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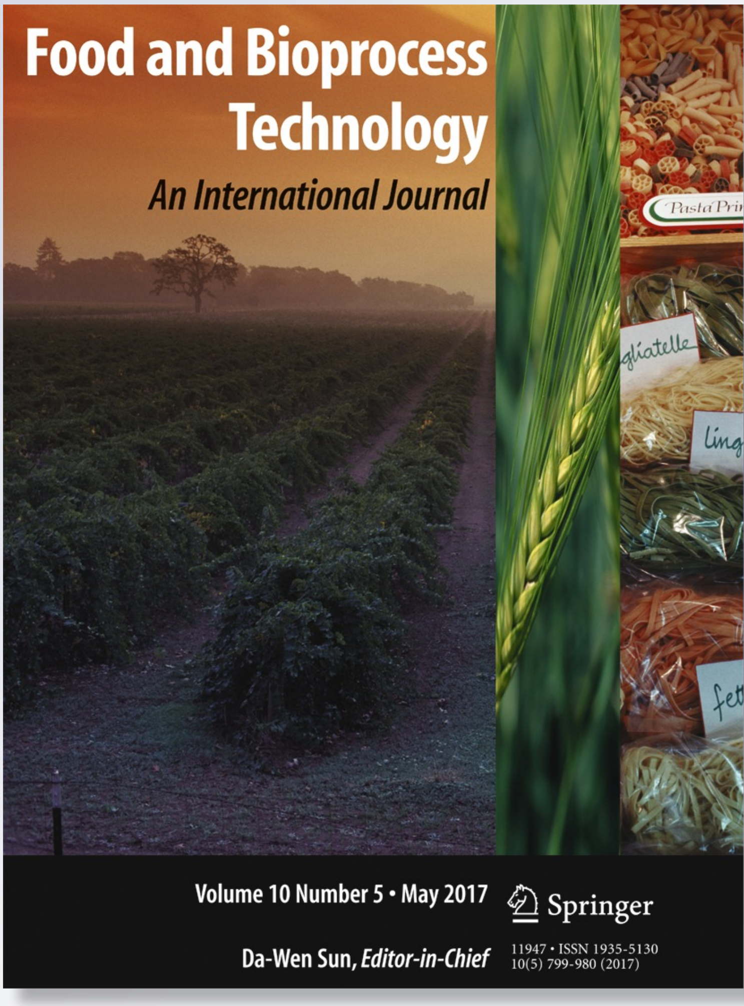

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ORIGINAL PAPER

Utilization of Plant Dietary Fibers to Reinforce Low-Calorie Dairy Dessert Structure

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Abstract Effect of plant fibers, carrageenan, and starch concentration on mechanical properties and syneresis measurements of low-calorie dairy desserts was studied simultaneously using the response surface methodology. Apple, bamboo, inulin, wheat, and psyllium fibers were tested individually, through five distinct experimental designs. Results were compared to a regular dairy dessert, formulated with sugar and whole milk, and a low-calorie formulation with no added fiber. Diet dessert with no added fiber presented higher syneresis and impaired mechanical properties as compared to regular formulation. Results showed that carrageenan, starch, and fibers played distinct roles in compensating the reduction observed on the syneresis test and mechanical properties of low-calorie desserts. While carrageenan and starch showed higher influence on reducing gel syneresis, fiber addition decreased the negative effect on mechanical properties resulting from the fat/sugar removal of the diet formulation.

Keywords Dairy dessert · Plant fibers · Syneresis · Texture

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Introduction

Semisolid dairy desserts are usually formulated with milk, sucrose, aroma, and thickeners such as starch or other hydrocolloids. Gel structure of dairy desserts containing starch and carrageenan is determined by the latter, while the other components act as fillers of the carrageenan network (Dello Staffolo et al. 2007).

Nowadays, the growing concern about health and obesity problems may be closely related to the increasing demand of low-calorie and reduced salt food products. In the dairy industry, low-calorie products are usually obtained by using skimmed milk and by the substitution of sugar by sweeteners. However, the quality of these products depends on their texture, which is substantially affected by the reduction of fat and/or sugar content, once their remaining solids are rather low (Pinheiro et al. 2005; Ribeiro et al. 2004).

In this sense, the addition of dietary fibers in low-calorie formulations may present both physiological and technological functionalities (Mudgil and Barak 2013; Redgwell and Fischer 2005). In the first case, it is known that dietary fibers achieve at least one of the following functions: increase the fecal bulk, stimulate colonic fermentation, and reduce post-prandial blood glucose (reduce insulin responses) and/or decrease pre-prandial cholesterol levels (Dhingra et al. 2012; Guillon et al. 2011; Mackie et al. 2015). Moreover, fiber consumption may decrease and/or prevent certain pathologies such as coronary disease, hypertension, diabetes, hypercholesterolemia, and gastrointestinal disorders (Chater et al. 2015; Dello Staffolo et al. 2012; Tungland and Meyer 2002; Wu et al. 2015). In addition, these compounds may prevent chronic diseases and reduce the risk of developing cancer because of their antioxidant capacity attributed to polyphenols which are commonly found in several plant fibers (Macagnan et al. 2016; Quirós-Sauceda et al. 2014). Considering the technological aspect, the addition of dietary fiber can impart some functional properties to foods. Increase in water holding capacity and oil holding capacity, stabilization of high fat food and emulsions, and the gel forming ability are some properties of fibers that allow the development of fiber-enriched products with improved texture and reduced syneresis (Elleuch et al. 2011; Gelroth and Ranhotra 2001).

Thus, the objective of the present study was to assess the effect of plant dietary fiber addition on the reinforcement of dairy dessert structure, by evaluating the syneresis and mechanical properties of products with reduced fat and sugar content.

Materials and Methods

Materials

Dairy desserts were formulated with milk powder (Nestlé, São Paulo, SP, Brazil) reconstituted with distilled water, corn starch (Molinos Río de La Plata, Buenos Aires, BA, Argentina), sucralose (Saporiti, Buenos Aires, BA, Argentina), and a commercial mixture of κ, ι, and λ carrageenan CC765 (Inmobal Nutrer, Avellaneda, BA, Argentina). Fibers from apple (Vitacel AF400-30, JRS, Rosenberg, BY, Germany), bamboo (Qualicel 40B, CFF, Gehren, TH, Germany), chicory root (inulin, Frutafit, Sensus, Roosendaal, NB, The Netherlands), *Plantago ovata* seed husk (psyllium, Metamucil, Procter & Gamble Co., Cincinnati, OH, USA), and wheat (Vitacel WF 101, JRS, Germany) were added to different formulations in order to evaluate the effect of these fibers on the mechanical and syneresis properties of the desserts. Apple fiber includes 5% of pectin, 4.6% of protein, 2.5% of fat, 3.5% of sucrose, 3.2% of glucose, 7.7% of fructose, and 1.2% of sorbitol. The inulin used in this work is ≥85.5% *w*/*w* of inulin, ≤9.5% of mono- and disaccharides, and ≤0.1% of ash and has a degree of polymerization ≥9, as declared by suppliers. The psyllium used in the present work is a pharmaceutical formula (Metamucil) containing *P. ovata* seed husk (49.15% *w*/*w*) and sucrose (50.85%). Suppliers of wheat and apple fibers indicated that these products are free from phytic acid and that the wheat fiber is gluten free. Other technological characteristics of apple, bamboo, inulin, psyllium, and wheat fibers are shown in Table 1, as provided by suppliers, and fiber characterization can be observed in Table 2.

Methods

Morphology and Particle Size Distribution for Dietary Fibers

The particle morphology of different dietary fiber powders were observed by environmental scanning electron microscopy (ESEM) with the equipment Electroscan 2010 (FEI Company, Hillsboro, OR, USA) employing an environmental secondary electron detector (ESD). The particle size distribution of fiber powders was determined by laser diffraction/scattering with the equipment Horiba LA-950 (Kyoto, Kyoto Prefecture, Japan) composed by a double optical system (650 nm laser diode-405 nm light emitting diode) and silicon photodiode detectors. The particle size measurements were conducted in triplicate for each dietary fiber.

Water Holding Capacity for Dietary Fibers

Currently, it can be found in the literature several definitions and measurement methodologies for water holding capacity (WHC) for the fibers. One of them establishes that WHC is the quantity of water that is bound to the fibers without the application of any external force, except for gravity and atmospheric pressure. It is calculated as the ratio of quantity of water held up to the initial dry weight of the residue (Raghavendra et al. 2006). Therefore, WHC of apple, bamboo, inulin, psyllium, and wheat fibers was determined in triplicate employing the method of Gould et al. (1989) and Sangnark and Noomhorm (2003) with slight modifications. A dried sample (3 g) was mixed with an excess of deionized and distilled water and allowed to hydrate for 2 h. The excess water was then removed by allowing the wet sample to drain during 30 min on a fine-meshed screen (filter paper Whatman no. 40) at room conditions (25 ± 1 °C, relatively humidity = 64 ± 2% and atmospheric pressure = 1010 ± 1 hPa). A portion of the wet sample on the screen was carefully removed, weighed, and dried to constant weight (± 0.5 mg) in a forced air oven (105 °C). WHC was calculated according to Eq. (1), and results were expressed as grams of water per gram of dry fiber.

$$\mathrm{WHC} = \frac{(\text{wet weight}-\text{dry weight})}{\text{dry weight}} \quad (1)$$

Sample Preparation

Firstly, skim milk powder was hydrated with distilled water in the proportion indicated by the supplier (10% *w*/*v*) and mixed for 30 min at room temperature using a magnetic stirrer. Samples were prepared by mixing starch and carrageenan and each fiber in the concentrations determined by the experimental design (“Experimental design” section 2.1.6) with 0.026% *w*/*v* sucralose, prior to addition of 100 mL of milk. After the milk addition, samples were mixed with a magnetic stirrer for 30 min. Then, samples were heated in a jacketed vessel connected to a thermostatic bath at 90 °C, for 20 min with continuous mechanical agitation at 100 rpm. Subsequently, all samples were placed into plastic cups (3 cm in diameter and 4.8 cm in height) covered with parafilm to avoid dehydration and

Table 1 Specifications of inulin, apple, wheat, bamboo, and psyllium fibers as provided by the suppliers and water holding capacity results (g $H_2$0/g d.m.) for different fibers

Type of fiber	Apple	Bamboo	Inulin	Psyllium	Wheat
Appearance	Micropowder	Powder	Powder	Powder	Powder
Color	Brownish	White	White	Beige	White
Odor	Apple	Without	Without	Without	Without
Taste	Fruit	Neutral	Neutral lightly sweet	Neutral	Neutral
pH (aqueous suspension 10% *w*/*v*)	3.7–4.1	4.0–6.0	Neutral	–	4.0–6.0
Heavy metals	Pb = 0.28 ppm				
	Cd <0.01 ppm				
	Hg <0.02 ppm	Pb <10 ppm	Free	–	Pb <10 ppm
Water holding capacity	6.73c ± 0.21	3.19a ± 0.09	NE	42.51d ± 0.50	3.61b ± 0.01

Different lowercase letters denote significant differences between samples (Tukey test; $\alpha = 0.05$)

NE not evaluated

stored at 2 °C for 24 h before mechanical properties and syneresis analysis to be performed.

In order to establish the influence of fiber addition on the evaluated responses, diet dairy desserts with no fiber (diet control sample) were formulated with 3% *w*/*v* starch, 0.3% *w*/*v* carrageenan, 0.026% *w*/*v* sucralose, and skim milk (100 mL). Moreover, regular dairy desserts without fiber were prepared with 100 mL whole milk (prepared with whole milk powder and distilled water), sucrose (13% *w*/*v*), 3% *w*/*v* starch, and 0.3% *w*/*v* carrageenan. The latter was used as standard of mechanical properties and syneresis.

Caloric values (kcal/100 g) for uncooked desserts, using the Atwater coefficients (lipids 9.00 kcal/g, proteins 4.02 kcal/g, and carbohydrates 3.87 kcal/g), were 37.00 kcal/100 g for diet dairy desserts and 108.00 kcal/100 g for regular dairy desserts. It should be noted that legal values for dietary fiber nutritional labeling can be different depending on the country or region where the product is registered. According to Tungland and Meyer (2002), short-chain fatty acids resulting from the fiber fermentation process in the large intestine provide a certain amount of energy from their metabolism in the liver. Thus, the energy content of a fiber is conditioned to the degree of fermentation. Fiber fractions that are not fermented to any extent have a caloric content approaching to 0 kcal/g, while data from caloric studies indicate that the average energy yield from the fiber fermentation in monogastric species is in the range of 1.5 to 2.5 kcal/g fiber. A current study (Menezes et al. 2016) recommends using the value 1.9 kcal/g dietary fiber on calculation of food total energy value. Therefore, 39.47 kcal/100 g is the energy content for low-calorie dairy desserts with bamboo and wheat fibers. Inulin and apple low-calorie dairy desserts have 39.59 and 40.42 kcal/100 g, respectively, owing to the presence of other nutrients in their powders, and psyllium dairy dessert has 40.77 kcal/100 g due to the presence of sucrose in their pharmaceutical formula.

Table 2 Chemical evaluation of dietary fibers (g/100 g): total fiber, soluble fiber, insoluble fiber, cellulose, hemicellulose, and lignin content from Dello Satffolo et al. (2011)

Type of fiber	Apple	Bamboo	Psyllium	Wheat
Total fiber	58.1b ± 1.0	95.3c ± 0.9	45.2a ± 0.8	94.4c ± 1.1
Insoluble fiber	44.8b ± 0.4	91.4c ± 0.5	37.5a ± 0.6	92.1c ± 0.6
Soluble fiber	13.3c ± 0.7	3.2a ± 0.8	7.1b ± 0.5	2.3a ± 0.6
Cellulose	30.2b ± 1.7	48.7c ± 1.0	6.5a ± 0.4	72.2d ± 0.7
Hemicellulose	5.7a ± 1.6	40.2d ± 1.7	29.5c ± 1.3	14.9b ± 0.9
Lignin	8.4b ± 0.8	2.0a ± 0.1	0.8a ± 0.1	2.6a ± 0.4

Inulin was not included due to its being a soluble fiber since it is obtained by extraction and purification from chicory root, a process that eliminates cellulose, hemicellulose, and lignin. In each row, different lowercase letters denote significant differences between. Samples (Tukey test; $\alpha = 0.05$)

Mechanical Properties

The mechanical properties of the dairy desserts were determined by uniaxial compression using a universal testing machine (TA XT2, Stable Micro Systems, Godalming, Surrey, England). The 3-cm diameter samples were compressed to 80% of their initial height (4.8 cm) with a crosshead speed of 0.5 mm/s using an acrylic plate (35 mm diameter) lubricated with silicon oil to avoid friction between sample and geometry (Casiraghi et al. 1985).

Hencky stress (σ_c) and strain (ε_H) were calculated from the force deformation data according to Eqs. (2) and (3), respectively (Peleg 1984).

$$\sigma_c = \frac{F(t)}{A(t)} \tag{2}$$

$$\varepsilon_H = \left| \ln\left(\frac{H(t)}{H_0}\right) \right| \tag{3}$$

where $F(t)$ is the force at time t, $A(t)$ is the contact area of the sample at time t, $H(t)$ is the height at time t, and H_0 is the height of the sample at the beginning of compression. Stress (σ_{rup}) and strain (ε_{rup}) at rupture/fracture were determined at the maximum point of the stress-strain curve, while the elasticity modulus (E) was obtained from the slope of the initial linear region of this curve (Thybo et al. 2000).

Syneresis

Syneresis was evaluated in triplicate, by modifications of the method described by Ferrero (1992). This method is based on capillary suction and consisted in placing the gels in contact with porous media adequately. So, after refrigeration, each sample was removed from the plastic cups and supported on filter paper Whatman no. 40 (diameter 12.5 cm), previously dried. After 1 h, gels were removed from the filters and the halo formed by the absorbed water was measured. Results were expressed in millimeters, which corresponds to distance run by water from the border of the sample to the border of the halo (Fig. 1) which was associated to the syneresis index.

Experimental Design

In order to study the simultaneous influence of carrageenan, starch, and fiber concentrations on the mechanical properties and syneresis of the formulated diet dairy desserts, a five-level, three-variable, central composite rotatable design (CCRD) was performed. For each fiber, an independent CCRD was carried out, resulting in five sets of experiments. The range and levels of the variables studied are shown in Table 3. The component concentrations for central point (C, in Table 3) were established at the first time. The concentrations of starch and carrageenan were based on typical market desserts taking into account the previous work (Dello Staffolo et al. (2007). The amount of fiber was selected following US regulations for fiber-fortified milk products (Fernández–García and McGregor 1997). The amount of sucralose was determined considering the sucrose content in the previous study, by extrapolation using a conversion scale for sweet powder between sucrose and sucralose (Friedman 1998). Then, the ranges of starch, fiber, and carrageenan were provided by the online software Protimiza

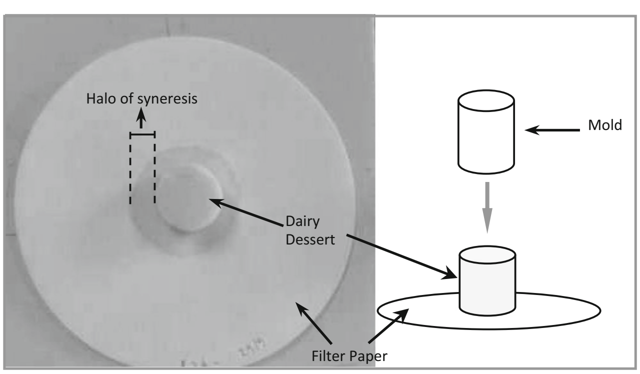

Fig. 1 Syneresis assay for dessert formulations

Experimental Design (2014), around the central point. Sucralose content (0.026% *w*/*v*) and milk volume (100 mL) were kept constant for all samples.

Each design required 17 sets of randomized experiments, which included 8 factorial points, 3 central points, and 6 extra axial points. Such conditions allowed for the description of the properties' behavior according to a quadratic polynomial equation (Eq. 4). The mechanical properties (σ_{rup}, ε_{Hrup}, and E) and the halo thickness obtained from syneresis results were taken as the responses of the experimental designs.

$$y = b_0 + b_1 C + b_2 F + b_3 S + b_{11} C^2 + b_{22} F^2 + b_{33} S^2 + b_{12} CF + b_{13} CS + b_{23} FS \quad (4)$$

where y is the response calculated by the model; C, F, and S are the coded carrageenan, fiber, and starch concentrations; and b_i ,b_{ii}, and b_{ij} are the coefficients estimated by the model representing the linear, quadratic, and two-factor interactions of the response, respectively.

Sensory Evaluation

Sensory evaluation was performed by an affective test with a 9-point structured scale (1 for "dislike extremely" and 9 for "like extremely") in a standardized test room in the morning. About 10 g dessert samples (regular no fiber, diet no fiber, and diet no fiber with fibers) was served at 10 °C in glass cups coded with random three digit numbers. Mineral water was provided for mouth rinsing. Two drops of artificial vanilla essence from a hydro-alcoholic solution (La Virginia, Argentina) were added before heating for all desserts during sample preparation, with the purpose of mimicking the typical market dessert. The attributes of overall acceptability, flavor, creaminess, gelatinous, and grainy were evaluated by a panel of 30 non-trained judges to determine the acceptability of the low-calorie desserts with plant fibers. The judges were regular consumers of dairy dessert and were recruited in a previous survey.

Statistical Analysis

The analysis of variance (ANOVA) was used to verify the model regression significance, and the proportion of variance explained by the fitted model was given by the coefficient of determination (R^2). Differences in means (Tukey test) and F tests were considered significant when $p < 0.05$.

Results and Discussion

Morphology and Particle Sizes for Dietary Fibers

The morphology of different fiber powders is not uniform as can be observed in Fig. 2. The apple fiber particles

Table 3 Experimental range and levels of both coded and real values of the independent variables

	Coded values			Real values (% *w*/*v*)		
	Carrageenan concentration	Fiber concentration	Starch concentration	Carrageenan concentration	Fiber concentration	Starch concentration
1	−1	−1	−1	0.2	0.9	2
2	1	−1	−1	0.4	0.9	2
3	−1	1	−1	0.2	1.7	2
4	1	1	−1	0.4	1.7	2
5	−1	−1	1	0.2	0.9	4
6	1	−1	1	0.4	0.9	4
7	−1	1	1	0.2	1.7	4
8	1	1	1	0.4	1.7	4
9A	−1.68	0	0	0.13	1.3	3
10A	1.68	0	0	0.47	1.3	3
11A	0	−1.68	0	0.3	0.63	3
12A	0	1.68	0	0.3	1.97	3
13A	0	0	−1.68	0.3	1.3	1.32
14A	0	0	1.68	0.3	1.3	4.68
15C	0	0	0	0.3	1.3	3
16C	0	0	0	0.3	1.3	3
17C	0	0	0	0.3	1.3	3

A axial points, *C* central points

showed an irregular polyhedral shape. Wheat and bamboo fibers presented irregular polyhedral and rod-like elongated shapes. On the other hand, inulin and psyllium exhibited both distinctive morphologies. The inulin particles seemed to be truncated icosahedrons, while psyllium fiber showed higher particle sizes than other fibers with irregular prism shapes.

The particle size analyzer provides the sphere diameter with the same volume as the particle vs. the volume fraction (q) of each size. Figure 3 shows particle size distributions with

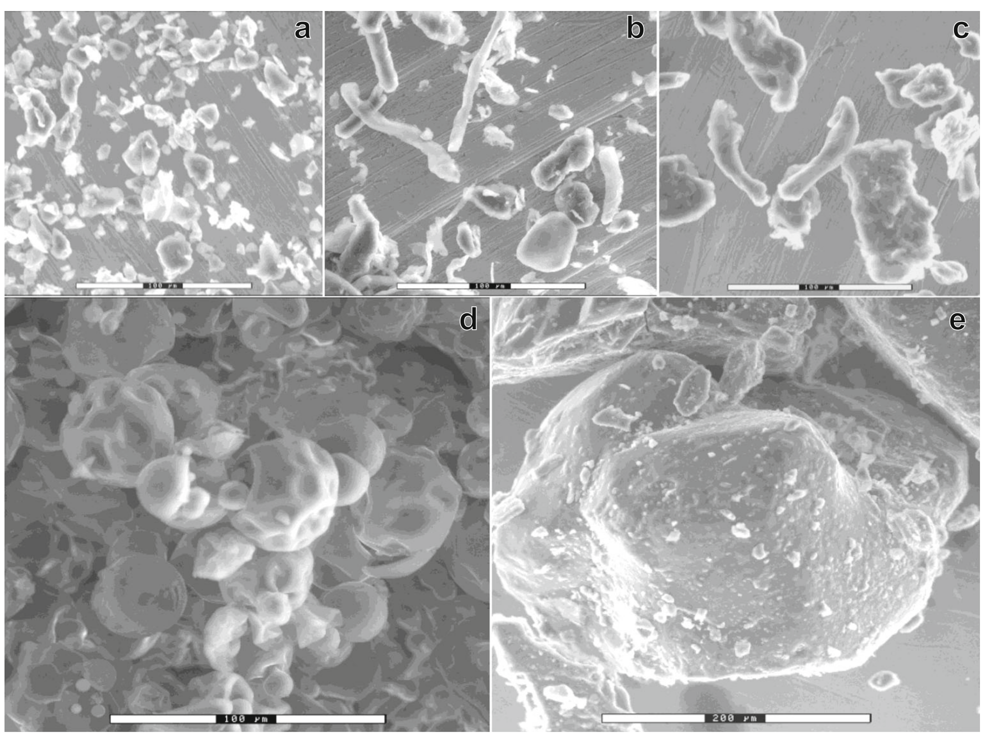

Fig. 2 Environmental scanning electron micrographs for dietary fibers. **a** Apple fiber. **b** Bamboo fiber. **c** Wheat fiber. **d** Inulin. The *bars* indicate 100 μm. **e** Psyllium. The *bar* indicates 200 μm

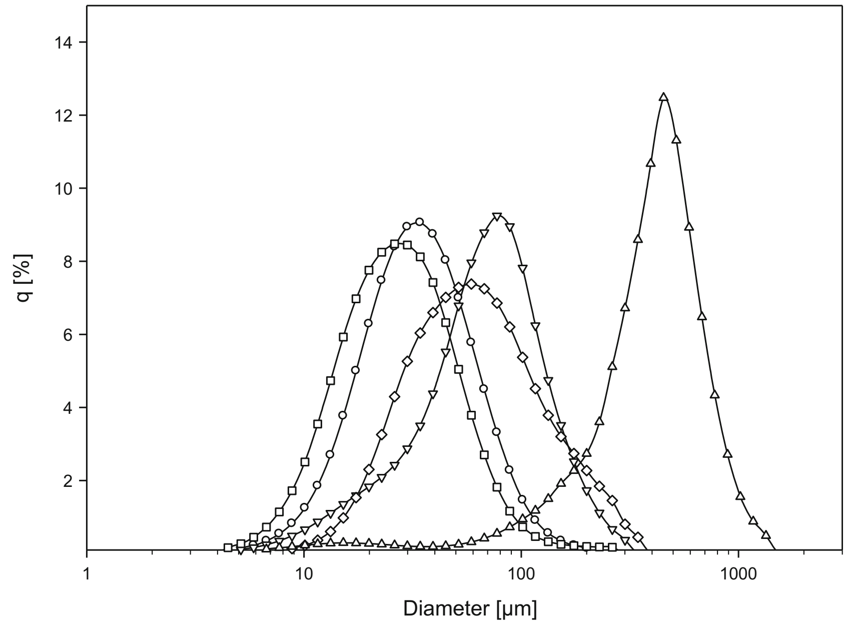

Fig. 3 Particle size distribution for powder fibers plotted as sphere diameter (μm) showing the same volume as the particle vs. volume fraction q (%) of each diameter -□- apple fiber, ○ bamboo fiber, -▿- inulin, -◊- wheat fiber, -△- psyllium

only one maximum (unimodal distribution) for all fibers. The median diameter value (D50) and the span index are considered the most meaningful parameters for the unimodal distribution (ISO 13320:2009). D50 is the size in microns that splits the distribution with half above and half below this diameter. The span index calculation $[(D_{v0.9} - D_{v0.1}) / D_{v0.5}]$ was used to express distribution width. The median values in ascending order are as follows: 24.75 μm for apple fiber, 30.91 μm for bamboo fiber, 55.64 μm for wheat fiber, 64.33 μm for inulin, and 391.79 μm for psyllium. The span indexes following the same order are 1.76, 1.65, 2.27, 1.71, and 1.32 μm for each fiber particle size distribution. Apple fiber showed the smallest particle size among the analyzed fibers with a medium span value. Psyllium showed the highest particle size with the lowest span value while wheat fiber presented an intermediate size with the highest polydispersity.

The particle size affects hydration properties and oil binding capacity (Raghavendra et al. 2006) and, consequently, may affect the texture and aspect of food products (Aufret et al. 1994; Sendra et al. 2010). In the preparation of low-calorie dairy desserts in this work, the different fibers have to hydrate with available water in the initial mix. Depending on its physicochemical characteristic, the fiber may be solubilized or not. Inulin is a soluble fiber (solubility in water at 25 °C = 12% *w*/*v*, according to Franck 2002); therefore, it is likely to be found soluble in the mixing step of preparing desserts. In contrast, bamboo and wheat are insoluble fibers; thus, they could keep their particle sizes during dessert manufacturing. Apple and psyllium contain both soluble and insoluble fractions. In addition, psyllium forms a viscous dispersion at concentrations below 1% *w*/*v* and a clear gelatinous mass at 2% *w*/*v* (Chan and Wypyszyk 1988). Then, the fibers could participate or interfere in gel formation, increasing or decreasing gel stiffness. In particular, the apple fiber used in this work seems to interfere in yoghurt gel formation as it was found in a previous work (Dello Staffolo et al. 2004).

Mechanical Properties

Mechanical properties of desserts formulated with 1.3% of different fibers, diet dairy desserts without fiber, and regular dairy desserts without fiber are presented in Fig. 4a–c. As compared to regular formulations, diet desserts with no fiber addition show significant lower stress at fracture and elasticity modulus ($p < 0.05$). Addition of 1.3% of different fibers promoted a considerable increase of these mechanical properties, increasing σ_{rup} and E about twice and 1.5 times, respectively, than that observed for diet desserts with no fiber addition. This amount of added fiber allowed compensating the negative effects that resulted from solid removal in the low-calorie dairy desserts and, in some cases, even producing tougher and firmer samples, as compared to regular formulation. For deformability (ε_{rup}), no significant difference ($p > 0.05$) was observed between the diet formulation with no added fiber and other samples, except for the dessert formulated with psyllium, in which an increase of approximately 30% was observed for this property (Fig. 4b).

The physicochemical properties of *Psyllium* could be responsible for the increase in the fracture properties (stress and strain), acting as a network builder, since this fiber showed the strongest gelling ability compared to the other fibers. Psyllium is known as gel-forming mucilage with strong water-absorbing and gelling capacities. Its bioactive fraction, the hemicellulose, is a highly branched arabinoxylan responsible for both capacities. The backbone consists of xylose units, while arabinose and xylose form the side chains

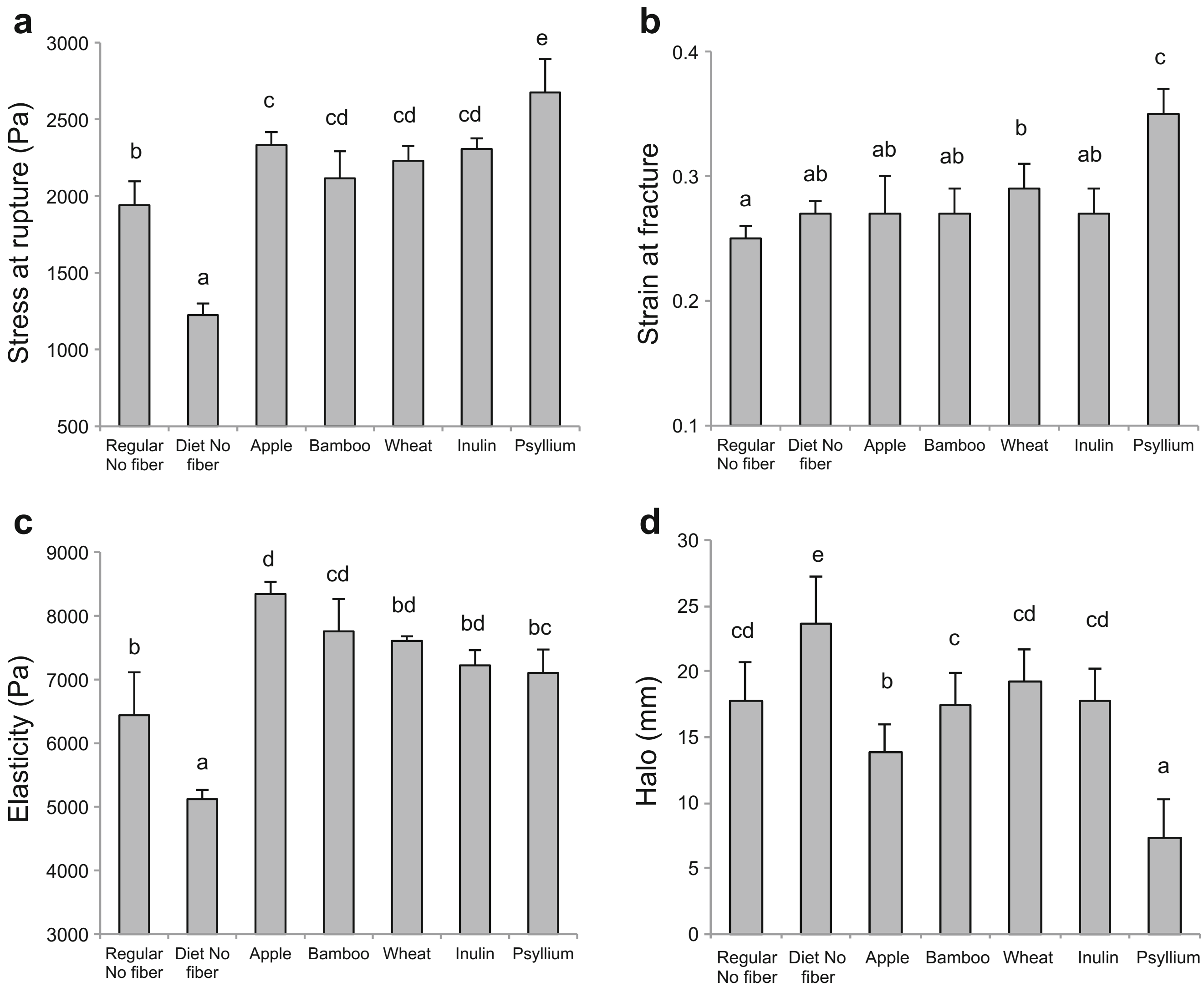

Fig. 4 Mechanical properties. **a** Stress at fracture (σ_{rup}). **b** Strain at fracture (ε_{rup}). **c** Elasticity modulus. **d** Syneresis index for dessert formulations. Diet desserts with dietary fibers are presented in ascending order with regard to their particle sizes. *Different letters above each column* indicate that average values differ significantly ($p < 0.05$)

(Theuwissen and Mensink 2008; Yu et al. 2008). Different types of mixed gels may be formed depending of the gelling capacity of the added polymers (strong or weak) (Aguilera and Stanley 1999). An increment on the stiffness is observed when the gel is produced by the stronger gelling agent (psyllium, in this case), and the other polymers reinforced the system behaving as fillers or dispersed phase. On the other hand, even though the apple fiber used in the present research shows a relatively low total fiber content (Table 2), its composition stands out for its higher lignin amount that, due to its high degree of crosslinking, may contribute to the high elasticity modulus of diet apple fiber dessert (Salmen 1982).

Similarities between mechanical properties of wheat and bamboo desserts may be attributed to the similar fiber composition of these ingredients. In both cases, soluble and insoluble fibers remained close to 2–3 and 90%, respectively, while no differences on the lignin amount was observed between them (Table 2). However, even though mechanical properties of inulin desserts did not show significant differences ($p > 0.05$) between wheat and bamboo results, the composition of inulin is different from the latter. Inulin is known for its texture modifier properties, with extensive application as fat replacer in the food industry (Meyer et al. 2011; Charalampopoulos and Rastall 2012). In this case, the fat substitution is based upon the ability of the inulin to stabilize the aqueous phase into a creamy structure that shows a fat-like mouthfeel (Ruiter and Voragen 2007).

Furthermore, taking into account the particle sizes of apple, bamboo, psyllium, and wheat fibers, an increment in the strain at fracture and a decrease in the elasticity modulus with the increasing of the particle size can be observed (Fig. 4a, c). In this sense, a positive ($r \leq 0.899$, $p < 0.05$) and a negative

($r \leq -0.919$, $p < 0.05$) correlation were found for stress at fracture and elasticity, respectively. No correlation was found between strain at rupture and the particle size indicating that differences for this parameter among the desserts with fibers may be best explained from the fiber chemical composition point of view.

Table 4 shows mechanical property model coefficients for low-calorie desserts with different fibers. Evaluation of the experimental design was carried out, indicating a good fitness of the mechanical properties (σ_{rup}, ε_{rup}, and E), with F_{model} much higher than F_{table} for all systems produced with the different fibers, using a 95% confidence level. For most systems, neither interactions nor quadratic effects were significant ($p > 0.05$), so that mechanical properties were mostly influenced by the linear effects. For most systems, σ_{rup} and ε_{rup} were only influenced by carrageenan (C) and fiber concentration (F). In fact, Verbeken et al. (2004) demonstrated that neither milk protein nor starch concentration influenced significantly the large deformation properties of dairy desserts with any added fiber in similar conditions presented in this work, which only showed high correlation to the carrageenan content. Exception was observed for psyllium formulations, in which the starch concentration (Fig. 5a) showed a significant ($p < 0.05$) and positive influence on rupture properties (stress and strain at fracture).

As previously observed in Fig. 4, similarities between bamboo and wheat fiber desserts are also evident on the evaluation of the significant effects on the mechanical properties (Table 4). Not only the mean values but also the significant effects of the desserts formulated with these fibers showed similar magnitudes.

Furthermore, for most of experimental designs carried out in the present research, both carrageenan and fiber concentration showed a significant ($p < 0.05$) and positive influence on ε_{rup} (Table 4). However, the carrageenan effect was quite similar to fiber concentration for ε_{rup} (Fig. 5d), indicating that, within the

Table 4 Fitted models for syneresis data (halo thickness in mm), stress at fracture (σ_{rup}), strain at fracture (ε_{rup}), and elasticity modulus (E): coefficient of determination (R^2) and F_{test} calculated as F_{model}/F_{table}

Fiber	Mean	Regression coefficients									R^2	F_{test}
		Linear			Interactions			Quadratic				
		S	C	F	S × C	S × F	C × F	S^2	C^2	F^2		
Stress at fracture												
Apple	2379.2	NS	NS	774.4	144.6	NS	−278.6	NS	208.5	−166.5	0.95	14.2
Bamboo	2323.7	NS	200.1	811.9	NS	NS	NS	NS	NS	NS	0.95	43.7
Wheat	2368.2	NS	142.9	890.9	NS	NS	NS	NS	NS	NS	0.97	60.0
Inulin	2236.7	NS	NS	766.0	NS	NS	NS	NS	NS	NS	0.95	38.8
Psyllium	2762.4	225.9	370.2	933.9	NS	NS	NS	NS	NS	NS	0.93	22.5
Strain at fracture												
Apple	0.2663	−0.0195	NS	0.0212	NS	NS	NS	NS	NS	NS	0.46	2.81
Bamboo	0.2858	NS	0.0243	0.0225	NS	NS	NS	NS	NS	NS	0.80	11.71
Wheat	0.2974	NS	0.0203	0.0250	NS	NS	NS	NS	NS	NS	0.82	15.46
Inulin	0.2800	NS	0.0261	0.0196	NS	NS	−1.85	NS	NS	NS	0.70	9.03
Psyllium	0.3569	0.0289	0.0166	0.0153	NS	NS	NS	NS	NS	NS	0.69	3.47
Elasticity modulus												
Apple	8305.5	757.8	325.8	2523.2	NS	NS	300.7	NS	346.1	NS	0.98	29.62
Bamboo	7630.6	NS	NS	1934.1	NS	NS	NS	NS	NS	NS	0.89	33.76
Wheat	7639.6	NS	NS	2263.9	−610.9	NS	159.2	NS	NS	140.4	0.95	18.97
Inulin	7072.5	NS	NS	1730.9	NS	NS	NS	NS	NS	NS	0.84	18.19
Psyllium	6806.1	NS	NS	2141.1	NS	NS	NS	NS	NS	NS	0.77	11.40
Syneresis												
Apple	13.8	NS	−4.0	−1.2	NS	NS	0.8	0.5	0.4	NS	0.87	4.73
Bamboo	17.5	NS	−3.6	−1.1	0.8	−0.3	1.6	NS	1.1	0.3	0.94	6.53
Wheat	19.1	0.2	−3.7	−1.6	−0.7	−0.9	2.2	−0.2	0.1	0.8	0.97	6.08
Inulin	17.9	−2.1	−4.0	−1.4	0.8	0.6	2.7	1.9	NS	1.0	0.88	2.10
Psyllium	7.2	−2.2	−1.4	−0.3	1.3	−1.1	−0.5	0.6	0.8	0.5	0.94	3.28

NS non-significant variables

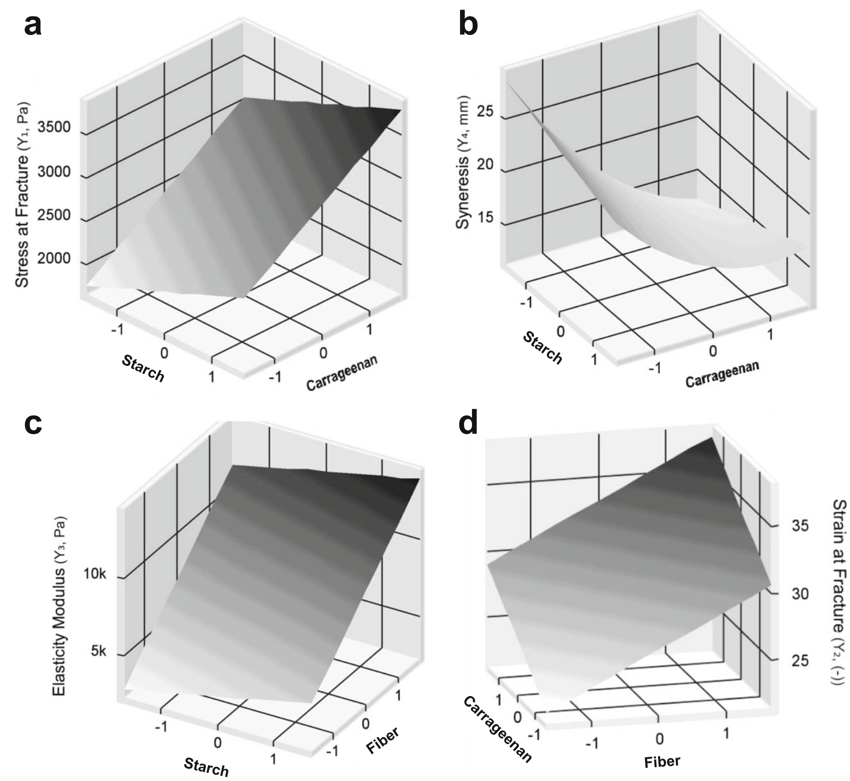

Fig. 5 Response surfaces for low-calorie dessert formulations. **a** Stress at fracture for psyllium. **b** Syneresis for bamboo fiber. **c** Elasticity modulus for apple fiber. **d** Strain at fracture for wheat fiber

concentration range studied, both carrageenan and fiber concentrations exerted similar influence on the deformability.

Considering the low deformation property, for most formulations, fiber concentration was the only statistically significant variable ($p < 0.05$), showing a positive effect on the elasticity modulus. This fact could be connected with the found correlation between fiber particle size and elasticity modulus. Apple fiber-containing desserts were the only systems also influenced by the concentration of starch and carrageenan (Fig. 5c). For this dessert, both starch and carrageenan concentrations showed a positive linear influence ($p < 0.05$) on the elasticity modulus but with much lower magnitude as compared to fiber concentration within the studied range. This behavior could be explained considering that apple fiber has the smallest particle size, and this fact could promote the influence of starch and carrageenan on the elasticity modulus. Additionally, starch and carrageenan influence together with fiber may contribute to the increased E value of apple fiber samples, as compared to other desserts (Fig. 4c).

Syneresis

Figure 4d shows the syneresis results of gels formulated with 1.3% of different fibers, diet dairy desserts without fiber addition, and regular dairy desserts without fiber. The higher the halo diameter, the more water released by the systems, indicating a higher syneresis.

Comparing regular and diet desserts with no fiber, an increase in halo diameter was observed on the reduced calorie formulation. In this case, the addition of fibers allowed compensating the water loss of the diet formulations promoted by the reduction of the fat and sucrose content. Indeed, syneresis of desserts formulated with inulin, bamboo, and wheat fibers did not differ significantly ($p > 0.05$) from regular no-fiber gels. Moreover, gels produced with apple and psyllium fibers showed even lower syneresis values (smaller halo diameter values). The free hydroxyl groups of the high amount of hemicellulose and lignin contained in psyllium and apple fiber, respectively, as compared to other fibers (Table 2), bind with water, reducing the syneresis of these gels. Moreover, combined with the effect of the fiber itself, the sucrose present in the psyllium formula and apple fiber could inhibit the starch retrogradation despite its small content, which could also contribute to the reduction of syneresis (Chang et al. 2004).

The halo diameter responses of low-calorie desserts with fibers correlate ($r = -0.907$; $p < 0.05$) with the water holding capacity (WHC) for apple, bamboo, psyllium, and wheat fibers. The WHC results are presented in Table 1. Inulin could not be evaluated from WHC analysis since this fiber is soluble in the assay conditions carried out in the present study. Fleury and Lahaye (1991) also observed that soluble fractions of fibers are lost during WHC measurement. The bamboo and the wheat fibers show low WHC, followed by the apple fiber, while psyllium displays the highest WHC. These values are inversely related to the results of halo diameter (Fig. 4d) and

Table 5 Sensory attribute scores (mean ± SEM) for regular no fiber, diet no fiber, and low-calorie desserts with plant dietary fibers

Dessert	Acceptability	Flavor	Creaminess	Gelatinous	Grainy
Regular no fiber	7.8bc ± 0.6	7.5cd ± 0.5	7.9c ± 0.3	8.0bc ± 0.4	8.0 ± 0.6
Diet no fiber	5.9a ± 0.4	6.9b ± 0.3	6.4a ± 0.2	7.8bc ± 0.4	8.1 ± 0.5
Apple	6.3ab ± 0.5	6.1a ± 0.4	7.5bc ± 0.2	7.9bc ± 0.5	7.9 ± 0.3
Bamboo	7.7bc ± 0.8	7.3bc ± 0.3	7.1b ± 0.4	7.6b ± 0.2	7.8 ± 0.4
Inulin	7.9bc ± 0.5	7.8cd ± 0.5	8.1c ± 0.3	6.7a ± 0.5	8.1 ± 0.6
Psyllium	6.5ab ± 0.9	6.9bc ± 0.7	7.8c ± 0.3	8.3cd ± 0.3	7.9 ± 0.5
Wheat	7.7bc ± 0.7	7.2bc ± 0.6	7.1b ± 0.4	7.7b ± 0.2	7.8 ± 0.6

In each column, different lowercase letters denote significant differences (Tukey test; $\alpha = 0.05$)

show that the WHC of fibers is directly associated to the syneresis of the formulated dairy desserts.

In Table 4 are presented syneresis model coefficients for low-calorie desserts with different fibers. The statistical significance of the adjusted model equations was evaluated by the F test analysis of variance (ANOVA). Even though good fit was not obtained for all systems, the equations were considered to be valid, indicating the trends of the studied variables, once the ratio of F_{cal}/F_{tab} was greater than 1 (Table 4).

All components (starch, carrageenan, and fibers) reduced syneresis (observed from linear effects), although the effect of starch was not significant for part of the samples (Fig. 5b). In these cases, the influence of starch may have been masked by the presence of other ingredients that showed significantly higher effect on WHC.

Generally, it was observed that carrageenan showed high influence on the syneresis of the low-calorie dairy desserts despite its lower concentration compared to starch and plant fibers. These results are in agreement with results obtained by Iop et al. (1999) for desserts with different combinations of sweeteners. Even though the carrageenan effect was about three times the effect exerted by the fiber considering the model fit, the addition of plant dietary fibers was essential to syneresis reduction (Fig. 4d).

Sensory Evaluation

The results of the affective test are shown in Table 5. The terms creaminess, gelatinous, and grainy are employed to describe food texture (Gunasekaran and Ak 2003). Creaminess is a highly desirable multidimensional attribute which contributes to acceptance of food products which have a velvety and smooth mouthfeel such as yoghurts, creams, and custards (Kilcast and Clegg 2002). Regular no-fiber desserts and low-calorie desserts with inulin and psyllium presented the highest scores for creaminess. Therefore, inulin and psyllium may contribute to the mimicking of fat in low-calorie desserts as low-calorie desserts without fiber obtained the lowest scores for this attribute. The jelly-like sensation analyzed by the gelatinous attribute has good value in low-calorie desserts with psyllium; this fact could be related with its physicochemical properties. In contrast, low-calorie desserts with inulin showed a low score, and it was significantly different ($p < 0.05$) from other formulations. The judges did not detect particles in the mouth when consuming the low-calorie desserts with fibers owing to the fact that no differences ($p > 0.05$) in the grainy attribute were found among samples assessed. This behavior could be explained considering that grainy perception seems to diminish in the presence of biopolymer networks (Appelqvist et al. 2015; Krzeminski et al. 2014) because this network may reduce the ability of judges to distinguish individual particles.

The flavor of low-calorie desserts with apple fiber decreased significantly ($p < 0.05$) compared to other formulations that could be attributed to its fruity taste and apple odor as declared by suppliers (Table 1). Low-calorie dairy desserts without fiber exhibited the lowest overall acceptability while apple and psyllium diet desserts presented intermediate scores for this attribute. Bamboo, inulin, and wheat diet desserts did not differ significantly ($p > 0.05$) from regular desserts without fiber, indicating that the addition of these fibers was suitable to enhance the overall acceptability of low-calorie dairy desserts.

Conclusions

Mechanical properties and syneresis for low-calorie dairy desserts with different plant dietary fibers were modeled employing the response surface methodology. Results revealed that the ingredients (carrageenan, starch, and fibers) played distinct roles as fat/sugar replacers on low-calorie dairy desserts. Carrageenan and starch showed higher influence on reducing gel syneresis of diet desserts. Fiber addition compensated the reduction on stiffness and elasticity as well as decreased syneresis of the low-calorie formulation, besides adding health benefits. In particular, bamboo and apple fibers increased elasticity bringing up a positive effect to diet desserts. Good correlations were found between particle size and water holding capacity from the fibers, and the variables allow interpretation of the influence of plant dietary fibers on measured properties.

From a sensory perspective, consumers distinguished some differences in creaminess and gelatinous attributes, specifically on inulin and psyllium low-calorie dairy desserts, which also may be determined by the physicochemical features of these fibers. In contrast, no perception of fiber particles was observed in the evaluated low-calorie dairy desserts because of their small sizes and the surrounding network.

Contemplating on both the need for low-calorie fiber desserts similar to regular desserts without fibers and having as much as possible the best technological and sensory properties, bamboo, inulin, and wheat may be considered the most suitable fibers for adding to low-calorie dairy desserts.

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