https://doi.org/10.17113/ftb.63.03.25.8841 original scientific paper

Opuntia ficus-indica as An Alternative Source of Mucilage in Low-Fat Ice Cream

Running title: *Opuntia ficus-indica* in Ice Cream Production

Eduarda França Ferreira Souza, Amanda Kelly Cristiano Mafra, Raquel Guidetti Vendruscolo, Marcio Schmiele and Larissa de Oliveira Ferreira-Rocha*

Institute of Science and Technology, Federal University of Jequitinhonha and Mucuri Valleys, MGT-367 Highway, Km 583, n. 5000, Diamantina, MG 39100-000, Brazil

Received: 24 August 2024
Accepted: 23 March 2025

SUMMARY

Research background. Cactus pear (*Opuntia ficus-indica*) is an excellent source of polysaccharides and bioactive compounds with notable health benefits. The mucilage of the cactus pear, primarily composed of water and complex carbohydrates, exhibits properties similar to gums due to its unique physiological characteristics. Recently, plant-derived mucilage has gained significant attention in the dairy industry for its potential as a natural thickening and colloidal stabilizing agent.

Experimental approach. This study investigates the application of freeze-dried cactus pear pulp from *Opuntia ficus-indica* L. Miller as a mucilage source and its interaction with a commercial stabilizer on the physical properties of low-fat cocoa ice cream (3.0 % fat). The research evaluates the impact of cactus pear pulp on the physicochemical properties and technological parameters of the ice cream. Ice cream samples containing 1.0 %, 1.5 %, and 2.0 % cactus pear pulp were compared with a control sample (0.0 % cactus pear pulp).

*Corresponding author:
E-mail: larissa.rocha@ict.ufvjm.edu.br

Results and conclusions. The findings reveal that cactus pear pulp is rich in fiber and phenolic compounds and exhibits significant technological potential due to its water absorption capacity (WAC), water solubility index (WSI), and oil absorption capacity (OAC). The incorporation of cactus pear pulp lowered the pH of the ice cream, enhanced its darkness and yellowness, increased the overrun, and delayed the melting process. These results suggest that cactus pear pulp works synergistically with the commercial stabilizer, highlighting its promise as a natural fat substitute and stabilizer for low-fat ice cream formulations.

Novelty and scientific contribution. This study presents a pioneering exploration of the use of freeze-dried *Opuntia ficus-indica* pulp in ice cream production. The findings offer valuable insights for the ice cream industry, providing a natural alternative for stabilizers and fat substitutes.

Keywords: freeze-dried cactus pear pulp; mucilage; low fat ice cream; physicochemical properties; technological parameters

INTRODUCTION

Opuntia ficus-indica (*O. ficus-indica*), a member of the Cactaceae family, is predominantly found in arid regions. The sustainable and mindful exploitation of this plant can significantly contribute to global goals aimed at reducing poverty and hunger, while fostering sustainability and innovation within the food industry. The primary substance produced by *O. ficus-indica* is mucilage, a compound mainly composed of water and polysaccharides. This mucilage plays a crucial role in the plant's adaptation mechanisms, helping to prevent dehydration or freezing through its cryostabilizing properties. The mucilage extracted from the cladodes of cactus pear is water-soluble and forms highly viscous colloidal solutions (*1*).

Structurally, mucilage a complex polymeric polysaccharide, is primarily composed of highly branched carbohydrate structures. These structures consist of monomeric units such as L-arabinose, D-xylose, D-galactose, L-rhamnose, and galacturonic acid. In addition to these carbohydrates, mucilage may also contain glycoproteins and various bioactive components, including tannins, alkaloids, and steroids. Upon hydrolysis, mucilage generates a heterogeneous mixture of monosaccharides and is commonly classified as gum-like due to its comparable physicochemical properties (*2*).

Vegetable mucilage has gained significant attention in dairy product development due to its effectiveness as a natural thickening and colloidal stabilizing agent (*3*).

It has been extensively studied in yogurt production for its ability to improve texture and minimize whey separation during storage (*4*). Additionally, mucilage offers other benefits in products

like fermented milk and cheeses, including effective fat reduction (*5–7*), the potential to create prebiotic foods (*5,6,8,9*) and support for the development of probiotic products (*6,8*).

Recent studies have explored the use of vegetable mucilage in ice cream to replace or reduce the reliance on commercial and costly additives. Mucilage serves as an effective cryoprotectant, compensating for the absence of various commercial stabilizers, while also providing desirable technological and sensory properties (*10–13*). Since it is challenging to achieve all desired properties in ice cream with a single stabilizer, combining two or three hydrocolloids in the mixture can produce synergistic effects. The quantity and type of stabilizer needed depend on factors such as the type and strength of the stabilizer, the levels of total solids and fat in the mixture, and other relevant factors (*14*).

The literature reveals a scarcity of studies on the application of cactus pear mucilage as a fat substitute in low-fat ice creams. Therefore, this study aimed to evaluate the application of freeze-dried cactus pear pulp from *Opuntia ficus-indica* L. Miller as a mucilage source and its interaction with a commercial stabilizer on the physical characteristics of ice cream. Additionally, the study sought to characterize of freeze-dried cactus pear pulp by assessing its physicochemical properties and technological parameters.

MATERIALS AND METHODS

Raw material and obtaining freeze-dried cactus pear pulp

The project is registered with the Ministry of the Environment, a Brazilian organization that includes the National System for Management of Genetic Heritage and Associated Traditional Knowledge (protocol number: AF2C488). The cactus (primary cladodes) were collected in the municipality of Couto de Magalhães de Minas, in the state of Minas Gerais, located at an altitude of 740 meters and geographical coordinates of 18°04'16" South and 43°28'31" West, respectively.

The primary cladodes of the cactus pears were first cleaned with potable water to remove surface dirt, sanitized in a 200 ppm sodium hypochlorite solution for 15 minutes, rinsed with potable water, and then frozen until use.

Cactus pear pulp was prepared as illustrated in Fig. S1. After thawing the cladodes overnight, the peel was removed to extract the pulp, which was cut into approximately 1.5 cm×1.5 cm pieces. These pieces were divided into 100g portions and frozen for freeze-drying at the MULTIFAR/PRPPG Center using a Freeze Dryer (FreeZone, Labconco®, Kansas, MO, EUA) with the following parameters: temperature -50 °C and pressure 50 Pa.

The freeze-dried cactus pear pulp was ground using a Wiley-type macro mill (TE-650, Tecnal, Piracicaba, Brazil) and then sieved with an 80-mesh sieve using a sieve shaker (Bertel, Bertel,

Caieiras, Brazil) to obtain a fine powder with a standard particle size of 180 µm. The ground and sieved cactus pear pulp was packaged in polypropylene bags and stored in a refrigerator until use. Fig. 1

Characterization of freeze-dried cactus pear pulp

Moisture content was determined using AOAC method 934.06 (*15*). Ash mass fraction was determined by burning the weighed mass of sample in a muffle furnace according to AOAC 923.03 (*16*). Total dietary fiber (TDF), insoluble dietary fiber (IDF), and soluble dietary fiber (SDF) were analyzed using the AOAC method 991.43 (*17*). Protein content was determined with a CHNS/O elemental analyzer (TruSpec Micro, LECO, St. Joseph, MI, EUA). Lipid content was assessed using the Bligh and Dyer method (*18*). Total carbohydrate content was calculated as the difference between 100 % and the sum of the percentages of lipids, proteins, and ash on a dry weight basis.

The pH was measured using the electrometric method with a digital pH meter (MS Tecnopon mPA – 210, Piracicaba, Brazil) with a 1:10 sample dilution in distilled water (*19*). Water activity (a_w) was assessed at 25 °C using a water activity instrument (4TE Duo, AquaLab, Pullman, WA, EUA).

Macrominerals (Ca, Mg, K, and P) were analyzed with a atomic absorption spectrometer (SpectrAA 50B, Varian, Mulgrave, Australia)

The fatty acid profile was determined in two stages: extraction and chromatographic determination. The lipid fraction was extracted from water-soluble extracts using a mixture of methanol (Sciavicco, Belo Horizonte Brazil), chloroform (Dinâmica, Química Contemporânea, Indaiatuba, Brazil) and water, according to the method described by Bligh and Dyer (*18*). Subsequently, derivatization was performed according to the method described by Hartman and Lago (*20*). The lipid fraction was added with 1 mL of 0.4 M methanolic potassium hydroxide (Êxodo Científica, Sumaré, Brazil) solution and kept in a water bath (SL-150, Solab, Piracicaba, Brazil) at 100 °C for 10 minutes. The tubes were then cooled and 3 mL of 1 M methanolic sulfuric acid solution were added, followed by incubation at 100 °C for another 10 minutes. After cooling, 2 mL of hexane (Êxodo Científica, Sumaré, Brazil) were added, and the tubes were homogenized in a vortex (NA 3600, Norte Científica, Araraquara, Brazil) for 10 seconds. The upper layer containing the fatty acid methyl esters (FAMEs) dissolved in hexane was then collected for chromatographic analysis. The fatty acid profile was analyzed using Gas Chromatography with a Flame Ionization Detector (GC-FID) (7820A, Agilent Technologies, Santa Clara, CA, USA). A 1 µL sample was injected in split mode with a 40:1 ratio at an injector temperature of 240 °C. Hydrogen was used as the carrier gas at a constant pressure of 15 psi. Fatty acid methyl esters (FAMEs) were separated on a DB-23 capillary column (60 m×0.25 mm×0.25 µm; Agilent Technologies, Santa Clara, CA, USA) under a temperature program: an initial

hold at 50 °C for 1 minute, an increase to 175 °C at 25 °C/min, followed by a rise to 230 °C at 2 °C/min, with a final isothermal hold for 6 minutes. The detector temperature was set at 240 °C. FAMEs were identified by comparing retention times with those of the FAME Mix 37 standard (P/N 47885; Sigma-Aldrich, St. Louis, MO, USA) (*21*). Results were expressed as the percentage of the total chromatogram area, incorporating FID correction factors and accounting for the conversion of esters to acids (*22*).

Water absorption capacity (WAC) and water solubility index (WSI) were determined following the method described by Schmiele *et al*. (*23*). Oil absorption capacity (OAC) was measured using the methodology outlined by Benítez *et al*. (*24*).

The color of the freeze-dried cactus pear pulp was evaluated using instrumental colorimetry according to the CIE Lab* system, with illuminant D65, a 10 ° viewing angle, and calibration in SCI mode (specular component included) using a spectrophotometer (CM-5, Konica Minolta, Chiyoda, Japan). The CIE parameters evaluated were: *L** value (100=white; 0=black), *a** (+, red; -, green), and *b** (+, yellow; -, blue).

The total phenolic compound (TPC) content was quantified using a modified version of the methodology described by Nascimento *et al.* (*25*), ensuring enhanced accuracy and reproducibility. Extraction was performed with a water:acetone (Isofar, Duque de Caxias, Brazil) (52:48) mixture over six cycles, with the supernatant adjusted to a final volume of 10 mL. The color reaction involved 100 µL of the extracting solution containing phenolics, 250 µL of 0.2 M Folin-Ciocalteu reagent (Êxodo Científica, Sumaré, Brazil), 3 mL of distilled water, and 1 mL of 15 % Na_2CO_3 solution. The reaction was allowed to develop in the dark for 30 minutes. A standard curve was prepared using gallic acid. Absorbance was measured at 750 nm with a spectrophotometer (UV-M5, Bel Photonics, Monza, Italy). Readings were taken in six replicates, and results were expressed in milligrams of gallic acid equivalents per 100 grams of sample (dry basis). A blank containing the extraction solvent was used to zero the equipment.

Raw materials and ingredients for ice cream preparation

The raw materials and ingredients for the preparation of the ice creams were: water; skimmed milk powder, composed of 50 % carbohydrate, 34.5 % protein, and 0 % fat (Itambé®, Belo Horizonte, Brazil); 35 % fat cream (Itambé®, Belo Horizonte, Brazil); sucrose (Delta®, Delta, Brazil); inverted sugar (Ingredientes Online, São Paulo, Brazil); dextrose (Ingredientes Online, São Paulo, Brazil); stabilizer (Super Liga Neutra - Selecta®, Jaraguá do Sul, Brazil); emulsifier (Emustab, Selecta®, Jaraguá do Sul); freeze-dried cactus pear pulp; cocoa powder (Sicao®, Extrema, Brazil).

Ice Cream Formulation and Preparation

The ice cream mixtures were prepared using a balanced syrup, resulting in a final fat content of 3.0 % (low-fat) relative to the total syrup volume, as detailed in Table 1. The concentration of freeze-dried cactus pear pulp varied from 0.0 % (control) to 2.0 %.

Table 1

Ice cream preparation process

The production of the ice cream began with the dissolution of the ingredients (Table 1) in water at 40 °C, with the exception of the cocoa powder. The mixture was blended and homogenized using an industrial blender (Model LQI-06, Vitalex, Catanduva, Brazil). It was then pasteurized at 70 °C for 30 minutes, followed by cooling and maturation. After maturation, the cocoa powder was added and incorporated into the mixture using the same industrial blender. The flavored mixture was then churned and frozen in a batch freezer (V-5, FortFrio, Betim, Brazil). Finally, the ice cream was hardened in a freezer at -18°C.

Physical properties of ice cream

The air incorporation rate, or overrun (%), was determined using the following equation:

$$\text{Overrun} = \left(\frac{(mass\ of\ mix - mass\ of\ ice\ cream)}{mass\ of\ ice\ cream}\right) \cdot 100 \quad /1/$$

The meltdown rate and the first dripping time of the ice cream samples were measured using methods adapted from previous studies (*11,26*). For the melting rate determination, samples (30 g) were stored at -12 °C (service temperature) for 24 hours. Each sample was then placed in an incubation chamber at 25±1 °C, on a sieve with a mesh size of 1.25 cm, positioned over a pre-weighed beaker. The melted material passing through the sieve was collected and weighed at 5-minute intervals for approximately 30 minutes using an electronic digital balance (±0.01 g) (S2202H, Bel, Piracicaba, Brazil) to ensure precise measurements. The results were analyzed by plotting the melted ice cream mass against time. Linear equations were generated to determine the melting rate (*27*). The moment the first drop was observed was recorded as the initial dripping time (*28*).

The color of the ice cream was evaluated using instrumental colorimetry based on the CIE Lab* system, with illuminant D65, a 10º viewing angle, and calibration in SCI mode (specular component included) on a spectrophotometer (CM-5, Konica Minolta, Chiyoda, Japan). Total color difference was determined according to the following equation:

$$\Delta E^* = \sqrt{\Delta a^2 + \Delta b^2 + \Delta L^2} \quad /2/$$

The experiment was conducted in triplicate for all samples.

Statistical analysis

The data were analyzed by Analysis of Variance followed by Tukey's test, at the 5 % significance level, using Sisvar 5.8 software (*29*).

RESULTS AND DISCUSSION

Characterization of freeze-dried cactus pears pulp

Table 2 summarizes the approximate composition of freeze-dried cactus pear pulp. The freeze-dried cactus pear pulp exhibited a final moisture content lower than the maximum limit of 15 % established by RDC Nº. 711, dated July 1, 2022 (*30*), for vegetable flours. This low moisture content ensures microbiological stability, making the freeze-dried cactus pear pulp suitable for conservation and storage.

Table 2

The water activity (a_w) of the freeze-dried cactus pear pulp was 0.37, and the pH was 4.35. With an aw below 0.6 and the observed pH value, the freeze-dried cactus pear pulp is well-protected against the growth of deteriorating microorganisms (*31*). The low pH can be attributed to the presence of organic acids, including malic, citric, and oxalic acids (*32*).

The moisture content and water activity (aw) of cactus pear mucilage vary among species, with differences influenced primarily by the variety and the harvesting season (dry vs. rainy). Higher moisture levels are associated with a shorter shelf life (*33,34*).

Proteins are essential for the formation of foams and emulsions, functioning as surfactants at air-water (surface property) or oil-water (hydrodynamic property) interfaces. They create a highly viscoelastic film capable of withstanding mechanical stress and gravity (*35*). The protein content in the freeze-dried cactus pear pulp was measured at 8.17 %. This finding is consistent with Gebremariam *et al*. (*34*), who reported a protein content of approximately 8 % in dry matter of cactus pears (*Opuntia ficus-indica*). In contrast, Du Toit *et al*. (*33*) observed protein levels in powdered mucilage ranging from 3.28 % to 3.64 %, with no significant variations over a 6-month harvesting period. Similarly, Du Toit, De Wit, and Hugo (*36*) reported protein values of 2.7 % to 3.2 % in *O. ficus-indica*.

The lipid content of the freeze-dried cactus pear pulp was 1.46 %. Yadav *et al*. (*37*) suggest that the lipid content in gums plays a significant role in reducing surface tension, thereby enhancing the stability of oil-in-water emulsions. A similar lipid content of 1.19 % was reported by Dick *et al*. (*38*) for powdered mucilage of *Opuntia monacantha*.

The ash content observed in this study was 16.85 %, which is higher than the 15.14 % reported by Dick *et al*. (*38*) for powdered mucilage from *Opuntia monacantha* cladodes. However, it is lower than the ash content reported in previous studies for *Opuntia ficus-indica* cladodes, with Malainine *et al*. (*39*) documenting values as high as 19.6 %.

The total phenolic content in the freeze-dried cactus pear pulp was 1242.16 mg GAE/100 g. Polyphenols are known to be the primary contributors to antioxidant activity. Numerous studies have focused on identifying natural antioxidants in cost-effective raw materials. For instance, apple pomace, with a phenolic content of 1016 mg GAE/100 g, is recognized as a significant source of natural polyphenols. Similarly, cactus pear cladodes can be considered a valuable and economical source of natural antioxidants (*40*).

The freeze-dried cactus pear pulp exhibits a significant mineral content, particularly in potassium (4.94 % DM), calcium (3.15 % DM), and magnesium (0.93 % DM). These findings are consistent with the mineral profile commonly reported for the genus *Opuntia ficus-indica*, where potassium and calcium are typically found in higher concentrations, followed by magnesium (*41*). The mineral composition of *Opuntia ficus-indica* is noteworthy, as the calcium present in the mucilage is bioavailable and can be absorbed in the human gastrointestinal tract. This suggests that *Opuntia* mucilage could have new and significant applications in the food industry (*42)*.

The freeze-dried cactus pear pulp contained a total dietary fiber (TDF) content of 43.34 %, comprising 26.07 % insoluble fiber (IF) and 17.26 % soluble fiber (SF). This composition is consistent with findings from *Opuntia ficus-indica* f. *amyloceae* (spiny cladodes), which reported a TDF content of 51.24 % and a SF/IF ratio of 1:3 (*40*). The higher IF content compared to SF in freeze-dried cactus pear pulp aligns with these findings, reinforcing the typical fiber distribution in *Opuntia* species.

The fatty acid profile of freeze-dried cactus pear pulp, presented in Table 3, revealed a predominant composition of polyunsaturated fatty acids (PUFA) at 54.01 %, with linoleic acid (18:2n-6) being the most abundant. Among the saturated fatty acids (SFA), palmitic acid had the highest concentration, with a content of 26.89 %. Oleic acid (9.36 %) was the only monounsaturated fatty acid (MUFA) found. This profile is consistent with that of chia mucilage, which also contains nutritionally beneficial fatty acids, further highlighting the potential of freeze-dried cactus pear pulp as a valuable nutritional ingredient (*13*).

Table 3

The physical characteristics of the freeze-dried *Opuntia ficus-indica* L. Miller pulp are summarized in Table 4.

The hydration properties of the freeze-dried *Opuntia ficus-indica* L. Miller pulp were characterized by a water solubility index (WSI) of 42.37 % and a water absorption capacity (WAC) of

5.60 g water/g DM, with an oil absorption capacity (OAC) of 2.93 g fat/g DM. This high fiber content is responsible for the considerable hydration properties observed. On the other hand, hydrophobic constituents, particularly the apolar radicals of proteinaceous amino acids, contribute to the oil absorption capacity. Additionally, dietary fibers can adsorb some oil on their surface, further influencing OAC values (*42*).

The freeze-dried cactus pear pulp exhibited a high luminosity value (L^*=79.86), a negative a^* value (-7.11) indicating a green hue, and a positive b^* value (27.09) suggesting a yellowish tint. This combination of values reflects a greenish-yellow color for the freeze-dried pulp, as detailed in Table 4. The observed color may be attributed to the presence of natural pigments such as chlorophylls and carotenoids, or tannic substances from the cactus pear's tegument (*43*).

Table 4

Physical properties of ice cream

Table 5 presents the average results for total solids, pH, overrun, and instrumental color parameters of the ice cream, along with the visual representation of the ice cream colors. The total solids content showed no significant difference ($p>0.05$) across the formulations, indicating that the incorporation of freeze-dried cactus pear pulp did not affect this parameter. The only variation among the formulations was in the concentration of mucilage, which ranged from 0.0 % to 2.0 % (Table 1).

Table 5

The pH values of the ice cream ranged from 5.94 (F3) - 6.42 (control sample), which is consistent with existing literature that reports pH values between 6 and 7 for ice creams incorporating mucilage (*11,12,44*). The results indicate that the freeze-dried cactus pear pulp significantly influenced the pH ($p<0.05$), with higher freeze-dried cactus pear pulp concentrations leading to lower pH values. This effect is similar to findings with quince seed powder in ice creams, where acidic compounds contributed to lower pH levels, despite the buffering effects of milk proteins (*45*).

The ice creams exhibited intermediate brightness values (L^*=39.91–43.68), positive a^* values (9.98–11.43), indicating a reddish hue, and positive b^* values (14.04–20.10), suggesting a yellowish tint. This resulted in a brownish color for the ice creams, as shown in Table 5. The observed color is consistent with the inclusion of cocoa in the formulation, which imparts a characteristic brown hue to the product.

There was a significant difference ($p<0.05$) in the color of the ice creams, with higher concentrations of freeze-dried cactus pear pulp leading to decreased L^* values and increased b^* values, indicating that the products became darker and more yellow. The freeze-dried cactus pear pulp itself had a yellowish-green color, as detailed in Table 4. While the a^* parameter of freeze-dried

cactus pear pulp did not notably affect the ice cream color—since the positive *a** values were primarily due to the cocoa addition—there was a discernible color change compared to the control. According to Adekunte *et al*. (*46*), perceptible color differences can be classified as very distinct (ΔE>3), distinct (1.5<ΔE<3), and small differences (ΔE<1.5). All samples showed a very distinct color compared to the control sample. It is observed that the higher the percentage of freeze-dried cactus pear pulp, the greater the color distinction, indicating that the cactus contributed to altering the color perception of the ice creams.

The incorporation of air into ice cream, known as overrun, is a critical physical characteristic that influences its texture, softness, and stability (*12*). In this study, increasing the levels of freeze-dried cactus pear pulp in the formulation led to a significant increase ($p<0.05$) in overrun, with values ranging from 19.83 % to 33.89 %.

Overrun values in ice creams with chia seed mucilage ranged from 25 % to 55 % (*13*), while those with quince seed powder ranged from 26.94 % to 30.03 % (*45*). Ice creams incorporating chia powder exhibited overrun values between 18.82 % and 40.21 % (*44*), and low-fat ice creams generally showed values from 11.64 % to 34.68 % (*26*).

The enhancement in overrun resulting from the addition of freeze-dried *O. ficus-indica* pulp presents a potential advantage for the dairy industry. Elevated overrun percentages contribute to improved texture and stability in ice creams by reducing ice crystal formation and enhancing product consistency throughout storage (*47*).

This effect is partly due to the cryostabilizing properties of certain polysaccharides present in cactus pear pulp (*48*).

Effective resistance to melting and shape retention are essential quality attributes for ice cream. Rapid melting can lead to structural loss before consumption, negatively impacting consumer satisfaction. Conversely, an excessively slow melting rate may signal potential defects, suggesting issues with the ice cream's formulation or processing (*14*).

Specifically, ice creams with higher concentrations of freeze-dried palm pulp exhibited melting times of 14.68 minutes and 13.04 minutes for formulations F3 and F2, respectively, demonstrating greater resistance to the onset of melting (Table 5). In contrast, there was no significant difference ($p<0.05$) in the melting rate.

Fig. 1 illustrates the melting characteristics of the different ice cream formulations, showing the ice cream's behavior regarding dripping time and melting rate. It was observed that the time to the first drip increased with higher concentrations of freeze-dried forage palm pulp, demonstrating that the addition of palm pulp delayed the onset of melting. However, once melting began, the melting rate remained unchanged.

Fig. 1

Similar results have been observed in ice creams containing basil seed gum, guar gum, and their mixtures, where these ingredients also contributed to improved melting resistance in low-fat ice creams (*23*).

A reduction in melting times were observed with the addition of quince seed powder, which has high polysaccharide and protein contents (*48*). Similarly, chia seed mucilage powder reduced the melting rate in ice creams compared to samples without stabilizers, aligning with results from studies using chia seed mucilage as a stabilizer (*11*). Previous research indicates that high concentrations of chia seed mucilage lead to increased melting resistance, attributed to the high viscosity of the ice cream mixture (*10*).

CONCLUSIONS

The freeze-dried cactus pear pulp demonstrates a high content of dietary fibers and phenolic compounds, along with notable technological potential due to its water absorption capacity (WAC), water solubility index (WSI), and oil absorption capacity (OAC).

Ice creams incorporating higher concentrations of freeze-dried cactus pear pulp demonstrates a high content of dietary fibers and phenolic compounds, along with notable technological potential.

Ice creams incorporating higher concentrations of CPP exhibited greater resistance to melting, characterized by extended melting onset times. These findings suggest that the freeze-dried cactus pear pulp holds promise as a fat substitute and stabilizer for low-fat ice creams, with the most effective results achieved at a concentration of 2.0 % freeze-dried cactus pear pulp. Future research should focus on the extraction and application of pure mucilage in ice cream formulations, as well as rheological studies and sensory evaluations, to further optimize and enhance the results obtained.CPP exhibited greater resistance to melting, characterized by lower melting rates and extended melting onset times. These findings suggest that the freeze-dried cactus pear pulp holds promise as a fat substitute and stabilizer for low-fat ice creams, with the most effective results achieved at a concentration of 2.0 % freeze-dried cactus pear pulp. Future research should focus on the extraction and application of pure mucilage in ice cream formulations, as well as rheological studies and sensory evaluations, to further optimize and enhance the results obtained.

ACKNOWLEDGEMENTS

The authors would like to thank the Federal University of Jequitinhonha and Mucury Valleys (UFVJM) and the Institute of Science and Technology (ICT) for the institutional support and the technical support from the MULTIFAR/PRPPG Center and the elemental analysis laboratory. They

are also grateful to the Institutional Program of Scientific Initiation Scholarships - PIBIC/CNPq for providing a research scholarship.

FUNDING

This study was supported by National Council for Scientific and Technological Development (CNPq) (#421777/2021-4 - Exploration of cactus pear for flour production and application in different food matrices).

CONFLICT OF INTEREST

None of the authors have any conflict of interest.

SUPPLEMENTARY MATERIAL

Supplementary material is available at www.ftb.com.hr.

AUTHORS' CONTRIBUTION

E. F. F. Souza and A. K. C. Mafra contributed to the research by conducting formal analyses, curating data, interpreting data and reviewing the literature. R. G. Vendruscolo contributed to the research by conducting lipid and fatty acid analyses, curating data and interpreting data. M. Schmiele made important contributions to the research, including the conceptualisation, review and editing, visualization, project administration, funding acquisition. L. O. F. Rocha contributed to the conceptualization, designing the methods of analysis, data curation, supervising and project administration, actively participating in the writing and editing of the manuscript.

ORCID ID

E. F. F. Souza https://orcid.org/0009-0001-3114-2656
A. K. C. Mafra https://orcid.org/0009-0004-2601-0239
R. G. Vendruscolo https://orcid.org/0000-0002-3867-7602
M. Schmiele https://orcid.org/0000-0001-8830-1710
L. O. Ferreira-Rocha https://orcid.org/0000-0001-6321-3546

REFERENCES

1. Vázquez-Ramírez R. Reversing gastric mucosal alterations during ethanol-induced chronic gastritis in rats by oral administration of Opuntia ficus-indica mucilage. World J Gastroenterol. 2006;12(27):4318.

https://doi.org/10.3748/wjg.v12.i27.4318

2. Tosif MM, Najda A, Bains A, Kaushik R, Dhull SB, Chawla P, *et al*. A Comprehensive Review on Plant-Derived Mucilage: Characterization, Functional Properties, Applications, and Its Utilization for Nanocarrier Fabrication. Polymers (Basel). 2021;13(7):1066.
https://doi.org/10.3390/polym13071066

3. Gürbüz Z, Erkaya-Kotan T, Şengül M. Evaluation of physicochemical, microbiological, texture and microstructure characteristics of set-style yoghurt supplemented with quince seed mucilage powder as a novel natural stabiliser. Int Dairy J. 2021;114:104938.
https://doi.org/10.1016/j.idairyj.2020.104938

4. Basiri S, Haidary N, Shekarforoush SS, Niakousari M. Flaxseed mucilage: A natural stabilizer in stirred yogurt. Carbohydr Polym. 2018;187:59-65.
https://doi.org/10.1016/j.carbpol.2018.01.049

5. Akl EM, Abdelhamid SM, Wagdy SM, Salama HH. Manufacture of Functional Fat-free Cream Cheese Fortified with Probiotic Bacteria and Flaxseed Mucilage as a Fat Replacing Agent. Curr Nutr Food Sci. 2020;16(9):1393-403.
https://doi.org/10.2174/1573401316666200227112157

6. Mehrinejad Choobari SZ, Sari AA, Daraei Garmakhany A. Effect of Plantago ovata Forsk seed mucilage on survivability of Lactobacillus acidophilus, physicochemical and sensory attributes of produced low-fat set yoghurt. Food Sci Nutr. 2021;9(2):1040-9.
https://doi.org/10.1002/fsn3.2074

7. Ribes S, Peña N, Fuentes A, Talens P, Barat JM. Chia (*Salvia hispanica* L.) seed mucilage as a fat replacer in yogurts: Effect on their nutritional, technological, and sensory properties. J Dairy Sci. 2021;104(3):2822-33.
https://doi.org/10.3168/jds.2020-19240

8. Arabshahi SS, Sedaghati M. Production of synbiotic Doogh enriched with Plantago psyllium mucilage. J Food Sci Technol. 2022; 59(10):3819-26.
https://doi.org/10.1007/s13197-022-05401-8

9. Ould Saadi L, Zaidi F, Sanz T, Haros CM. Effect of faba bean and chickpea mucilage incorporation in the structure and functionality of kefir. Food Sci. Technol. Int. 2020;26(6):503-11.
https://doi.org/10.1177/1082013220908089

10. BahramParvar M, Goff HD. Basil seed gum as a novel stabilizer for structure formation and reduction of ice recrystallization in ice cream. Dairy Sci Technol. 2013;93(3):273-85.
https://doi.org/10.1007/s13594-013-0122-9

11. Feizi R, Goh KKT, Mutukumira AN. Effect of chia seed mucilage as stabiliser in ice cream. Int Dairy J. 2021;20:105087.
https://doi.org/10.1016/j.idairyj.2021.105087
12. Lozano E, Padilla K, Salcedo J, Arrieta A, Andrade-Pizarro R. Effects of Yam (*Dioscorea rotundata*) Mucilage on the Physical, Rheological and Stability Characteristics of Ice Cream. Polymers (Basel). 2022;14(15):3142.
https://doi.org/10.3390/polym14153142
13. Maestrello C, Figueiredo IL, Takahashi GCS, Pimentel TC, Visentainer JV, Bergamasco RC, *et al*. Replacing Emulsifier in a Prebiotic Ice Cream: Physical and Chemical Evaluation and Acceptance. J Culin Sci Technol. 2018;16(1):76–87.
https://doi.org/10.1080/15428052.2017.1333934
14. Bahramparvar M, Mazaheri Tehrani M. Application and Functions of Stabilizers in Ice Cream. Food Rev. Int. 2011;27(4):389–407.
https://doi.org/10.1080/87559129.2011.563399
15. AOAC Official Method 925.10. Solids (Total) and Moisture in Flour, MD, USA: AOAC International; 2005.
16. AOAC Official Method 923.03. Ash of Flour (Direct Method), MD, USA: AOAC International; 2005.
17. AOAC Official Method 991.43. Total, soluble, and insoluble dietary fiber in foods, MD, USA: AOAC International; 1999.
18. Bligh EG, Dyer WJ. A rapid method of total lipid extraction and purification. Can J Biochem Physiol. 1959;37(8):911–7.
https://doi.org/10.1139/o59-099
19. Adolfo Lutz Institute. Physicochemical Methods for Food Analysis. São Paulo, Brazil: Adolfo Lutz Institute; 2008 (in Portuguese). Available from:
http://www.ial.sp.gov.br/resources/editorinplace/ial/2016_3_19/analisedealimentosial_2008.pdf
20. Hartman L, Lago RC. Rapid preparation of fatty acid methyl esters from lipids. Lab Pract. 1973;22(6):475-476.
21. Andressa I, Paiva MJA, Pacheco FC, Santos FR, Cunha JS, Pacheco AFC, *et al*. Germination as a strategy to improve the characteristics of flour and water-soluble extracts obtained from sunflower seed. Food Biosci. 2024;61:104763. https://doi.org/10.1016/j.fbio.2024.104763
22. Visentainer JV. Analytical aspects of the flame ionization detector response of fatty acid esters in biodiesels and foods. Quim Nova. 2012; 35:274-279 (in Portuguese).
https://doi.org/10.1590/S0100-40422012000200008

23. Schmiele M, Jaekel LZ, Ishida PMG, Chang YK, Steel CJ. Gluten-free pasta with high protein content obtained by conventional processing. Cienc Rural. 2013; 43(5): 908-914 (in Portuguese). https://doi.org/10.1590/S0103-84782013000500026

24. Benítez V, Cantera S, Aguilera Y, Mollá E, Esteban RM, Díaz MF, *et al*. Impact of germination on starch, dietary fiber and physicochemical properties in non-conventional legumes. Food Res. Int. 2013;50(1):64-9.
https://doi.org/10.1016/j.foodres.2012.09.044

25. Nascimento GKS, Silva MS, Andressa I, Fagundes MB, Vendruscolo RG, Oliveira JR, *et al*. A new advancement in germination biotechnology of purple creole corn: Bioactive compounds and in situ Enzyme activity for water-soluble extract and pan bread. Metabolites. 2024;14(1):35. https://doi.org/10.3390/metabo14010035

26. Javidi F, Razavi SMA, Behrouzian F, Alghooneh A. The influence of basil seed gum, guar gum and their blend on the rheological, physical and sensory properties of low fat ice cream. Food Hydrocoll. 2016;52:625-633.
https://doi.org/10.1016/j.foodhyd.2015.08.006

27. Soukoulis C, Chandrinos I, Tzia C. Study of the functionality of selected hydrocolloids and their blends with κ-carrageenan on storage quality of vanilla ice cream. LWT - Food Sci Technol. 2008;41(10):1816–27.
https://doi.org/10.1016/j.lwt.2007.12.009

28. Kavaz A, Yüksel M, Dağdemir E. Determination of certain quality characteristics, thermal and sensory properties of ice creams produced with dried Besni grape (*Vitis vinifera* L.). Int J Dairy Technol. 2016;69(3):418-424.
https://doi.org/10.1111/1471-0307.12277

29. Ferreira D F. SISVAR: a computer statistical analysis system. Ciênc. Agrotec. 2011; 35(6):1039-1042.

30. Brazil. Ministry of Health. Collegiate Board Resolution - RDC N° 711 of 01/07/2022. Establishes the sanitary requirements for starches, cookies, whole grains, processed cereals, bran, flours, whole flours, food pastes, and breads. National Health Surveillance Agency – Anvisa. 2022 (in Portuguese).

31. Franco BDGM, Landgraf M. Food Microbiology. São Paulo, Brazil: Atheneu; 2008. (in Portuguese).

32. Stintzing FC, Carle R. Cactus stems (*Opuntia* spp.): A review on their chemistry, technology, and uses. Mol Nutr Food Res. 2005;49(2):175-194.
https://doi.org/10.1002/mnfr.200400071

33. Du Toit A, De Wit M, Fouché HJ, Taljaard M, Venter SL, Hugo A. Mucilage powder from cactus pears as functional ingredient: influence of cultivar and harvest month on the physicochemical and technological properties. J Food Sci Technol. 2019;56(5):2404-2416. https://doi.org/10.1007/s13197-019-03706-9

34. Gebremariam T, Melaku S, Yami A. Effect of different levels of cactus (*Opuntia ficus-indica*) inclusion on feed intake, digestibility and body weight gain in tef (*Eragrostis tef*) straw-based feeding of sheep. Anim Feed Sci Technol. 2006;131(1–2):43-52. https://doi.org/10.1016/j.anifeedsci.2006.02.003

35. Fennema OR, Damodaran S, Parkin KL. Fennema's food chemistry. Boca Raton, FL, USA: CRC Press; 2017.

36. Du Toit A, de Wit M, Hugo A. Cultivar and harvest month influence the nutrient content of *Opuntia* spp. cactus pear cladode mucilage extracts. Molecules. 2018;16;23(4):916. https://doi.org/10.3390/molecules23040916

37. Yadav MP, Fishman ML, Chau HK, Johnston DB, Hicks KB. Molecular characteristics of corn fiber gum and their influence on CFG emulsifying properties. Cereal Chem. 2007;84(2):175-180. https://doi.org/10.1094/CCHEM-84-2-0175

38. Dick M, Dal Magro L, Rodrigues RC, Rios AO, Flôres SH. Valorization of *Opuntia monacantha* (Willd.) Haw. cladodes to obtain a mucilage with hydrocolloid features: Physicochemical and functional performance. Int J Biol Macromol. 2019;15(123):900-9. https://doi.org/10.1016/j.ijbiomac.2018.11.126

39. Malainine ME, Dufresne A, Dupeyre D, Mahrouz M, Vuong R, Vignon MR. Structure and morphology of cladodes and spines of *Opuntia ficus-indica*. Cellulose extraction and characterisation. Carbohydr Polym. 2003;51(1):77-83. https://doi.org/10.1016/S0144-8617(02)00157-1

40. Ayadi MA, Abdelmaksoud W, Ennouri M, Attia H. Cladodes from *Opuntia ficus indica* as a source of dietary fiber: Effect on dough characteristics and cake making. Ind Crops Prod. 2009;30(1):40-7. https://doi.org/10.1016/j.indcrop.2009.01.003

41. Méndez LP, Flores FT, Martín JD, Rodríguez Rodríguez EM, Díaz Romero C. Physicochemical characterization of cactus pads from *Opuntia dillenii* and *Opuntia ficus indica*. Food Chem. 2015;188:393-8. https://doi.org/10.1016/j.foodchem.2015.05.011

42. Contreras-Padilla M, Rodríguez-García ME, Gutiérrez-Cortez E, Valderrama-Bravo M del C, Rojas-Molina JI, Rivera-Muñoz EM. Physicochemical and rheological characterization of *Opuntia ficus* mucilage at three different maturity stages of cladode. Eur Polym J. 2016; 78:226-34.

https://doi.org/10.1016/j.eurpolymj.2016.03.024

43. Koocheki A, Taherian AR, Razavi SMA, Bostan A. Response surface methodology for optimization of extraction yield, viscosity, hue and emulsion stability of mucilage extracted from *Lepidium perfoliatum* seeds. Food Hydrocoll. 2009; 23(8):2369-79.
https://doi.org/10.1016/j.foodhyd.2009.06.014

44. Arnak BG, Tarakçi Z. Use of chia (*Salvia hispanica* L.) mucilage powder as a replacer of salep in ice cream production. J Food Process Preserv. 2021;45:e16060.
https://doi.org/10.1111/jfpp.16060

45. Kurt A, Atalar I. Effects of quince seed on the rheological, structural and sensory characteristics of ice cream. Food Hydrocoll. 2018; 82:186-95.
https://doi.org/10.1016/j.foodhyd.2018.04.011

46. Adekunte AO, Tiwari BK, Cullen PJ, Scannell AGM, O'Donnell CP. Effect of sonication on colour, ascorbic acid and yeast inactivation in tomato juice. Food Chem. 2010;122(3):500-7.
https://doi.org/10.1016/j.foodchem.2010.01.026

47. Liu X, Sala G, Scholten E. Role of polysaccharide structure in the rheological, physical and sensory properties of low-fat ice cream. Curr Res Food Sci. 2023;100531.
https://doi.org/10.1016/j.crfs.2023.100531

48. Dertli E, Toker OS, Durak MZ, Yilmaz MT, Tatlısu NB, Sagdic O, *et al*. Development of a fermented ice-cream as influenced by in situ exopolysaccharide production: Rheological, molecular, microstructural and sensory characterization. Carbohydr Polym. 2016;136:427.
https://doi.org/10.1016/j.carbpol.2015.08.047

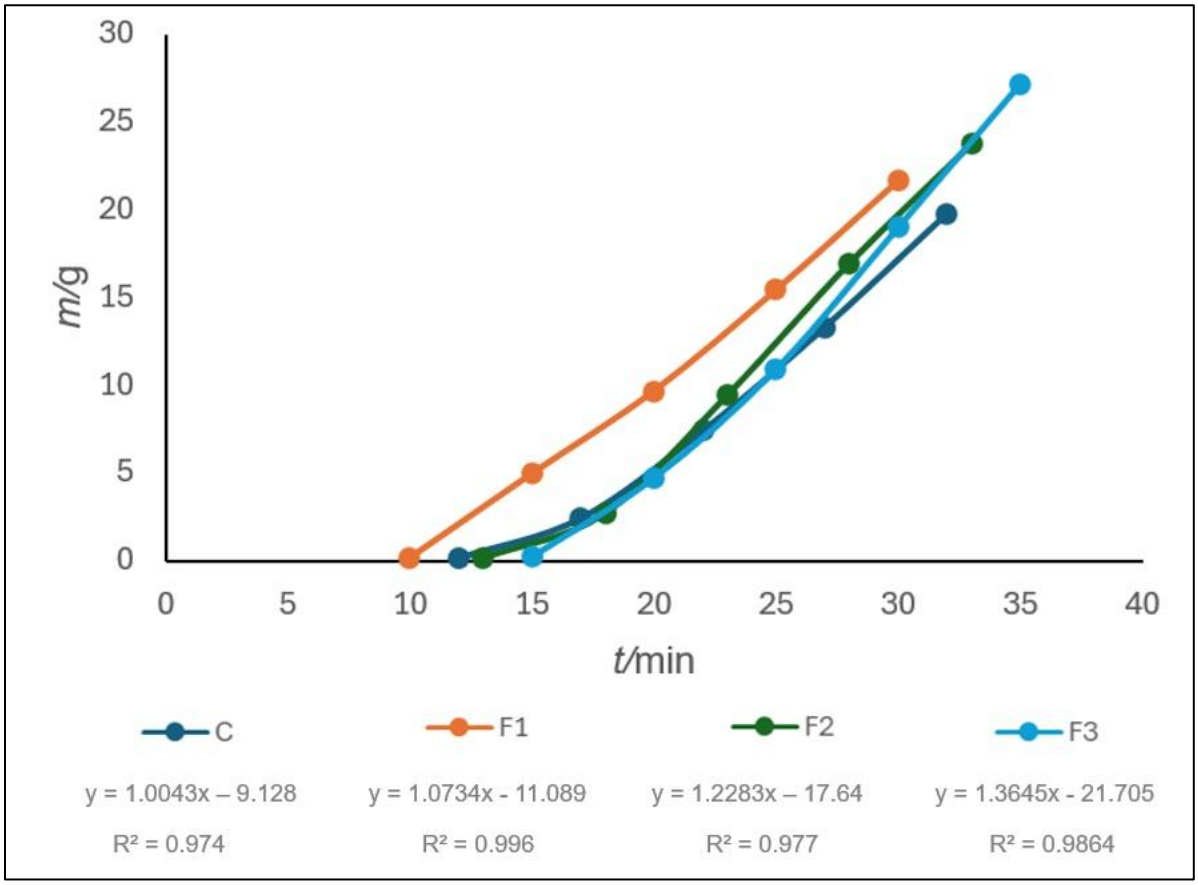

Fig. 1. Mass loss of ice cream samples during melting: C – control ice cream, without freeze-dried cactus pear pulp addition; F1 – ice cream with 1 % freeze-dried cactus pear pulp addition; F2 – ice cream with 1.5 % CPP freeze-dried cactus pear pulp addition; F3 – ice cream with 2.0 % freeze-dried cactus pear pulp addition

Table 1. Composition of chocolate ice cream formulations: C (without freeze-dried cactus pear pulp), F1 (with 1.0 % freeze-dried cactus pear pulp), F2 (with 1.5 % freeze-dried cactus pear pulp), and F3 (with 2.0 % freeze-dried cactus pear pulp).

Ingredient *w*/%	C	F1	F2	F3
Water	53.28	53.28	53.28	53.28
Skimmed milk powder	13.96	13.96	13.96	13.96
Cream (35 % fat)	7.07	7.07	7.07	7.07
Sucrose	6.43	6.43	6.43	6.43
Inverted sugar	7.35	7.35	7.35	7.35
Dextrose	5.05	5.05	5.05	5.05
Stabilizer	0.94	0.94	0.94	0.94
Emulsifier	0.94	0.94	0.94	0.94
Cocoa powder	2.98	2.98	2.98	2.98

Table 2. Composition of freeze-dried cactus pear pulp.

Parameters *w*/%	Freeze-dried cactus pear pulp
Protein	8.17±0.00
Lipid	1.46±0.05
Ash	16.85±0.05
IDF	26.07±3.07
SDF	17.26±1.06
TDF	43.34±2.04
Carbohydrate	73.52
K	4.94±1.86
Ca	3.15±1.72
Mg	0.93±0.11
P	0.15±0.02
Moisture	8.47±0.29
Total solids	91.53±0.29
w (TSPC as GAE)/(mg/100 g)	1242.16±49.44
a_w	0.37±0.00
pH	4.35±0.08

Results are expressed as mean value±standard error. CPP: freeze-dried cactus pear pulp; IDF: insoluble dietary fiber; SDF: soluble dietary fiber; TDF: total dietary fiber; TSPC: total soluble phenolic compounds; GAE: gallic acid equivalent.

Table 3. Fatty acid profile of freeze-dried cactus pear pulp

Fatty Acids	IUPAC nomenclature	Common nomenclature	*w*/%
Saturated fatty acids (SFA)			
C6:0	Hexanoic acid	Caproic acid	0.23±0.00
C8:0	Octanoic acid	Caprylic acid	0.30±0.01
C12:0	Dodecanoic acid	Lauric acid	0.34±0.01
C13:0	Tridecanoic acid	Tridecylic acid	0.50±0.01
C14:0	Tetradecanoic acid	Myristic acid	0.69±0.03
C16:0	Hexadecanoic acid	Palmitic acid	26.89±0.49
C17:0	Heptadecanoic acid	Margaric acid	1.29±0.03
C18:0	Octadecanoic acid	Stearic acid	2.54±0.01
C24:0	Tetracosanoic acid	Lignoceric acid	3.86±0.13
∑SFA			36.63
Monounsaturated fatty acids (MUFA)			
C18:1n9c	9-Octadecenoic acid (cis)	Oleic acid	9.36±0.24
∑MUFA			9.36
Polyunsaturated fatty acids (PUFA)			

C18:2n6c	cis-9, cis-12-Octadecadienoic acid	Linoleic acid	41.59±0.65
C18:3n3	cis-9, cis-12, cis-15-Octadecatrienoic acid	Linolenic acid	12.43±0.16
∑PUFA			54.01
n6/n3			3.35

Results are expressed as mean value±standard error. SFA: saturated fatty acids; MUFA: monounsaturated fatty acids; PUFA: polyunsaturated fatty acids; n6/n3: ratio between omega-6 and omega-3 fatty acids

Table 4. Physical characteristics of freeze-dried cactus pears pulp

Parameters	Results
WAC/(g/g DM)	5.60±0.13
WSI/%	42.37±8.26
OAC/(g/g DM)	2.93±0.02
*L**	79.86±0.11
*a**	-7.11±0.05
*b**	27.09±0.30

Results are expressed as mean value±standard error. WAC: water absorption capacity; WSI: water solubility index; OAC: oil absorption capacity; DM: dry matter.

Table 5. Evaluated parameters of physical properties of ice cream samples: C (without freeze-dried cactus pear pulp), F1 (with 1.0 % freeze-dried cactus pear pulp), F2 (with 1.5 % freeze-dried cactus pear pulp), and F3 (with 2.0 % freeze-dried cactus pear pulp)

Parameters	C	F1	F2	F3
w (total solids/(g/100g)	(42.00±0.75)^{ns}	(41.61±0.05)^{ns}	(40.88±0.11)^{ns}	(41.16±0.63)^{ns}
pH	(6.42±0.05)^{a}	(6.16±0.01)^{b}	(6.01±0.01)^{c}	(5.94±0.00)^{d}
Overrun	(19.83±0.00)^{d}	(20.23±0.00)^{c}	(26.79±0.00)^{b}	(33.59 ±0.00)^{a}
*L**	(43.68±0.62)^{a}	(39.91±0.97)^{b}	(41.02±0.77)^{ab}	(41.21±1.50)^{ab}
*a**	(11.03±0.32)^{ab}	(9.98±0.49)^{c}	(10.54±0.09)^{bc}	(11.43±0.11)^{a}
*b**	(14.04 ±0.18)^{d}	(15.09±0.28)^{c}	(18.06±0.11)^{b}	(20.10±0.31)^{a}
Δ*E**	0.00	4.09	4.94	6.60
Melting rate/(g/min)	(0.70±0.13)^{ns}	(0.70±0.07)^{ns}	(0.64±0.18)^{ns}	(0.64±0.04)^{ns}
t(first dripping)/min	(11.50b±1.22)^{c}	(10.18±0.78)^{c}	(13.04±0.48)^{ab}	(14.68±0.34)^{a}

Results are expressed as mean value±standard error. Δ*E*: total color difference. Different letters on the same line indicate significant differences between samples at the 5 % significance level, according to the Tukey test.

SUPPLEMENTARY MATERIAL

Fig. S1. Process for obtaining freeze-dried cactus pear pulp