSP	L	L	L	L	L	L	L	L	L	SS	S	S	S	S	S
DDSP	L	SS	SS	SS	S	S	S	S	S	S	S	S	S	S	S

[a] Here, L: liquid, SS: semi-solid and S: solid.

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moderate heat exposure during oil extraction, which partially denatures proteins within the seed matrix, enhancing their ability to interact and form a continuous gel network. Further enhancement observed in DDSP could have resulted from additional thermal exposure during debittering, which further unfolded the native proteins. This unfolding increased the exposure of both hydrophilic and hydrophobic groups, facilitating stronger protein–water interactions and cross-linking within the gel matrix.[41,44,45] DOSP exhibited a higher LGC, indicating poor gelation capacity. Prolonged heat exposure at 85 °C during debittering caused irreversible protein denaturation and degradation of other gel-forming biopolymers, mainly pectin and cellulose. Once structurally compromised, these components lost their ability to form stable gels.[41,44,45] The gelation behaviour observed across treatments clearly highlighted the sensitivity of protein- and polysaccharide-based gelling systems in the seed powders to thermal processing. Controlled heat treatment (50–55 °C), as applied in DSP and DDSP, enhanced gelation by improving protein functionality without compromising biopolymer integrity. Whereas, over-processing as seen in DOSP, eliminated these functionalities.

3.4. Proximate composition

The proximate composition of the various pomelo seed powders (OSP, DSP, DOSP and DDSP) is presented in Table 2. In both OSP and DOSP, fat was the predominant component, accounting for approximately 35–40% of dry weight, followed by carbohydrates (25–30%) and protein (15–18%). Upon defatting, there was a notable increase in protein content. DSP and DDSP showed protein levels exceeding 40%, indicating that oil extraction concentrated the protein fractions. A significant mineral presence in all seed powder samples was suggested by considerable ash contents (3–8%). This composition trend mirrors that of other citrus species.[15,17] The fat and protein profiles of OSP and DOSP are comparable to those of common oilseeds such as groundnut (fat ∼45–50% and protein ∼25%), almond (fat ∼49% and protein ∼21%), sunflower (fat ∼51% and protein ∼20%) and safflower (fat ∼35–40% and protein ∼15–20%). This supports the underexplored potential of pomelo seeds as a viable source of edible oil.[47] Defatted DSP and DDSP had high protein levels (>40%) with substantial carbohydrates (∼30%), similar to leguminous functional ingredients like soybean (protein ∼40% and carbohydrate ∼30%),[41] locust bean (protein ∼27% and carbohydrate ∼55%)[45] and guar bean (protein ∼25% and carbohydrate ∼50%).[42] These observations highlighting, the potential use of pomelo seed powders as functional food ingredients in products such as emulsified desserts, jellies, plant-based creams and nutritionally enhanced beverages.

3.5. Naringin and limonin

A near-complete removal of bitterness-inducing compounds was observed following both alkali and solvent treatments applied to pomelo seed powders (Table 2). In DOSP, alkali treatment led to a 98% reduction in naringin content, while solvent extraction in DDSP resulted in a 99% decrease. Similarly, limonin content declined by approximately 99% in both DOSP and DDSP. The mechanism behind this reduction varies with the treatment. In alkali processing, the elevated pH disrupts flavanone glycosides such as naringin and interferes with the conversion of limonoate A-ring lactones into limonin, a non-volatile bitter triterpenoid. Additionally, the boiling step in the alkali treatment likely contributed to thermal degradation of these compounds, creating a synergistic debittering effect.[24,27] Although direct lye treatment on citrus seeds is limited in the literature, similar approaches have been effective in the pulp and pomace of pomelo and kinnow.[24,46]

In DSP, bitterness reduction also occurred upon solvent extraction. Naringin, a moderately polar flavonoid, exhibits high solubility in ethanol due to polarity compatibility.[47] Ethanol with a relative polarity of 0.654 aligns closely with the polarity of naringin, facilitating efficient extraction, especially at elevated temperatures. Yields of ∼10–17 mg g^{-1} of naringin have been reported for pomelo peel and *Citrus paradisi* albedo using 80% ethanol and ultrasonic-assisted extraction.[48,49] Similar patterns were observed with limonoids. Limonin, being less polar than naringin, was effectively extracted in acetone (relative polarity: 0.355). Previously, acetone extraction at elevated temperatures yielded 3–4 mg g^{-1} of limonin from kinnow pomace and pulp residues.[46] In *Citrus limon*, acetone recovered approximately 25 mg l^{-1} of limonin from juice, and in *Citrus sinensis* seeds, as high as 400 mg/100 g was extractable.[29,50] Notably, a partial reduction of bitterness was also observed during the oil extraction phase. In DSP, naringin content decreased by ∼19% and limonin by ∼32%, indicating that petroleum ether used for oil removal could also extract a significant quantity of bitterness-related compounds from the pomelo seed powders.[46]

3.6. Anti-nutritional factors

Anti-nutritional compounds present in seeds can interfere with digestion and reduce mineral bioavailability.[51,52] In this study, key anti-nutritional factors, tannins, phytic acid and trypsin inhibitors were effectively reduced to undetectable levels in DSP, DOSP, and DDSP, indicating complete removal (Table 2). The reduction can be attributed to sequential processing steps. Initial soaking for 24 h, followed by multiple rinsing to remove surface mucilage, likely facilitated the leaching of water-soluble anti-nutritional components. Soaking has been widely reported to reduce tannins and phytic acid in cereals and legumes by more than 50%.[51,52] Thermal treatments during oil extraction and debittering further enhanced elimination, as extended heating degrades heat-labile compounds. Both tannins and phytic acid are thermo-sensitive and decrease by over 95% under heat exposure, while trypsin inhibitors, being proteinaceous, are readily denatured.[51,52] The elevated temperatures employed during oil extraction (50 °C), drying (50 °C, 24 h) and debittering (up to 85 °C) likely caused irreversible structural damage, rendering these compounds undetectable in the final powders. The complete removal of anti-nutritional factors confirms the safety and functional suitability of the seed

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powders for food applications such as in dairy, supporting both consumer health and enhancing product quality.

3.7. Quality parameters of ice creams

Incorporation of pomelo seed powders had a significant effect on the melting characteristics and structural stability of the ice creams (Fig. 3a–c). Initial drip time notably increased with increasing seed powder concentration. Drip time increased from 2.19 min in the control (NC) to 4.56–6.48 min with DOSP (1–5%) and to 9.25–17.58 min with DDSP at the same inclusion levels. A similar trend was observed in the melting rate, which improved from 0.84 g minute^{-1} in NC to 0.77–0.64 g min^{-1} (DOSP1–DOSP5) and 0.58–0.32 g min^{-1} (DDSP1–DDSP5). Consequently, the total melting time of 25 g of ice cream rose from 29.14 minutes (NC) to 31.17–41.12 minutes (DOSP1–DOSP5) and 43.11–78.25 minutes (DDSP1–DDSP5), indicating improved thermal stability. Furthermore, DDSP demonstrated significantly superior performance. At concentrations of 1–5%, DDSP showed an ∼102–170% increase in initial drip time, an ∼24–50% reduction in melting rate and an ∼38–90% increase in complete melting time compared to DOSP. Notably, at 4–5% concentration, DDSP closely matched the stability of the guar gum-based mix (PC) with drip time (16.11–17.58 min), melting rate (0.39–0.32 g min^{-1}) and complete melting time (65.26–78.25 min) comparable to PC (17.11 min, 0.31 g min^{-1} and 79.14 min, respectively). This enhancement in melting properties is attributed to the superior ES, gelation ability, WAI, OAI and SI of DDSP. These properties collectively supported the formation of a cohesive and stable ice cream matrix. In untreated ice creams, fat droplets tend to coalesce and phase-separate, resulting in rapid melting of the free water phase.[4] The improved ES in DDSP stabilized formulations reduced fat coalescence, enhancing dispersion and thermal resistance. Additionally, fibres present in DDSP could absorb free water,

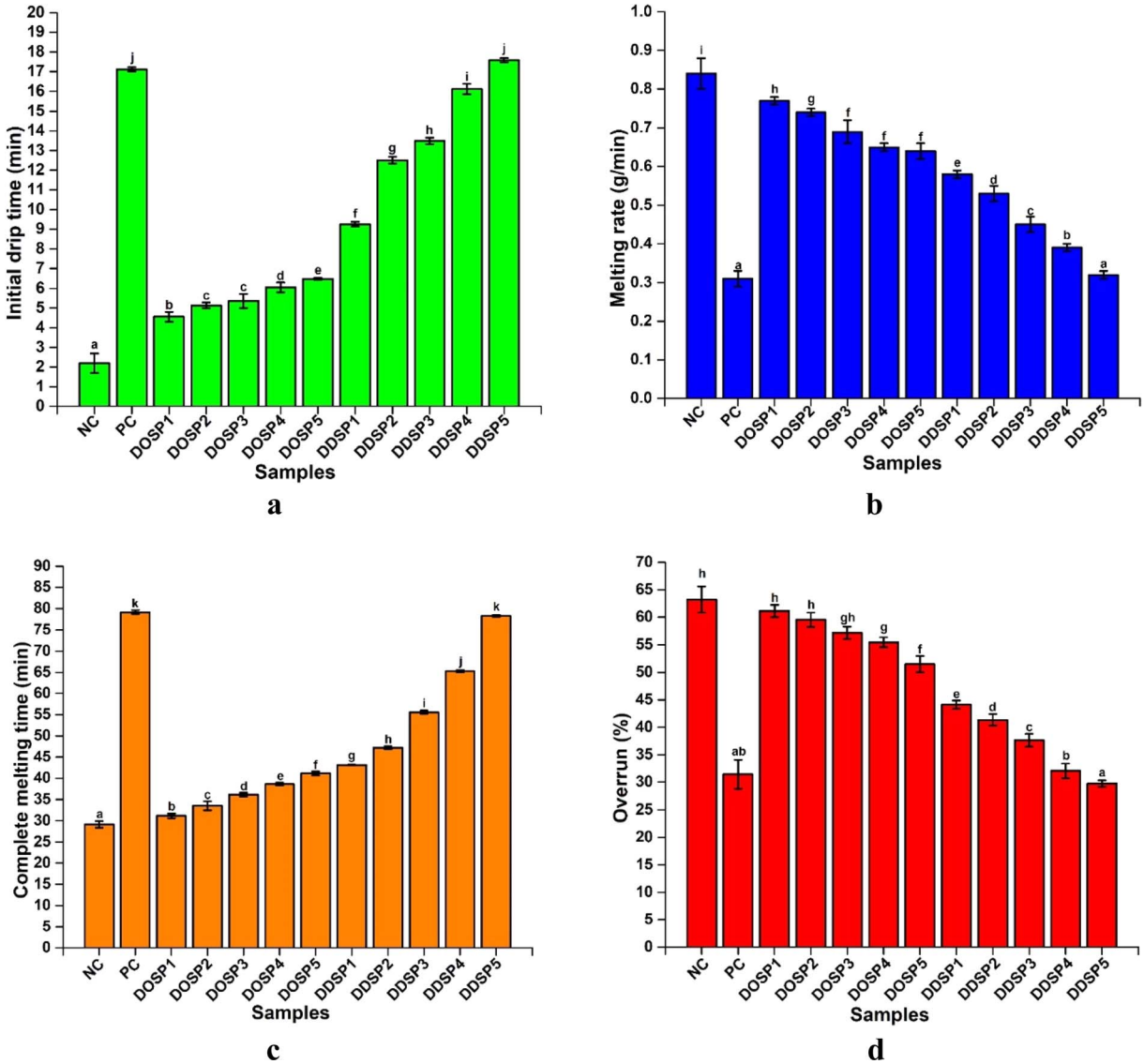

Fig. 3 Changes in (a) initial drip time (min), (b) melting rate (g min^{-1}), (c) complete melting time and (d) overrun (%) of the ice creams prepared from different pomelo seed fractions. Samples are coded as mentioned in Table 1.

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contributing to hydrogen-bonded water networks in its frozen matrix. This likely resulted in the formation of a compact gel, minimizing thermal gradients during cooling, delaying melt onset.[53] In parallel, proteins in DDSP could also play a crucial role in stabilizing the ice cream matrix by binding with both fat and free water, limiting fat aggregation and water migration.[36,54,55] This controls both ice crystal growth and improves melting resistance, as documented for globulin-type amphiphilic legume proteins and soy protein isolates.[53,55] Quince seed and red pitaya powders have also shown similar effects, where their high protein contents contributed to enhanced fat entrapment and water-holding, leading to improved emulsion and freeze-thaw stability in dairy systems.[36,54]

The overrun behaviour of the ice creams further confirmed these functional enhancements. Overrun, a measure of volume expansion due to air incorporation, was significantly reduced in the DDSP-containing samples (Fig. 3d). Higher concentrations (4–5%) of DDSP produced overrun levels comparable to PC, indicating low air entrapment and strong matrix stability. Conversely, DOSP-containing ice creams showed much higher overruns, pointing to a weak internal network incapable of restricting foam formation. This mirrored the behaviour observed in NC, which lacked any stabilizer and showed excessive aeration due to freely available casein.[53,56] The poor performance of DOSP was likely due to excessive heat exposure during its preparation, leading to irrecoverable denaturation of proteins and biopolymers that are responsible for emulsification and gel formation. In contrast, DDSP proteins which underwent further denaturation during ice cream processing resulted in limited foam expansion, but exhibited strong gel-forming capability, improved consistency and overall stability.

Since the ice creams prepared with DOSP showed significantly inferior stability and appearance as well as greater deviation from the properties of the PC formulation (Fig. 2 and 3), they were excluded from further analysis. Subsequent studies

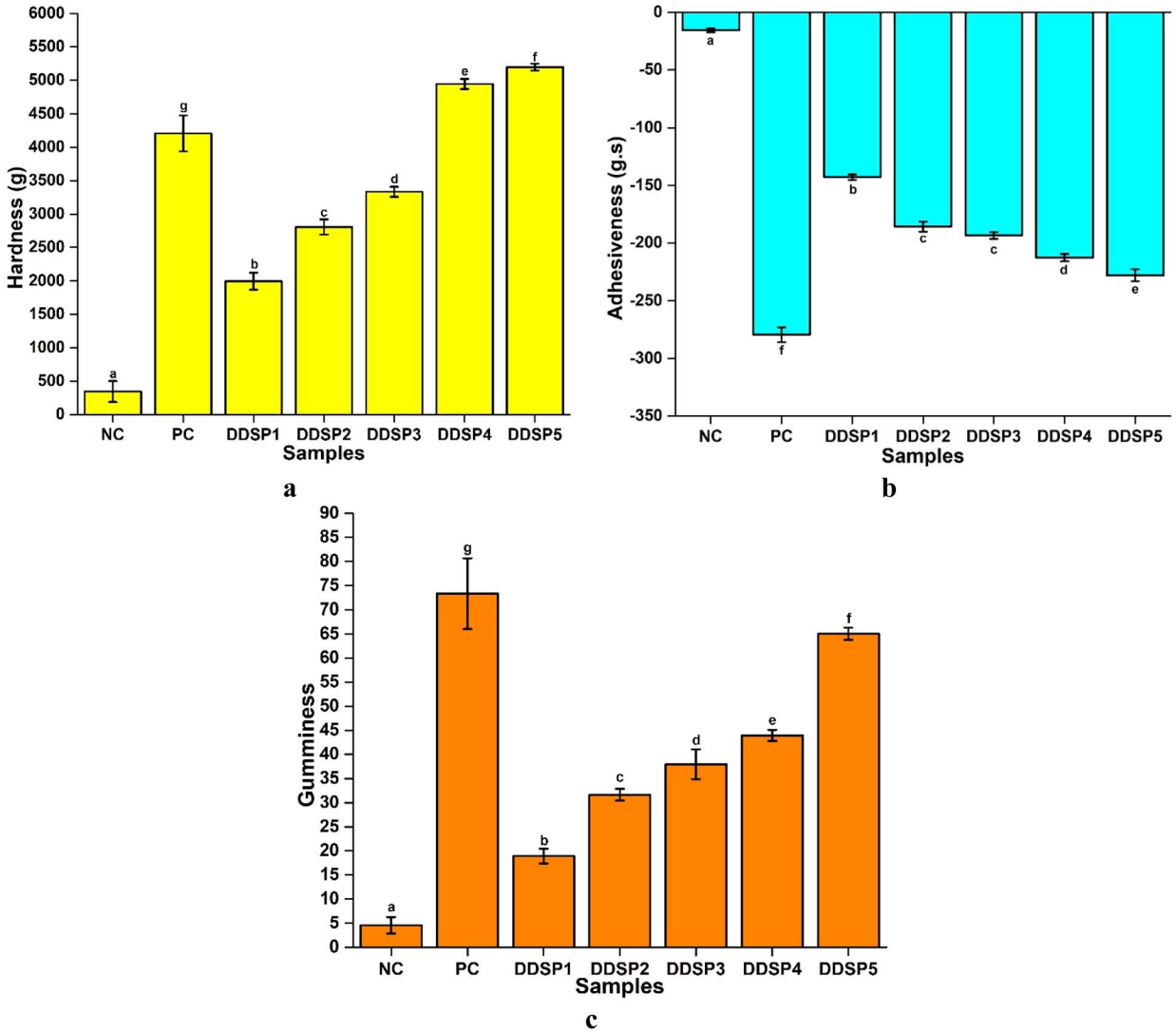

Fig. 4 Changes in (a) hardness (g), (b) adhesiveness (g.s) and (c) gumminess of the ice creams prepared from different pomelo seed fractions. Samples are coded as mentioned in Table 1.

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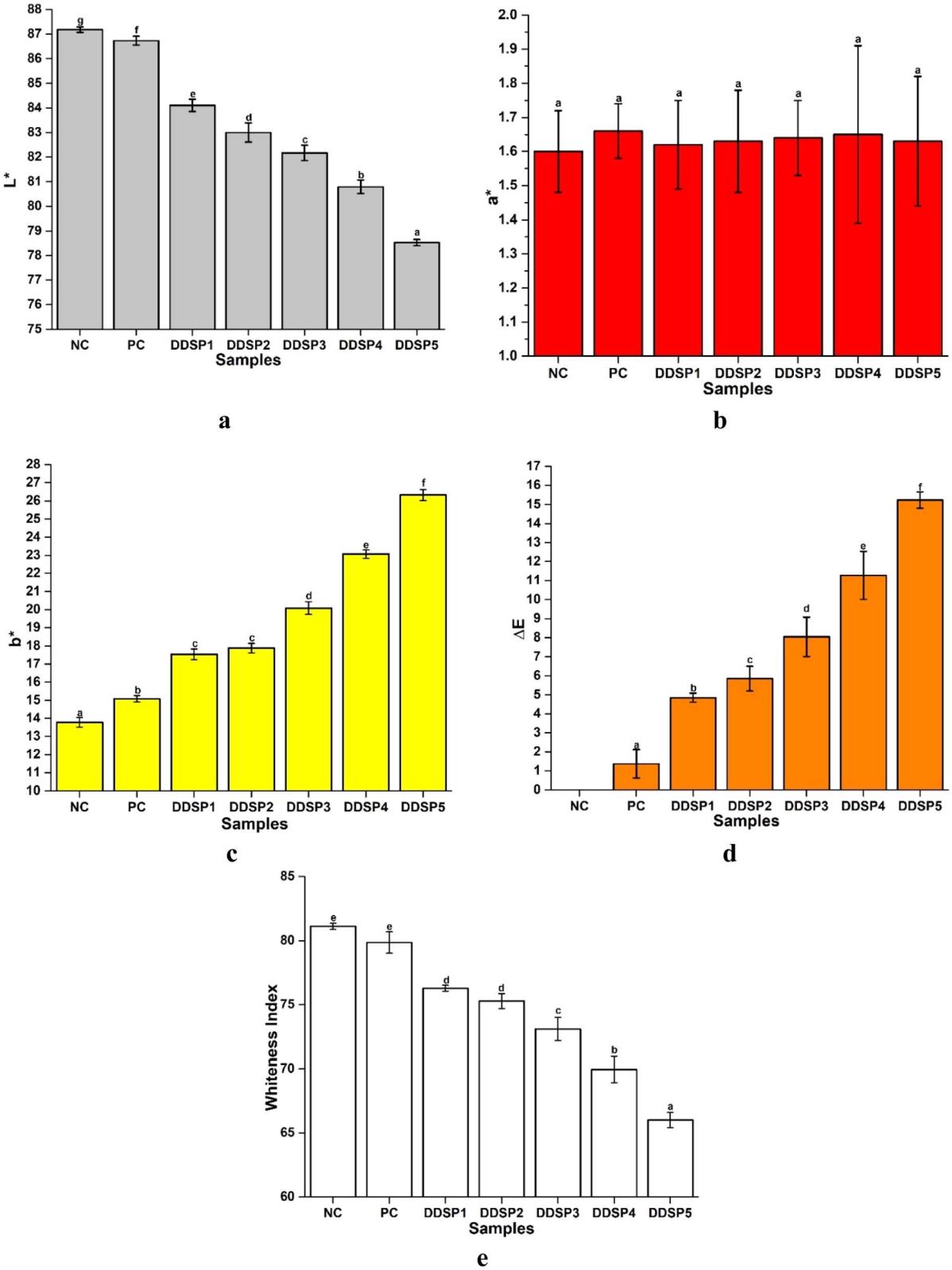

Fig. 5 Changes in (a) L^*, (b) a^*, (c) b^* values, (d) colour difference and (e) whiteness index of the ice creams prepared from different pomelo seed fractions. Samples are coded as mentioned in Table 1.

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on texture, colour, rheology and sensory attributes were carried out exclusively on the DDSP-incorporated ice creams.

3.8. Textural quality of ice creams

Ice creams formulated with increasing concentrations of DDSP exhibited progressive increases in hardness, adhesiveness and gumminess (Fig. 4). In DDSP1, increases in hardness from 344.35 g to 1997.24 g, adhesiveness from −15.46 g s to −142.88 g s, and gumminess from 4.53 to 18.91 were recorded. Higher concentrations further increased these textural values, reaching up to 5196.73 g, −227.81 g s and 65.04 respectively in DDSP5. Hardness (4944.10 g) and adhesiveness (−212.65 g s) of DDSP4 and gumminess of DDSP5 (73.32) closely matched with the respective values of PC (4207.01 g, −279.43 g s, 65.04). These improvements reflected the role of DDSP as a natural stabilizer, functioning similarly to established food hydrocolloids.[36,53,55] The combination of fibre and protein in DDSP decreased aeration within the dairy matrix, resulting in a denser structure. These biopolymers–protein complexes interacted with milk proteins and other solutes to form a uniform, cohesive network, which enhanced both adhesiveness and gumminess. The progressive increase in hardness with higher DDSP levels was attributed to better dispersion of the stabilizer within the ice cream mix, reducing solute migration and allowing numerous nucleation sites for ice crystal formation.[31] This promoted uniform and rapid freezing, resulting in a firmer texture. Guar gum in PC as well as DDSP at higher concentrations increased the elasticity and structural cohesion of the ice cream mixes. Upon freezing, their thicker consistencies provided greater resistance to deformation, resulting in increased final hardness, adhesiveness and gumminess values of the ice creams.[31]

3.9. Colour of ice creams

The colour attributes of the ice cream samples were notably affected by the incorporation of DDSP, particularly at higher concentrations (Fig. 5). NC displayed the highest L^* value of 87.18, followed by PC (86.73). The visible darkening of the ice cream mixes with increasing concentrations of DDSP (Fig. 2) was supported by the progressively declining L^* down to 84.11 in DDSP1 and further to 78.53 in DDSP5. This was the impact of enhanced pigment content from DDSP and reduced reflectance due to biopolymer loading from the powders. Minimal influence on the red–green balance was observed with a^* values remaining relatively stable (1.60–1.66) across all samples. However, b^* increased significantly at higher powder concentrations. NC showed a b^* value of 13.78, that rose to 20.08, 23.07 and 26.32 in DDSP3, DDSP4 and DDSP5 respectively, indicating a shift towards a more yellow-toned appearance, attributed to natural pigments and heat-induced browning compounds present in the heat-processed seed powders. The values of ΔE further supported the visible deviation in appearance from the control. While PC showed a minor shift (ΔE = 1.37), DDSP3, DDSP4 and DDSP5 exhibited considerable colour changes (ΔE = 8.04, 11.27 and 15.23 respectively). ΔE values above 3 are generally perceptible to the human eye, confirming that seed powder incorporation led to clearly noticeable visual differences, especially at 4–5% concentrations.[36,53,55] WI values exhibited an opposite trend to b^*, decreasing from 81.12 in NC to 73.10 in DDSP3, 69.94 in DDSP4 and 66.00 in DDSP5, confirming the visual dulling effect due to seed material addition. The slight difference between PC (WI = 79.85) and DDSP2 (WI = 75.28) suggests that, at 2% powder inclusion, the ice cream still maintained a reasonably clean appearance comparable to commercial stabilizers.

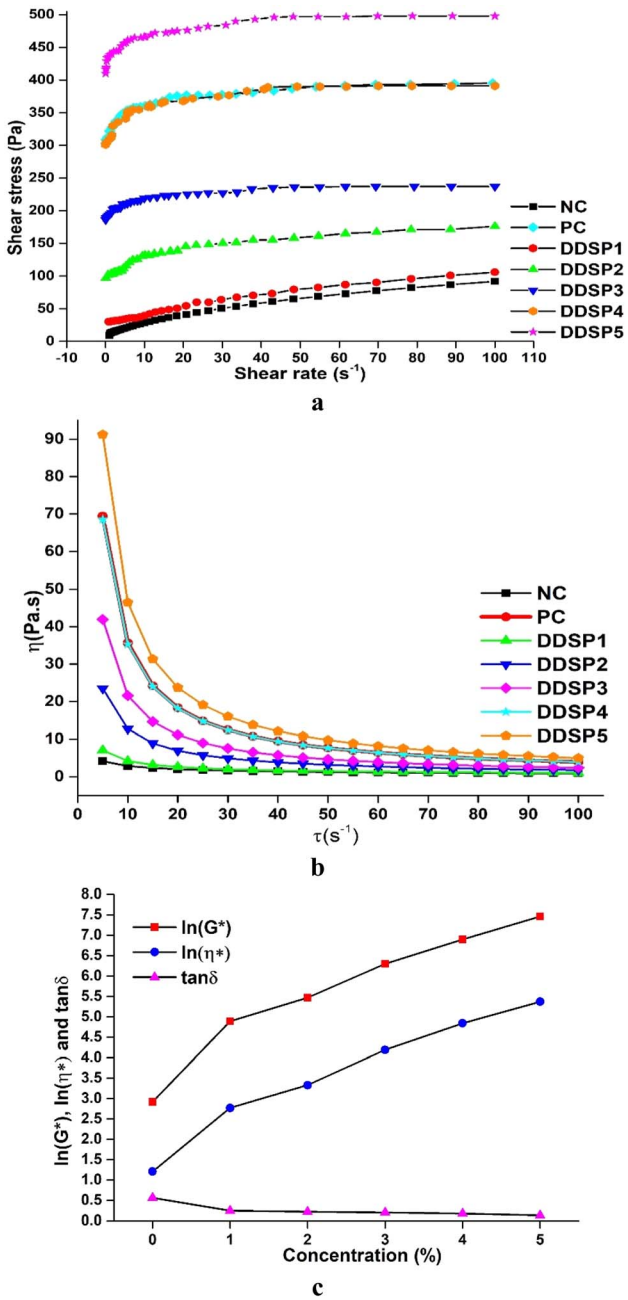

Fig. 6 Plots of (a) shear rate *vs.* shear stress, (b) shear rate *vs.* apparent viscosity and (c) variation in the complex modulus, complex viscosity and loss tangent as a function of concentration of the different ice cream mixes. Samples are coded as mentioned in Table 1.

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3.10. Rheological properties of ice creams

3.10.1. Steady shear properties. The steady shear properties of the ice cream mixes displayed a shear thinning behaviour, with all the samples displaying reductions in apparent viscosity (η_{50}) with increasing shear rates (τ) (Fig. 6a and b). These observations were consistent with similar behaviour exhibited by ice cream mixes incorporated with quince seed powder, xanthan gum and pomelo peel fibre.[31,36,37] The colloidal system in ice cream matrices consists of fat droplets coated with proteins and emulsifiers as the dispersed phase. The shear thinning behaviour of the mixes is an outcome of the increased alignment of aggregated molecules. Increasing shear rates disrupted these temporary aggregates and structurally realigned the ruptured fat globules and casein micelles, increasing their flow. The H–B model was found to be adequate ($R^2 > 0.97$) in explaining the flow behaviours (Table 4). The apparent viscosity (η_{50}), consistency index (K) and yield stress (τ_0) increased with increasing DDSP concentration, whereas the flow behaviour index (n) decreased. For instance, in NC, η_{50} was 1.28 ± 0.003 Pa s, K was 3.96 ± 1.28 Pa s and τ_0 was 3.26 ± 0.91 Pa. These values increased progressively with concentration. Between, DDSP1-DDSP5, η_{50} rose from 1.52 ± 0.004 Pa s to 9.33 ± 0.003 Pa s, K increased from 7.36 ± 0.98 Pa s to 47.92 ± 1.39 Pa s and τ_0 increased from 23.83 ± 3.56 Pa to 398.74 ± 3.18 Pa. Concurrently, the n value decreased from 0.95 ± 0.01 in NC to 0.66 ± 0.01 in DDSP1 and further to 0.17 ± 0.01 in DDSP5, confirming a stronger shear-thinning response in the seed powder incorporated samples.

DDSP incorporated at 4–5% concentrations mirrored the rheological behaviour displayed by guar gum-associated mixes (PC), which showed a η_{50} of 7.66 ± 0.005 Pa s, a K of 75.52 ± 0.17 Pa s, an n value of 0.14 ± 0.01 and a τ_0 of 252.48 ± 2.85 Pa. Additives akin to guar gum such as basil seeds, quince seed powder and soy protein isolates also demonstrated similar increases in viscous properties of ice cream mixes.[36,55,57] The increase in K and η_{50} and the reduction in the flow behaviour index were a result of interactions between the soluble protein and carbohydrate constituents with the aqueous phase, reinforcing the non-Newtonian pseudoplasticity of the ice cream mixes. The increase in total solids occurred due to the insoluble DDSP fractions. The biopolymers within DDSPs can form associations with water molecules through hydrogen bonding and with the lipophilic phase of ice cream through the apolar side segments of their carbon backbones. Both these interactions prevented intermolecular migration. The high molecular weight DDSP components created increased friction within the matrix, whereas the low molecular weight components enhanced hydrogen bonding, resulting in increased viscosity. Self-association of protein and carbohydrate fractions through glycosylation within the ice cream matrix, further increased water restriction and molecular hindrance.[4,36,37] Yield stress is another important parameter of ice cream quality and sensory assessment. Its increase with increasing DDSP concentrations indicated the creation of firmer structures and stable emulsions, representative of more uniform particle volumes, enhanced intermolecular associations and reduced phase separation within the colloidal product matrix during creaming, aging and sedimentation,[36] enhancing stability of the serum phase and potentially improving the creaminess, mouthfeel and scoopability of the ice creams.

3.10.2. Dynamic rheological properties. Viscoelasticity of the ice creams is directly correlated with the distribution of air cells and fat globules, micellar action of the emulsifier protein on the globules and optimality of the processing and aging procedures.[36,37] The dynamic rheological properties (G' and G'') of the ice creams as a function of frequency (ω) are presented in Fig. 7. Both moduli demonstrated increments with increasing DDSP concentration. No crossover-point between G' and G'' was observed, signifying the dominance of elastic behaviour over viscous behaviour throughout the frequency range. This trend persisted across all DDSP concentrations, indicating a gel-like structure within the ice cream matrix. The increased viscoelasticity in the ice creams was attributable to the water-binding capacity of the carbohydrate and protein components of DDSP. An increase in DDSP concentration of the mixes hence amplified their resistance to deformation. These findings were corroborated by measurements of complex viscosity (η^*), complex modulus (G^*) and loss tangent (tan δ) (Fig. 6c). The tan δ remained below 1 and decreased with increasing DDSP concentration, indicating a shift towards more solid-like behaviour. Concurrently, the rise in G^* suggested enhanced rigidity and structure formation and η^* displayed increased resistance to flow.

Table 4 Apparent viscosity and Herschel–Bulkley model parameters of the ice cream mixes[a]

	Herschel–Bulkley model parameters				
Concentration	η_{50} (Pa s)	K (Pa s)	n	τ_0 (Pa)	R^2
PC	7.66 ± 0.005[e]	75.52 ± 0.17[g]	0.14 ± 0.01[a]	252.48 ± 2.85[e]	0.98
NC	1.28 ± 0.003[a]	3.96 ± 1.28[a]	0.95 ± 0.01[g]	3.26 ± 0.91[a]	0.99
DDSP1	1.52 ± 0.004[b]	7.36 ± 0.98[b]	0.66 ± 0.01[f]	23.83 ± 3.56[b]	0.99
DDSP2	3.18 ± 0.002[c]	25.98 ± 2.05[c]	0.34 ± 0.02[e]	75.38 ± 2.49[c]	0.98
DDSP3	4.65 ± 0.001[d]	36.71 ± 2.36[d]	0.30 ± 0.01[d]	161.53 ± 1.85[d]	0.98
DDSP4	7.63 ± 0.001[e]	44.91 ± 1.73[e]	0.20 ± 0.03[c]	283.71 ± 1.65[f]	0.98
DDSP5	9.33 ± 0.003[f]	47.92 ± 1.39[f]	0.17 ± 0.01[b]	398.74 ± 3.18[g]	0.97

[a] Mean with different subscripts across the rows are significantly different ($p \leq 0.05$) as indicated through Duncan's multiple range test. Here, η_{50}: apparent viscosity, K: consistency index, n: flow behaviour index, τ_0: yield stress.

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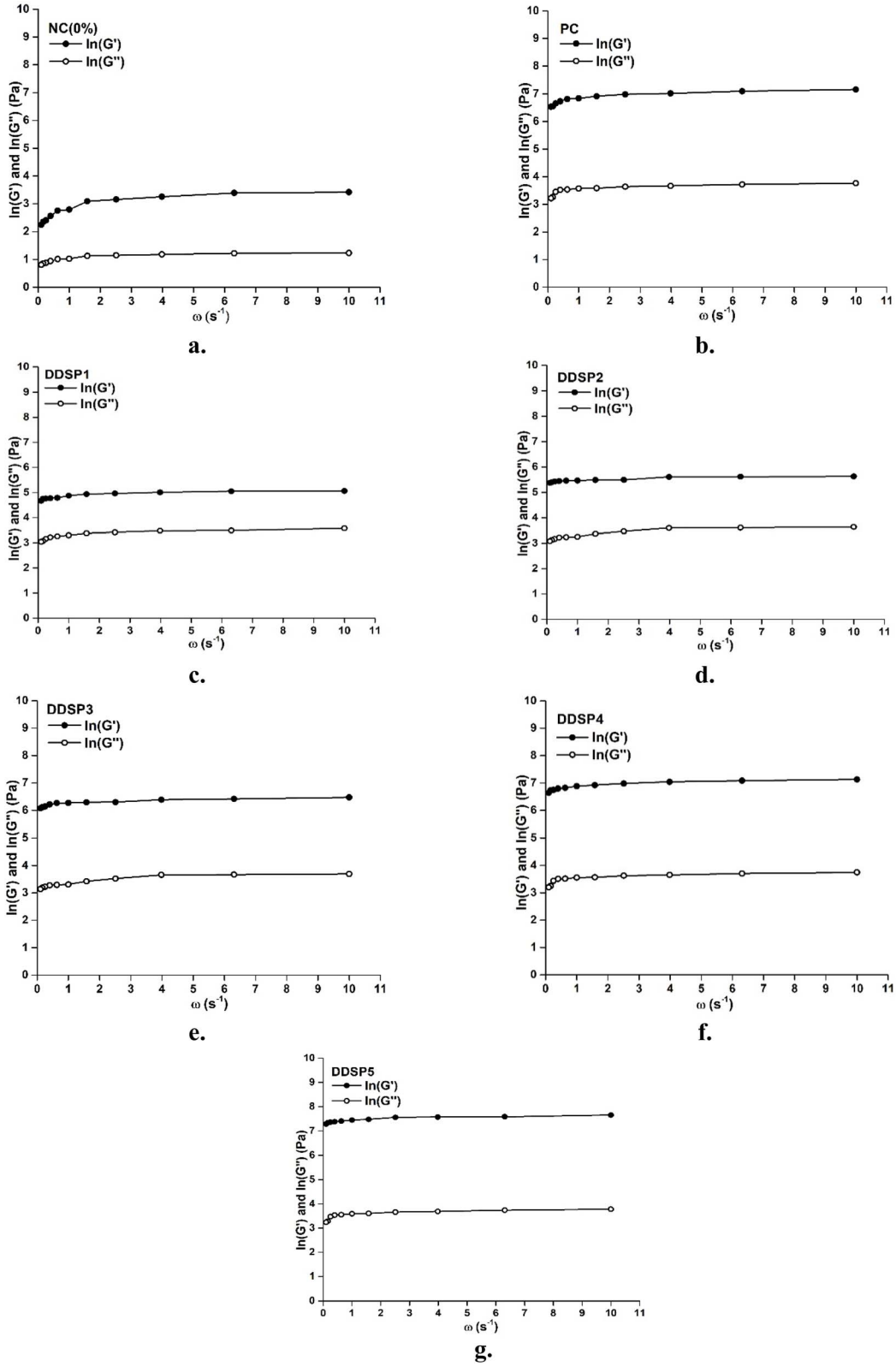

Fig. 7 (a–g) Plots of the storage (G') and loss (G'') modulus as a function of frequency for the ice cream mixes. Samples are coded as mentioned in Table 1.

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Table 5 Parameters of power law functions describing the storage modulus and loss modulus of the ice cream mixes[a]

	Power law parameters					
	$G' = K'(\omega)^{n'}$			$G'' = K''(\omega)^{n''}$		
Concentration	K' (Pa)	n'	R^2	K'' (Pa)	n''	R^2
PC	6.843 ± 0.01^{de}	0.020 ± 0.0001	0.99	3.532 ± 0.01^{c}	0.0303 ± 0.0001	0.92
NC	2.823 ± 0.06^{a}	0.097 ± 0.0002	0.98	1.027 ± 0.08^{a}	0.094 ± 0.0002	0.98
DDSP1	4.872 ± 0.01^{b}	0.017 ± 0.0000	0.98	3.302 ± 0.02^{b}	0.034 ± 0.0001	0.99
DDSP2	5.488 ± 0.02^{bc}	0.010 ± 0.0001	0.95	3.336 ± 0.07^{b}	0.039 ± 0.0002	0.97
DDSP3	6.269 ± 0.09^{cd}	0.013 ± 0.0002	0.98	3.391 ± 0.02^{bc}	0.038 ± 0.0001	0.99
DDSP4	6.888 ± 0.02^{de}	0.014 ± 0.0001	0.99	3.516 ± 0.02^{c}	0.0305 ± 0.0001	0.95
DDSP5	7.458 ± 0.01^{e}	0.010 ± 0.0001	0.98	3.552 ± 0.02^{c}	0.0302 ± 0.0001	0.98

[a] Mean with different subscripts across the rows are significantly different ($p \leq 0.05$) as indicated through Duncan's multiple range test. Here, G': storage modulus, G'': loss modulus, K: slope, and n: y -intercept.

These structural enhancements further indicated the formation of robust emulsions within the colloidal matrix due to progressive DDSP inclusion (Fig. 6c and 7). The relationship between G' and G'' modelled using a power law established the same (Table 5). Positive n values across all concentrations indicated the generation of strong gel-like characteristics. The

Table 6 Triplet sensory scores representing the preferences for different quality attributes of the ice creams recorded by the judges[a]

Attributes	Not satisfactory	Fair	Medium	Good	Excellent	Codes	Triplets of the sensory scores		
Appearance									
S0				15	6	S0A	82.14	25	17.85
S1				8	13	S1A	90.47	25	9.52
S2				12	9	S2A	85.71	25	14.28
S3				14	7	S3A	83.33	25	16.66
S4				8	13	S4A	90.47	25	9.52
S5				7	14	S5A	91.66	25	8.33
S6				5	16	S6A	94.04	25	5.95
Taste									
S0		12	7	2		S0T	38.09	25	25
S1				5	16	S1T	94.04	25	5.95
S2			11	8	2	S2T	64.28	25	22.61
S3			15	4	2	S3T	59.22	25	22.61
S4			6	9	6	S4T	75	25	17.85
S5			3	9	9	S5T	82.14	25	14.28
S6			2	9	10	S6T	84.52	25	13.09
Creaminess									
S0	6	8	7			S0C	26.19	17.85	25
S1				8	13	S1C	90.47	25	9.52
S2			3	18		S2C	71.42	25	25
S3			4	17		S3C	70.23	25	25
S4				18	3	S4C	53.57	25	25
S5				13	8	S5C	84.52	25	15.47
S6				10	11	S6C	88.09	25	11.90
Mouthfeel									
S0		18	3			S0M	28.57	25	25
S1				4	17	S1M	95.23	25	4.76
S2			9	12		S2M	64.28	25	25
S3			10	11		S3M	63.09	25	25
S4			5	9	7	S4M	77.38	25	16.66
S5				9	12	S5M	89.28	25	10.71
S6				7	14	S6M	91.66	25	8.33

[a] Here, S0: negative control S1: positive control S2–S6: samples DDSP1–DDSP5 4. S0A–S6A: triplets associated with the quality attribute of appearance for controls to samples; S0T–S6T: triplets associated with the quality attribute of taste for controls to samples; S0C–S4C: triplets associated with the quality attribute of creaminess for controls to samples; S0M–S4M: triplets associated with the quality attribute of mouthfeel for controls to samples.

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Table 7 Total number of judges with different preferences, the triplets associated with scores and the relative weightage for the quality attributes of the ice creams[a]

Quality attributes	Not important	Somewhat important	Important	Highly important	Extremely important		Triplets for sensory scores				Triplets for relative weightage		
Appearance			6	11	4	QA	72.61	25	20.23	QA_{rel}	0.2088	0.0719	0.0582
Taste				4	17	QT	95.23	25	4.76	QT_{rel}	0.2739	0.0719	0.0136
Creaminess				9	12	QC	89.28	25	10.71	QC_{rel}	0.2568	0.0719	0.0308
Mouthfeel				8	13	QM	90.47	25	9.52	QM_{rel}	0.2602	0.0308	0.0273

[a] QA: triplet for the sensory score of appearance; QT: triplet for the sensory score of taste; QC: triplet for the sensory score of creaminess; QM: triplet for the sensory score of mouthfeel; QA_{rel}: triplet for relative weightage of appearance; QT_{rel}: triplet for relative weightage of taste; QC_{rel}: triplet for relative weightage of creaminess; QM_{rel}: triplet for relative weightage of mouthfeel.

Table 8 Values of overall membership functions for the ice creams and their quality attributes

B0	B1	B2	B3	B4	B5	B6	BA	BT	BC	BM
0.09217	0	0	0	0	0	0	0	0	0	
0.35346	0	0	0	0	0	0	0	0	0	
0.614749	0	0.149017	0.108737	0	0	0	0	0	0	
0.876039	0	0.371909	0.328278	0.173497	0.029208	0.067978	0	0	0	
1	0.173059	0.594802	0.547818	0.381318	0.226164	0.26797	0.0956	0	0	
0.839387	0.366749	0.817694	0.767359	0.589139	0.42312	0.467962	0.4956	0	0	
0.533795	0.560439	1	0.9869	0.79696	0.620076	0.667953	0.8956	0	0.2288	0.1812
0.228204	0.754129	0.943387	1	1	0.817032	0.867945	1	0.3908	0.6288	0.5812
0	0.947818	0.632484	0.705596	0.991652	1	1	0.634701	0.7908	1	0.9812
0	1	0.321581	0.39251	0.628768	0.96759	0.858035	0.140386	1	0.932773	1

observed increases in K' and K'' reflected enhanced three-dimensional network bonds. DDSPs paralleled the behaviour seen in guar gum-containing samples. In DDSP4 and DDSP5, the dynamic rheological behaviour closely mirrored that of PC (Fig. 7). The incorporation of high molecular weight polysaccharides or amphiphilic proteins within the colloidal matrices enhanced their viscoelasticity as observed by their oscillatory interactions.[36,37,54,55]

3.11. Sensory analysis of the ice creams

In this study, a fuzzy logic-based approach was employed to address the similarity of the tested samples and to minimize the imprecision and subjectivity inherent in sensory data, particularly when panellists record preferences as crisp numerical values rather than linguistic terms. Fuzzy logic enables the transformation of qualitative, language-based sensory perceptions into quantitative measures, providing a more nuanced aggregation and interpretation of multidimensional sensory attributes.[38]

The 21-member panel marked their preferences among the seven ice creams (NC, PC and DDSP 1–5) and their quality attributes using the five-point hedonic scale. Based on the responses provided, triplets associated with the sensory scores of tested samples and their quality parameters were calculated (eqn (25)).[38] These triplets were designated as SA, ST, SC and SM. Similarly, the triplets associated with the quality parameters, namely appearance, taste, creaminess and mouthfeel were QA, QT, QC and QM (Table 6).

$$S_x a/Q_a = \frac{n_1(0\ 0\ 25) + n_2(25\ 25\ 25) + n_3(50\ 25\ 25) + n_4(75\ 25\ 25) + n_5(100\ 25\ 0)}{n_1 + n_2 + n_3 + n_4 + n_5} \tag{25}$$

where, $S_x a$: triplets associated with sensory score; x: sample number; a: quality attributes; Q_a: triplets associated with different quality attributes in general; n_1–n_5: number of judges providing each response.

The overall relative weightages of the sensory parameters (Q_{rel}, Table 7) were then calculated using eqn (26). These values were used to calculate the overall sensory scores of the ice creams (SO_x, eqn (27)). The overall membership function (By) was then calculated from SO_x (eqn (28) and Table 6) and denoted as B0–B6.[38] Likewise, the membership functions of the quality parameters were calculated from their triplet values (eqn (28) and Table 7) and denoted as BA, BT, BC and BM (Table 8).

$$Q_{arel} = \frac{Q_a}{Q_{sum}} \tag{26}$$

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where, Q_{arel}: triplets associated with the relative weightage for each quality attributes; Q_a: triplets associated with different quality attributes; Q_{sum}: the sum of the first digit of the triplets of the quality attributes.

$$SO_x = S_xA \times QA_{rel} + S_xT \times QT_{rel} + S_xC \times QC_{rel} + S_xM \times QM_{rel} \quad (27)$$

where, S_xA: triplets of the ice creams for appearance; S_xT: triplets of the ice creams for taste; S_xC: triplets of the ice creams for creaminess; S_xM: triplets of the ice creams for mouthfeel; QA_{rel}: triplets for the relative weightage of appearance; QT_{rel}: triplets for the relative weightage of taste; QC_{rel}: triplets for the relative weightage of creaminess; QM_{rel}: triplets for the relative weightage of mouthfeel.

The similarity values and their quality attributes calculated using eqn (29) are mentioned in Tables 9 and 10. The de-fuzzified sensory data were then categorized under linguistic adjectives namely "not satisfactory, fair, medium, good, very good and excellent" in the case of the ice creams and "not at all necessary, somewhat necessary, necessary, important, highly important and extremely important" in case of the quality attributes.[38]

$$B_y = \frac{y-(a-b)}{b}, \text{ for } (a-b) < y < a$$
$$B_y = \frac{(a+c)-y}{c}, \text{ for } a < y < (a+c) \quad (28)$$
$$= 0, \text{ for all other values}$$

where, a, b and c: triplets associated with the overall sensory scores; y: 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100

$$S_m(F_jB_y) = \frac{F_j \times B_y'}{\text{maximum of}\left(F_j \times F'_j \text{ and } B_y \times B_y'\right)}$$
$$F_1 = (1\ 0.5\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0)$$
$$F_2 = (0.5\ 1\ 1\ 0.5\ 0\ 0\ 0\ 0\ 0\ 0)$$
$$F_3 = (0\ 0\ 0.5\ 1\ 1\ 0.5\ 0\ 0\ 0\ 0)$$
$$F_4 = (0\ 0\ 0\ 0\ 0.5\ 1\ 1\ 0.5\ 0\ 0)$$
$$F_5 = (0\ 0\ 0\ 0\ 0\ 0\ 0.5\ 1\ 1\ 0.5)$$
$$F_6 = (0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0.5\ 1) \quad (29)$$

where, S_m: similarity values of the samples and their quality attributes; F_j: F_1, F_2, F_3, F_4, F_5, F_6, F_7, F_8, F_9, F_{10}, F_{11}, F_{12}, and F_{13} of standard 6-point fuzzy scale; B_y: overall membership functions for the samples and the quality attributes.

Similarity values of the ice creams designated S1 as the top-ranked (rank 1) followed by S5 (rank 2) and S6 (rank 3). Ice creams prepared from guar gum (S1) and DDSP 3–5% (S4–S6) were under the "very good" category, indicating high acceptability by the panelists. Ice creams from DDSP 1–2% (S2 and S3) were under the "good" category and the negative control (S0) was "satisfactory". Taste was identified as the most critical parameter influencing consumer preference of the ice cream samples, followed by creaminess, mouthfeel and appearance. Taste was rated under the "extremely important" category, whereas creaminess, mouthfeel and appearance were "highly important." There was no statistically significant difference between the sensorial perceptions of PC, DDSP4, and DDSP5, indicating that DDSP at higher concentrations provided

Table 9 Similarity values of the quality attributes of the ice creams and their rankings[a]

Scale factors	Appearance	Taste	Creaminess	Mouthfeel
Not at all necessary, F1	0	0	0	0
Somewhat necessary, F2	0	0	0	0
Necessary, F3	0.1373	0	0	0
Important, F4	**0.7756**	0.0781	0.2172	0.1887
Highly important, F5	0.861	0.6726	**0.8838**	**0.8612**
Extremely important, F6	0.1853	**0.7883**	0.6183	0.6388
Rank	IV	I	II	III

[a] Highlighted numbers indicate the highest scores of the similarity values of each quality parameter.

Table 10 Similarity values of the ice creams and their rankings[a]

Scale factors	S0	S1	S2	S3	S4	S5	S6
Not satisfactory, F1	0.0809	0	0	0	0	0	0
Fair, F2	0.4374	0	0.075	0.0936	0.0245	0.0105	0.0045
Satisfactory, F3	**0.7839**	0.121	0.3615	0.4053	0.24	0.1763	0.145
Good, F4	0.5985	0.4721	**0.6956**	**0.7231**	0.5872	0.5273	0.486
Very good, F5	0.1491	**0.8426**	0.659	0.6252	**0.7647**	**0.8142**	**0.8109**
Excellent, F6	0	0.5003	0.205	0.1783	0.3179	0.4202	0.4558
Rank	VII	I	VI	V	IV	II	III

[a] Highlighted numbers indicate the highest scores of the similarity values of each ice cream. S0: NC, S1: PC, S2: DDSP1, S3: DDSP2, S4: DDSP3, S5: DDSP4, and S6: DDSP6.

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a sensory experience comparable to ice cream stabilized with guar gum.

The rheological data supported this observation. Apparent viscosity (η_{50}) increased at higher DDSP concentrations. Measured at a shear rate of 50 s^{-1}, this parameter approximates the human oral experience. The elevated viscosity likely contributed to a more uniform and stable coating of the ice cream across the tongue, enhancing the intensity and duration of flavour perception. This textural behaviour could also simulate creaminess, which is typically associated with high-fat ice creams, thereby offering a richer mouthfeel despite the absence of additional milk fat.[58–60] Furthermore, the improved emulsifying and stabilizing properties of DDSP inhibited large ice crystal formation, enhancing the smoothness, consistency and mouthfeel of the product, especially recorded in DDSP4 and DDSP5 samples.[58] Negative sensory responses in NC further validates the structural and sensory advantages conferred by DDSP. Its absence led to perceptible flaws in texture and flavour delivery of NC, resulting in significantly lower sensory scores across all evaluated parameters.[58–60] Visual appeal of the samples also improved with DDSP inclusion. The gelling behaviour of the DDSP contributed to a firmer product structure, enhancing the visual integrity and presentation of the ice creams. Such structural firmness is often associated with premium-quality ice creams and may have positively influenced panellist perceptions.

DDSP4 received the highest overall acceptability score among all samples. Its rheological and structural characteristics closely mimicked those of the guar gum-stabilized PC, confirming that DDSP can function effectively as a natural alternative stabilizer in ice cream formulations without compromising consumer satisfaction.

3.12. Nutritional quality of the ice cream

DDSP4, which demonstrated the highest overall sensory acceptability showed favourable nutritional characteristics (Table 11). It combined a balanced macronutrient profile with moderate energy content, positioning it as a potentially healthier alternative to conventional low-fat ice creams.[59] Commercial low-fat ice creams typically contain protein levels between 3–4.5 g/100 g. DDSP4 offered an elevated protein content without negatively affecting its taste or texture. The fat content remained considerably lower than that of regular and some low-fat ice creams, which usually contain 2–5 g fat per 100 g. The unhindered creaminess despite lower fat was likely due to the thickening and emulsifying properties of DDSP that mimic fat-based creaminess. Carbohydrate levels in DDSP4 were within the range found in standard low-fat ice creams. Commercial products often contain added sugars as high as 22–25 g/100 g. In contrast, the DDSP4 formulation achieved desirable sweetness and palatability with a lower added sugar contribution, aided by the structural and flavour-enhancing properties of the seed powder. The overall energy content of DDSP4 was lower than that of most traditional and some reduced-fat ice creams, often exceeding 160–180 kcal/100 g.[31,57–60] This supports the formulation's potential as a low-calorie dessert option that does not compromise sensory appeal.

Table 11 Nutritional quality of the ice cream having 4% de-oiled and debittered *Citrus maxima* seed fraction

Parameters	Content
Total carbohydrate content (g/100 g)	27.88 ± 1.05
Added sugar (g/100)	20
Total protein content (g/100 g)	5.75 ± 0.33
Total fat content (g/100 g)	1.54 ± 0.02
Energy (kcal/100 g)	148.38 ± 1.88

4. Conclusions

In this study, DDSP was successfully utilized as a natural stabilizer and emulsifier in the development of low-fat ice cream formulations. Proximate analysis revealed that the raw seed powder (OSP) was rich in fat and subsequent oil extraction significantly increased its protein and carbohydrate compositions. Debittering enhanced seed powder quality by effectively removing bitterness-causing compounds and anti-nutritional factors. Functional property analysis showed that de-oiling substantially improved the seed powder's performance, while debittering had a limited effect, indicating that lipid content was the primary factor limiting its functionality. This was clearly reflected in the final ice cream products. Samples formulated with DDSP (DDSP1–DDSP5) exhibited superior melt resistance, controlled overrun and enhanced visual appeal compared to those prepared with DOSP, which were subsequently excluded from further evaluation due to poor quality. Texture analysis of DDSP-based formulations showed increased hardness, adhesiveness and gumminess with rising concentrations, consistent with the development of a strong gel-like structure within the matrix. Rheological evaluations supported these findings, as apparent viscosity, consistency index and yield stress increased, while the flow behaviour index decreased with higher DDSP levels. Dynamic rheology further indicated the formation of robust three-dimensional networks, evidenced by increasing storage modulus (G'), loss modulus (G''), complex viscosity and declining loss tangent values. Colour analysis revealed a gradual yellowing of the ice cream with increasing DDSP concentration, reflected in rising b^* values and decreasing L^* values and whiteness index. Sensory evaluation, interpreted *via* fuzzy logic, identified the DDSP4 formulation as the most preferred sample in terms of taste, creaminess, mouthfeel and appearance. A detailed sensory acceptance study comparing samples with different additives can be performed to check consumer preferences, offering a future research direction. Nutritional analysis of DDSP4 confirmed its low-caloric content, supporting its potential as a fat replacer in healthier dessert formulations.

Overall, DDSP demonstrated significant potential as a dual-function ingredient, serving both as a stabilizer and emulsifier in the production of low-fat ice creams. Its functional and nutritional properties position it as a promising commercial additive and a sustainable value-added application for pomelo

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seed byproducts. Future research can expand its use across other low-calorie food systems including ice cream mixes, desserts or creams, contributing to waste valorisation and circular economy within the citrus processing industry.

Ethical statement

All procedures involving human participants were conducted in accordance with the Declaration of Helsinki and the Indian Council of Medical Research (ICMR) National Ethical Guidelines for Biomedical and Health Research Involving Human Participants, 2017. The study protocol was reviewed and approved by the Mizoram University Institutional Human Ethical Committee (Ref. no. MZU/HEC/2024/011, dated 17/06/2024). Written informed consent was obtained from all participants prior to their inclusion. Participation was voluntary and confidentiality of participant information was strictly maintained throughout the study.

Author contributions

Sayantan Chakraborty; investigation, data curation, formal analysis, writing original draft. Gunjana Deka; resources, data curation. Jinku Bora; resources, data curation. Himjyoti Dutta; review and editing, visualization, methodology, conceptualization, supervision.

Conflicts of interest

The authors declare no conflicts of interest relevant to this article.

Note added after first publication

This article replaces the version published on 4th September 2025, which contained errors in the Introduction, Sections 2.2, 2.12, 3.10.1, 3.10.2 and 3.11. This also included errors with eqn (23), (25) and (29), and in Tables 9 and 10.

Data availability

All data supporting this article have been included as part of the manuscript.

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