Mucilage powder from cactus pears as functional ingredient: influence of cultivar and harvest month on the physicochemical and technological properties

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Abstract Cactus pear mucilage is a novel, inexpensive hydrocolloid that is used to add nutrients, body and texture to functional food products. However, varied physicochemical and technological properties of powders when cultivar and harvest month of cladodes differ could lead to differentiation in the application of mucilage powders. To that end, three *Opuntia ficus-indica* (Algerian, Morado and Gymno-Carpo) cultivars and one *Opuntia robusta* (Robusta) cultivar were harvested over a 6 month period and evaluated in this study. February mucilage powders were the most porous with highest oil absorption and oil holding capacity, lowest water holding and swelling capacity, and lowest ability to increase viscosity. August mucilage powders had the smallest impermeable particles, highest water holding and hydrophobic properties, as well as the best emulsifying capacity, stability and ability to increase viscosity. *Opuntia robusta* produced brighter, darker green, more viscous mucilage while *Opuntia ficus-indica* powders were dull, light yellow-green with a lower viscosity and emulsifying capacity. Overall, the mucilage powders were easy to pour and free-flowing yet were microbiologically

safe due to low water activity and pH levels. Robusta mucilage was successfully applied in mayonnaise products to replace up to 50% egg yolk and 30% oil. It was concluded that mucilage powders might contribute to the textural and nutritional quality of food products. The acceptance of mucilage powder as an active functional and nutraceutical food ingredient will also lead to the development of cactus as a commercially viable crop in arid and semi-arid areas where few other crops can survive.

Keywords *Opuntia ficus-indica* · *Opuntia robusta* · Cladode · Nopal · Carbohydrate polymer · Emulsifying agent

Introduction

Food developers search for new, inexpensive, non-caloric, natural hydrocolloids to use in functional food products, which not only have health benefits but also improve the physical and structural properties of food (Smith and Charter 2010; Elleuch et al. 2011). Innovative, functional food products are not dietary supplements or taken to treat specific disorders, but form part of a normal diet and address specific dietary requirements (Smith and Charter 2010). Fibre-rich ingredients are incorporated in functional foods because they are effective in correcting or improving viscosity, texture, appearance and sensory characteristics. Therefore they can be used as additives to stabilise, thicken and emulsify functional food products (Elleuch et al. 2011). The acceptance of mucilage powder as an active functional and nutraceutical fibre-rich ingredient could lead to the development of cactus pears as a commercially viable crop in arid and semi-arid areas (Du Toit et al. 2018).

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Cactus pears are efficiently adapted to obtain and retain water, which allows it to thrive in arid and semi-arid regions (Salisbury and Ross 1992). One of these adaptations is the slimy fluid (mucilage) found in the cladodes, which consists mostly of soluble fibre. The mucilage molecules have complex structures that absorb and hold huge amounts of water (Trachtenberg and Mayer 1981). Mucilage molecules are unbranched, negatively charged, water-soluble hetero-polysaccharide chains that repel themselves, causing them to stretch throughout the solute, resulting in increased viscosity (Trachtenberg and Mayer 1981). These properties may be retained in freeze-dried mucilage which may make it a useful ingredient in food products. Cactus pear cladode flour and mucilage are classified as nutraceutical products owing to their therapeutic and pharmacological potential. Regular ingestion of functional foods containing cladode or mucilage powder could contribute to the control and the prevention of cholesterol, diabetes, ulcers and cancer (Nazareno 2013).

Mucilage powders obtained from cladodes harvested in hot and dry conditions (post-fruit harvest in February) are low in kilojoules and rich in minerals (Du Toit et al. 2018), however, the careful selection of cultivar and harvest month was recommended depending on the purpose of application (Du Toit et al. 2018). The fibre's water holding capacity, fat-emulsification, viscosity and texturizing capacity depend on chemical composition, physicochemical properties (porosity, particle size, pH, conductivity) and technical properties (hydration and oil-emulsification capacities) (Cui and Roberts 2009; Elleuch et al. 2011). The physicochemical and technological characteristics of freeze-dried mucilage powders may be affected when cladodes are harvested from different cultivars, species, growth stage (post-harvest/dormant stages) and weather conditions (seasons). The aim of this study was to determine the influence of cultivar and harvest time on the physicochemical and technological properties of freeze-dried mucilage powder.

Materials and methods

Sample collection

Cladodes were obtained from an experimental cactus pear orchard outside Bloemfontein, Free State, South Africa (29°10'53" S, 25°58'38" E). Bloemfontein is 1348 m above sea level and a summer rainfall region (average 556 mm). The driest period is from May to October, of which July is the driest month, whereas March is the wettest month (World Weather and Climate Information 2016). In this study, mature cladodes (five from each of the two replications) of three *Opuntia ficus-indica* cultivars (Algerian,

Morado and Gymno-Carpo) and one *Opuntia robusta* (Robusta) were harvested and the extracted and freeze-dried mucilage evaluated over 6 months. February–April was regarded as the post-harvest stage while in May–August, cactus pears were dormant. The sampling of young mature cladodes from the north side of the plant and at approximately hip height took place from February to August 2015. Mucilage was extracted according to the patented extraction procedure of Du Toit and De Wit (2011) using unpeeled cladodes. The unpeeled cladodes were sliced, microwave cooked for 4 min (800 W), macerated, centrifuged at 8000 rpm for 15 min and then freeze-dried for 72 h in a Perano freeze-drier at -60°C (Du Toit et al. 2018). The mucilage was packaged in vacuum-sealed bags and stored in the freezer at -18°C until use.

Methods

Particle size and porosity of mucilage powder particles

The mucilage powders were ground manually using a mortar and pestle. The particles were measured during scanning electron microscopy (SEM) and the average particle sizes (μm) were calculated for each cultivar. Mucilage powders were inspected with SEM using a JEOL scanning electron microscope (JSM-7800F Extreme-resolution Analytical Field Emission JEOLFE-SEM) from the first (February 2015) and the last (August 2015) months. The samples were mounted on a metal stub before sputter coating with gold (Glauert 1974).

Bulk and tapped density and compressibility index

Bulk and tapped density were determined using the methods described by Ayadi et al. (2009) using 3 g of the freeze-dried mucilage samples. The bulk and tapped density (g/ml) were calculated by dividing the weight (g) with the volume (ml) of the powder. The compressibility index was calculated using the method described in Particle Analytical (2007). Subsequently, the compressibility index was rated as follows: 1–10 = excellent, 11–15 = good, 16–20 = fair, 21–25 = passable, 26–31 = poor, 32–37 = very poor, > 38 = very, very poor.

Moisture and solids content

Moisture content (%) and solid content (%) were determined for every mucilage powder sample according to standard procedures (Reeb and Milota 1999).

Water activity (a_w)

The water activity of mucilage powder samples was determined using a Novasina Thermoconstanter (RTD-200 TH-2) at 22 °C and the a_w determined as ERH/100 (equilibrium relative humidity).

pH and conductivity

Mucilage powders were reconstituted for pH (10%), conductivity (10%), viscosity (5%) and technological property (5%) determinations. For all determinations, the required amount of freeze-dried mucilage was dissolved in 20 ml distilled water. A paste was made using 2 ml water, followed by mixing for 10 s using a Genie vortex (Scientific Industries Vortex-Genie 2 Vortex Mixer 12, Fisher Scientific). Distilled water (18 ml) was then added and vortexed again for 10 s. The reconstituted mucilage (RM) was homogenized for 30 s using a Kenwood Triblade Hand Blender (HB716) and allowed to stand for an hour to dissolve fully. A calibrated Eutech pH 2700 pH/mV/°C/°F instrument (Thermo Fisher Scientific Inc.) was used to determine pH and conductivity (mV = mS) at 22 °C on 10% RM of the 24 samples.

Viscosity

A rotational digital RV Brookfield laboratory Viscometer (Brookfield DV3T Viscometer) was used to determine the single point viscosity of 5% RM samples. The single point viscosity reading was taken for each sample, using disk spindle nr. 5 of the RV spindle series, at 20 rpm, 22 °C after 60 s.

Colour determination

Colour was determined by taking six readings of the freeze-dried mucilage powder samples, using a CR-400 Konica Minolta Chroma Meters Measuring Head (L^* , a^* , b^*). Chroma (C^*) and hue (h°) was calculated from the a^* and b^* coordinates using the following formulas (Color-Mine.org 2014).

$$C^* = \sqrt{a^{*2} + b^{*2}}$$

$$h^\circ = \tan^{-1} \left(\frac{b^*}{a^*} \right)$$

Protein content

The N content of 0.6 g freeze-dried mucilage powder samples was determined using a Leco Nitrogen analyser (FP-528, LECO Corporation) with thermal combustion and

the Crude Protein content calculated by multiplying the N content with 6.25 (Association of Official Analytical Chemists (AOAC) 2000).

Technological, foaming and emulsifying properties

The water solubility index (WSI), water absorption capacity (WAC), swelling capacity (SW), water holding capacity (WHC), oil absorption capacity (OAC), oil holding capacity (OHC) and emulsifying capacity/stability tests were done on the 24 5% RM samples as described in Du Toit (2017) and Du Toit et al. (2019a, in press). For foaming tests, the methods of Kaur and Singh (2005) were followed using 5% RM. The RM (20 ml) was homogenized using a Kenwood Triblade hand blender (HB716) for 30 s. The volume of foam was recorded immediately (10 s), after 2 min, 10 min and 12 min and expressed as percentage increase in volume.

Technological properties: application of mucilage as an emulsifying and fat-replacing agent in mayonnaise-type products

Mayonnaise is an emulsion and contains a large amount of fat (70–80%). It is easily prepared and is not exposed to direct heat for cooking. Thus, mayonnaise served as the ideal product for testing the fat-replacement and emulsification properties of mucilage. Robusta mucilage harvested in August was used as it displayed the highest protein content and freeze-dried powder yield (Du Toit 2017, Du Toit et al. 2019a in press), high emulsification ability and stability over 60 s, had the highest viscosity and had excellent water-holding, and oil-absorption properties (Tables 1 and 3). The control mayonnaise (Food and Cookery 1991) recipe (ingredients, amount and method) was standardized. The ingredients were egg yolk (12.66%), sunflower oil (78.28%), mustard powder (1.12%), granulated white sugar (1.45%), salt (1.26%), lemon juice (3.51%) and white wine vinegar (1.72%). For egg-replacement mayonnaise products, 25% (3.17% mucilage and 9.5% egg yolk), 50% (6.33% each mucilage and egg yolk) and 100% (12.66% mucilage and 0% egg yolk) were produced for evaluation. The oil in the control formula was replaced with RM to produce fat-replacement mayonnaise products that replaced 15% (11.74% mucilage and 66.54% oil), and 30% (23.49% mucilage and 54.80% oil) oil. Since mayonnaise is often used as a condiment, potato salad was made using the different mayonnaise products. A sensory panel evaluated the acceptability and preference of the products. Fifty panellists were included (ASTM Manual Series: MNL 13 1992) of which 80% were women and 20% were men.

Table 1 Physicochemical properties: bulk density, tapped density, compressibility index, moisture and solids content, water activity, pH (10% RM), conductivity (10% RM) and viscosity (5% RM) of mucilage powder extracted from four cactus pear cultivars harvested from cladodes over 6 months

Cultivar	Bulk density (g/ml)	Tapped density (g/ml)	Compressibility index (%)	Moisture content (%)	Solids content (%)	Water activity	pH (10% RM)	Conductivity (10% RM) (mS/cm)	Viscosity (5% RM) (cP)
Algerian	0.59 ± 0.34	0.73 ± 0.12	18.65 ± 3.29	15.60 ± 1.82	84.40 ± 1.82	0.34 ± 0.04	4.16 ± 0.21	96.30 ± 11.06	243.33 ^a
Morado	0.5 ± 0.05	0.62 ± 0.11	20.53 ± 4.84	16.23 ± 2.31	83.77 ± 2.31	0.35 ± 0.04	4.08 ± 0.18	100.60 ± 8.99	231.67 ^a
Gymno-Carpo	0.56 ± 0.73	0.67 ± 0.16	16.77 ± 2.76	15.83 ± 1.63	84.17 ± 1.63	0.34 ± 0.03	4.08 ± 0.10	101.13 ± 4.67	120.00 ^a
Robusta	0.56 ± 0.52	0.68 ± 0.12	19.15 ± 4.33	15.39 ± 1.87	84.61 ± 1.87	0.34 ± 0.04	4.24 ± 0.09	92.20 ± 4.57	673.33 ^b
Significance level	(<i>p</i> = 0.546)	(<i>p</i> = 0.576)	(<i>p</i> = 0.433)	(<i>p</i> = 0.889)	(<i>p</i> = 0.889)	(<i>p</i> = 0.924)	(<i>p</i> = 0.246)	(<i>p</i> = 0.198)	(<i>p</i> = 0.005)
Harvest month									
February	0.36 ± 0.53 ^a	0.48 ± 0.10 ^a	23.98 ± 5.31	16.09 ± 1.20 ^a	83.91 ± 1.20 ^b	0.34 ± 0.01 ^{bc}	3.98 ± 0.14 ^a	105.23 ± 6.08 ^b	70.00
April	0.55 ± 0.35 ^b	0.67 ± 0.12 ^b	17.30 ± 3.08	18.79 ± 1.46 ^b	81.21 ± 1.46 ^a	0.36 ± 0.03 ^{bcd}	4.01 ± 0.12 ^a	103.73 ± 6.23 ^b	70.00
May	0.55 ± 0.27 ^b	0.66 ± 0.10 ^{ab}	16.51 ± 2.04	14.82 ± 0.40 ^a	85.18 ± 0.40 ^b	0.38 ± 0.01 ^d	4.14 ± 0.09 ^{ab}	97.78 ± 4.99 ^{ab}	340.00
June	0.60 ± 0.11 ^b	0.72 ± 0.02 ^b	17.66 ± 3.23	13.97 ± 3.38 ^a	86.03 ± 0.38 ^b	0.36 ± 0.02 ^{cd}	4.19 ± 0.09 ^{ab}	94.90 ± 5.34 ^{ab}	385.00
July	0.61 ± 0.20 ^b	0.74 ± 0.08 ^b	18.05 ± 0.98	15.60 ± 0.90 ^a	84.40 ± 0.90 ^b	0.32 ± 0.02 ^{ab}	4.15 ± 0.09 ^{ab}	97.60 ± 5.33 ^{ab}	462.50
August	0.64 ± 0.07 ^b	0.80 ± 0.03 ^b	19.15 ± 3.72	15.32 ± 1.61 ^a	84.68 ± 1.61 ^b	0.29 ± 0.01 ^a	4.36 ± 0.11 ^b	86.13 ± 6.62 ^a	575.00
Significance level	(<i>p</i> < 0.001)	(<i>p</i> < 0.001)	(<i>p</i> = 0.061)	(<i>p</i> < 0.001)	(<i>p</i> < 0.001)	(<i>p</i> < 0.001)	(<i>p</i> < 0.001)	(<i>p</i> = 0.003)	(<i>p</i> = 0.107)
Means	0.55 ± 0.52	0.68 ± 0.13	18.78 ± 3.88	15.76 ± 1.82	84.24 ± 1.82	0.34 ± 0.04	4.14 ± 0.16	97.56 ± 8.19	317.08

Opuntia ficus-indica (Algerian, Morado and Gymno-Carpo), *Opuntia robusta* (Robusta); RM reconstituted mucilage; cultivar means with different superscripts in the same column differ significantly (*p* < 0.05); Month means with different superscripts in the same column differ significantly (*p* < 0.05)

Statistical methods

A one-way analysis of variance (ANOVA) procedure was used to determine the effect of month and cultivar on the technological properties of mucilage powders (NCSS 11 Statistical Software 2016). The Tukey–Kramer multiple comparison test ($\alpha = 0.05$) was carried out to determine whether significant differences exist between treatment means (NCSS 11 Statistical Software 2016). Pearson correlation analysis was performed between measured attributes (NCSS 11 Statistical Software 2016). Only selected correlations were used in discussions where appropriate.

Results and discussion

Physicochemical properties

Particle size and porosity of mucilage powder particles

The particle size of high fibre mucilage powders influences solubility, rheological behaviour and digestion (Dhingra et al. 2012). Larger particles may be influenced by gravity and show a tendency to sediment, whereas smaller particles may retain water and oil more effectively. The average particle sizes were Algerian (335 μm), Morado (326 μm), Gymno-Carpo (430 μm) and Robusta (246 μm). Thus, *O. robusta* (Robusta) powders had the smallest particle size while *O. ficus-indica* (Gymno-Carpo) had the largest particles on average as seen in Fig. 1a, b. The difference in particle size is evident in Fig. 1a, b as both the SEM photographs were taken at a scale of 100 μm and at a magnification of X80. It may be assumed that particle sizes differed as a consequence of the manual grinding procedure. The porous nature of February particles along with the solid nature of August particles was observed in all cultivars as seen in Algerian particles demonstrated in Fig. 1c, d. The pores in February particles may influence the available surface area and play a role in technological properties such as absorption and binding of mucilage powders (Dhingra et al. 2012). The absence of calcium oxalate crystals (Fig. 1), may be attributed to heating during the extraction procedure (Bernardino-Nicanor et al. 2015).

Bulk, tapped density and compressibility index

Bulk and tapped density depends on the density of the mucilage powder, the inter-particle spaces, and is influenced by sample treatment, preparation and storage (Particle Analytical 2007). Although no cultivar effect was observed in mucilage powders, the February powders, which had highly disorganized, sponge-like particles

(Fig. 1c), had significantly lower ($p < 0.001$) bulk density (0.36 g/ml) and tapped density (0.48 g/ml) than the other months thus the February powders packed more densely (Table 1). Powders from the other months (April–August) did not differ from each other (Table 1) indicating that interactions between particles were lower, which created more inter-particle spaces causing the powders to be more loosely packed. These results were slightly lower than values reported (0.68 and 0.69 g/ml) for mucilage powders (Gebresamuel and Gebre-Mariam 2012). Density values of 0.593–0.769 g/ml were recorded for differently treated cladode powders (León-Martínez et al. 2010). Spiny and spineless cladode powders had respective bulk density values of 0.703 and 0.647 g/cc (Ayadi et al. 2009) and Sáenz et al. (2012) observed 0.35 and 0.45 g/ml in purified cladode powders.

The compressibility index reflects the ability of a powder to settle and flow (Particle Analytical 2007). A free-flowing powder's bulk and tapped densities have closer values than a poorly flowing powder, as the interactions between particles are greater. In this study, an almost perfect correlation existed between bulk and tapped density ($r = 0.993$). Therefore, the powders with higher bulk density values also had higher tapped density values. According to the compressibility index values (Table 1), most of the mucilage powders were rated as having fairly good abilities to flow and pour (16.51–19.15%), while February powders would pour less easily as the compressibility index (23.98%) was higher. No significant cultivar or seasonal effects were observed for compressibility index.

Moisture and solids content

The moisture content of mucilage powders would affect the safety of the powder as increased moisture content promote bacterial growth and thereby reduce shelf life. Solids content influence the nutritional as well as rheological properties. The moisture content (Table 1) in freeze-dried mucilage was on average 15.76% and the solids 84.24%. There were no significant differences between cultivars. However, April mucilage (from cladodes harvested after the rainy season) had significantly higher ($p < 0.001$) moisture (18.79%) and lower solids (81.21%) than the other months (Table 1) and would, therefore, have the lowest functional properties and the shortest shelf-life. The moisture content was overall higher than was reported in dried mucilage powders from Ethiopian cultivars (11.57%) (Gebresamuel and Gebre-Mariam 2012). It is known that it is notoriously difficult to dry mucilage and cladodes and that the most effective drying techniques require high temperatures for the moisture content to drop to sufficiently low levels (León-Martínez et al. 2010). In this study, the

Fig. 1 Magnification of February mucilage powder to demonstrate average size difference between a *Opuntia ficus-indica* (Gymno-Carpo) and b *Opuntia robusta* (Robusta) ($\pm 100 \mu\text{m}$ at $\times 80$) as well

as particle magnification to demonstrate the porosity of February powder particles c Algerian ($\pm 100 \mu\text{m}$ at $\times 80$) and the solidity of August powder particles d Algerian ($\pm 100 \mu\text{m}$ at $\times 80$)

mucilage was freeze-dried. Therefore, the mucilage molecules did not release all bound water even under pressure applied during the freeze-drying procedure. Water molecules are, however, chemically or physically trapped in freeze-dried mucilage powders due to the water holding capacity of mucilage molecules. Thus nourishment for pathogenic microorganisms would be restricted in mucilage powders (Fenema 1996).

Water activity

The water activity (Table 1) in mucilage powders only differed significantly ($p < 0.001$) between months, as it was lower in August (0.29) during the dry season and higher in May (0.38) after the rainy season. Since water activity was consistently below 0.4, there was no degradative fungal, yeast or bacterial growth, meaning that freeze-dried mucilage is safe and unable to support microbial growth (Fenema 1996). Ayadi et al. (2009) reported higher values of 0.762 for spiny and 0.767 for spineless cladode flour.

pH and conductivity

The February RM (3.98) showed significantly ($p < 0.001$) lower pH levels than August RM (4.36), while the pH was not significantly different between the cultivars (Table 1). The pH values below 4.6 ($pH < 4.5$), indicated that the freeze-dried mucilage could not be spoiled by bacteria, but was only susceptible to spoilage by fungi (Brown 2007), although the very low water activity observed in all samples will inhibit fungal growth. Gebresamuel and Gebre-Mariam (2012) reported pH values of 5.57–6.43 in different concentrations (1–12%) of *O. ficus-indica* mucilage dispersions. Dehydrated cladodes harvested at different maturity stages; 60 g (22 days) and 200 g (64 days), had pH values of between 4.07 and 4.35 (Rodríguez-García et al. 2007).

Conductivity values (Table 1) did not differ significantly between cultivars but was significantly higher in February (105.23 mS/cm) and April (103.73 mS/cm) compared to August (86.13 mS/cm) ($p = 0.003$). Mucilage molecules are negatively-charged polyelectrolytes and

depend on electrostatic interactions for their biophysical and hydrodynamic properties (Trachtenberg and Mayer 1981). An abundance of free moving ions when acidity is high could, therefore, reduce the repulsion in the negatively charged mucilage molecules. It was deduced that the lower viscosity observed in February RM was a result of the higher conductivity and the lower pH levels. The viscosity and flow properties of mucilage could, therefore, be manipulated by adding substances containing cations (Dickinson 2003) or by harvesting cladodes when the pH level is at its lowest. Thus, the varied pH and conductivity values observed between months could have a direct influence on mucilage viscosity.

Viscosity

Cultivar had a significant ($p = 0.005$) effect on the viscosity of RM (Du Toit 2017; Du Toit et al. 2019b in press). In Table 1, RM Robusta solutions had significantly higher viscosity (673.33 ± 375.59 cP), while Gymno-Carpo had the lowest viscosity (120.00 ± 95.50 cP). Post-harvest freeze-dried mucilage powders (February and April) from all four cultivars had a lower capacity to increase the viscosity (Fig. 2), as the pH was lower and conductivity higher. As months progressed to winter, the viscosity and pH increased (Fig. 2) while the conductivity decreased (Table 1). The trend of increasing viscosity over months might be attributed to temperature differences between summer and winter. Hot long summer days and warmer nights possibly influence cladode pH, conductivity and thus mucilage viscosity (Du Toit 2017; Du Toit et al. 2019b, in press).

Colour determination

The effect of cultivar and harvest month on the colour determinations of the freeze-dried mucilage powders are given in Table 2. Although no significant cultivar effects were observed for all the colour parameters, the month of harvest had a significant effect on all colour parameters. L^* for February (89.54) and April (87.39) were significantly ($p < 0.001$) higher than May (76.52), June (76.41) and August (76.20), indicating a lighter colour (closer to white) for the freeze-dried mucilage powders. The a^* values (indication of green) showed that February powders (-3.36) were significantly less green than August powders (-6.68). However, b^* for August powders (24.99) were significantly more yellow than July powders (20.96). July powders (21.7) had significantly ($p = 0.041$) lower Chroma values (duller) than August mucilage powders (25.89). The Hue values differed significantly between February powders (97.94°) which were yellow-green and August powders (105.02°) which were a greener colour. The average value of 101.9° for Hue indicated a yellow-green colour. The colour of mucilage powder could be described as dull and light yellow-green. The average colour coordinates reported here correlated roughly with those reported by Sáenz et al. (2012) for unpurified cladode powder at $L^* = 71.6$, $a^* = -5.5$, $b^* = 23.2$, $C^* = 23.8$ and $h^\circ = 103.4$. The brighter, darker and greener colouration observed in August powders might be a result of seasonal changes, because photosynthetic activity increased at the end of winter which lead to higher chlorophyll production. It has been reported that *Opuntia* spp. plants suffered photosynthetic impairment during the extreme cold temperatures in winter months (Ojeda-Pérez et al. 2017). In previous studies, researchers reported an undesirable green colour in baked products when cladode flour was used to replace cake flour (Ayadi et al. 2009). As mucilage

Fig. 2 Viscosity [cP (centipoise)] (single point) of 5% reconstituted mucilage powders extracted from the cladodes of four cultivars harvested over 6 months, measured at 20 rpm

Table 2 Physicochemical properties: lightness (L^*), red/green (a^*), yellow/blue (b^*), chroma (C^*) and hue (h°) of mucilage powder extracted from four cactus pear cultivars harvested from cladodes over 6 months

	L^*	a^*	b^*	C^*	h°
<i>Cultivar</i>					
Algerian	81.70 $\pm$ 8.15	– 4.49 $\pm$ 1.74	22.91 $\pm$ 1.12	23.39 $\pm$ 1.33	101.94 $\pm$ 3.03
Morado	82.14 $\pm$ 7.43	– 4.6 $\pm$ 1.21	23.79 $\pm$ 2.93	24.25 $\pm$ 3.03	100.89 $\pm$ 2.15
Gymno-Carpo	83.00 $\pm$ 8.28	– 4.23 $\pm$ 1.62	23.41 $\pm$ 1.73	23.84 $\pm$ 1.72	100.23 $\pm$ 4.01
Robusta	76.78 $\pm$ 1.75	– 6.07 $\pm$ 1.54	23.65 $\pm$ 1.71	24.47 $\pm$ 1.47	104.54 $\pm$ 4.13
Significance level	($p = 0.424$)	($p = 0.189$)	($p = 0.876$)	($p = 0.798$)	($p = 0.173$)
<i>Harvest month</i>					
February	89.54 $\pm$ 6.68 ^b	– 3.36 $\pm$ 0.37 ^b	24.15 $\pm$ 1.21 ^{ab}	24.39 $\pm$ 1.21 ^{ab}	97.94 $\pm$ 0.91 ^a
April	87.39 $\pm$ 7.57 ^b	– 4.84 $\pm$ 1.39 ^{ab}	23.22 $\pm$ 2.62 ^{ab}	23.76 $\pm$ 2.59 ^{ab}	101.82 $\pm$ 3.57 ^{ab}
May	76.52 $\pm$ 2.26 ^a	– 3.87 $\pm$ 2.13 ^{ab}	23.52 $\pm$ 1.37 ^{ab}	23.90 $\pm$ 1.69 ^{ab}	100.56 $\pm$ 4.13 ^{ab}
June	76.41 $\pm$ 1.03 ^a	– 4.91 $\pm$ 0.34 ^{ab}	23.79 $\pm$ 1.35 ^{ab}	24.30 $\pm$ 1.38 ^{ab}	101.66 $\pm$ 0.53 ^{ab}
July	79.37 $\pm$ 4.16 ^{ab}	– 5.42 $\pm$ 1.83 ^{ab}	20.96 $\pm$ 1.12 ^a	21.70 $\pm$ 1.36 ^a	104.40 $\pm$ 4.35 ^{ab}
August	76.20 $\pm$ 1.73 ^a	– 6.68 $\pm$ 0.87 ^a	24.99 $\pm$ 1.20 ^b	25.89 $\pm$ 1.08 ^b	105.02 $\pm$ 2.28 ^b
Significance level	($p < 0.001$)	($p < 0.036$)	($p = 0.038$)	($p = 0.041$)	($p = 0.042$)
Means	80.91 $\pm$ 6.94	– 4.85 $\pm$ 1.61	23.44 $\pm$ 1.88	23.99 $\pm$ 1.92	101.9 $\pm$ 3.61

Opuntia ficus-indica (Algerian, Morado and Gymno-Carpo), *Opuntia robusta* (Robusta); Cultivar means with different superscripts in the same column differ significantly ($p < 0.05$); Month means with different superscripts in the same column differ significantly ($p < 0.05$)

powders would be used in smaller quantities than cladode flour, the discolouration observed in food products may be limited.

Technological properties

The mean data from all four cultivars are reflected in Sect. 3.2 and Table 3.

Water solubility index (WSI)

The higher the soluble fraction of dietary fibre, the greater the capacity to increase viscosities, act as emulsifiers, reduce the glycaemic index and lower plasma cholesterol in functional food products (Elleuch et al. 2011). Harvest month did not significantly influence the water solubility of freeze-dried mucilage ($p = 0.98$). The average WSI of 78.8% (Table 3) in mucilage powder was higher than that in cladode flour (5.23–27.84%) (Ayadi et al. 2009). Sepúlveda et al. (2007) reported values of between 69.79 and 78.88% for dried mucilage powder.

Water absorption capacity (WAC)

The WAC is the ability of powder particles to retain water when water is withdrawn. Mucilage powder from June (1.66 ml/g) (Table 3) had significantly higher WAC compared to February (0.31 mg/g) and April (0.33 ml/g) ($p = 0.013$). The higher WAC in June powders may be a

result of the higher solids content observed in June powders (Table 1) although not significant, June powders had the highest solids content (86.03%), and February (83.91%) was lower. The average mucilage WAC (0.89 ml/g) was higher than values (0.24 g/g) reported by Sáenz et al. (2012) from four differently purified cladode powders.

Swelling capacity (SW)

The ability of the insoluble fraction of freeze-dried mucilage to swell (Table 3), was not significantly different between months ($p = 0.507$), however, May (2.33 g/g) and June (2.25 g/g) powders had the highest SW while February (1.53 g/g) powder had the lowest SW. The SW of mucilage powder from two species of cactus pear (*O. ficus-indica* and *O. stricta*) was between 3.15 and 9.01 ml/g (Gebresamuel and Gebre-Mariam 2012). Sepúlveda et al. (2013) found SW values for flour from unpeeled and peeled cladodes to be 5.86 ml/g and 6.49 ml/g respectively. Sáenz et al. (2012) determined SW to be 7.02–8.27 ml/g in purified cladode flour.

Water holding capacity (WHC)

Flour or powders that entrap and control the movement of water molecules, improve the textural quality of food products (Fenema 1996). Mucilage harvested in April (3.61 ml/g) had significantly lower WHC values

Table 3 Technological properties: protein content, water solubility index, water absorption capacity, swelling capacity, water holding capacity, oil absorption capacity and oil holding capacity, foaming (5% RM) and emulsification capacity (5% RM) of mucilage powder extracted from cactus pear cladodes harvested over 6 months

Harvest month	Chemical content Protein content g/100 g	Technological properties					Foaming			
		Water solubility index (%)	Water absorption capacity (ml/g)	Swelling capacity (g/g)	Water holding capacity (ml/g)	Oil absorption capacity (g/g)	Oil holding capacity (ml/g)	10 s (%)	2 min (%)	12 min (%)
February	3.40 ± 1.20	79.90 ± 11.57	0.31 ± 0.32 ^a	1.53 ± 0.68	5.29 ± 1.13 ^{ab}	4.79 ± 0.32 ^b	1.78 ± 0.21 ^b	16.25 ± 2.50	8.75 ± 8.54	0.00 ± 0.00 ^a
April	3.30 ± 1.36	79.73 ± 3.77	0.33 ± 0.10 ^a	1.97 ± 0.44	3.61 ± 0.59 ^a	3.45 ± 0.48 ^a	1.02 ± 0.38 ^a	13.75 ± 6.29	10.00 ± 7.36	1.88 ± 2.39 ^{ab}
May	3.94 ± 1.28	78.07 ± 7.83	1.05 ± 0.92 ^{ab}	2.33 ± 0.24	6.41 ± 1.67 ^{ab}	3.36 ± 0.76 ^a	0.94 ± 0.25 ^a	22.50 ± 19.36	5.00 ± 3.54	4.38 ± 3.15 ^{ab}
June	3.35 ± 0.53	78.40 ± 5.90	1.66 ± 0.54 ^b	2.25 ± 0.59	7.24 ± 1.57 ^{ab}	3.07 ± 0.28 ^a	0.99 ± 0.17 ^a	18.13 ± 5.54	7.50 ± 6.77	8.13 ± 8.00 ^b
July	3.28 ± 0.71	80.05 ± 1.63	0.95 ± 0.52 ^{ab}	2.04 ± 0.94	9.99 ± 4.28 ^{ab}	3.11 ± 0.21 ^a	1.18 ± 0.38 ^{ab}	16.25 ± 4.79	0.00 ± 0.00	0.00 ± 0.00 ^a
August	3.39 ± 0.60	76.65 ± 7.63	1.02 ± 0.12 ^{ab}	1.86 ± 0.51	15.69 ± 10.93 ^b	3.58 ± 0.15 ^a	1.43 ± 0.22 ^{ab}	25.00 ± 50.00	1.25 ± 2.50	0.00 ± 0.00 ^a
Significance level	(<i>p</i> = 0.937)	(<i>p</i> = 0.980)	(<i>p</i> = 0.013)	(<i>p</i> = 0.507)	(<i>p</i> = 0.035)	(<i>p</i> < 0.001)	(<i>p</i> = 0.003)	(<i>p</i> = 0.978)	(<i>p</i> = 0.114)	(<i>p</i> = 0.028)
Means	3.44 ± 0.92	78.80 ± 6.43	0.89 ± 0.65	2.00 ± 0.60	8.04 ± 5.92	3.56 ± 0.70	1.22 ± 0.39	18.65 ± 20.09	5.42 ± 6.28	2.40 ± 4.45
Harvest month										
Emulsification										
20 s (%)										
February		94.29 ± 5.29 ^a			93.09 ± 4.80 ^{ab}		86.81 ± 6.81 ^{ab}			85.10 ± 4.06 ^{ab}
April		95.67 ± 3.70 ^a			90.35 ± 6.83 ^a		74.69 ± 20.27 ^a			78.59 ± 9.82 ^a
May		100.00 ± 0.00 ^b			99.75 ± 0.50 ^b		97.70 ± 2.80 ^b			93.40 ± 3.78 ^b
June		100.00 ± 0.00 ^b			99.62 ± 0.48 ^b		95.75 ± 3.58 ^b			87.16 ± 2.12 ^{ab}
July		99.93 ± 0.15 ^b			99.82 ± 0.22 ^b		95.65 ± 3.72 ^b			90.21 ± 5.35 ^{ab}
August		100.00 ± 0.00 ^b			100.00 ± 0.00 ^b		98.21 ± 3.57 ^b			92.27 ± 3.74 ^b
Significance level		(<i>p</i> = 0.014)			(<i>p</i> = 0.002)		(<i>p</i> = 0.013)			(<i>p</i> = 0.011)
Means		98.31 ± 3.38			97.11 ± 4.99		91.47 ± 11.81			87.79 ± 6.98

RM = Reconstituted mucilage; Month means with different superscripts in the same column differ significantly (*p* < 0.05)

($p = 0.035$) than those harvested in August (15.69 ml/g). The low WHC observed in April and February may be attributed to the low solids content, low pH, high conductivity and low viscosity of the mucilage powders from these 2 months (Tables 1, 3). The difference between February and April (Table 3) powders may be connected to the more porous February particles, which increases surface area and thus WHC. The significantly higher pH, lower conductivity and higher viscosity may be responsible for the significantly higher WHC in August powders (15.69 ml/g) (Table 3). The average WHC (8.04 ml/g) (Table 3) compared well with values obtained for cladode flour in other studies, indicating its potential for use in commercial products containing high water content. Sepúlveda et al. (2013) obtained values of 10.22 and 10.08 g/g for whole and peeled cladode flour respectively, while Sáenz et al. (2012) reported 5.41–5.86 g/g after different purification treatments. López-Cervantes et al. (2011) demonstrated exceptional WHC between 6.48 and 14.44 g/g and concluded that cladode flours could be used to improve the texture of foods such as baked goods and desserts.

Oil absorption capacity (OAC)

The capacity of fibre (such as mucilage) to bind fats, depend more on porosity, surface properties, density and particle size than on its molecular structure. This capacity relates to the good mouthfeel and flavour of food products (Fenema 1996; Cui and Roberts 2009). In February, the mucilage powders demonstrated significantly higher ($p < 0.001$) OAC (4.79 g/g) compared to all the other months, possibly because of the porous nature of all February cultivars (as discussed in Sect. 3.1.1) and the higher surface area of particles (Elleuch et al. 2011). Sepúlveda et al. (2013) reported lower OAC results of 1.48 and 1.34 g/g for whole and peeled cladode flour respectively. Sáenz et al. (2012) determined lower values of between 1.29 and 1.95 g/g for differently purified mucilage powders. Ayadi et al. (2009) also reported lower results (1.29 g/g) for spiny and (1.31 g/g) spineless cladode flour.

Oil holding capacity (OHC)

The OHC of flours or powders is associated with enhanced flavour, because the mouthfeel is improved (Fenema 1996) and high-fat products and emulsions are stabilized with increased OHC (Elleuch et al. 2011). In Table 3, February mucilage powders (1.78 ml/g) had significantly ($p = 0.003$) higher ability to hold oil than April (1.02 ml/g), May (0.94 ml/g) and June (0.99 ml/g) mucilage powders, which were not significantly different from each other, presumably for similar reasons mentioned for OAC

(porosity of powder). The mucilage powders harvested in July (1.18 ml/g) and August (1.13 ml/g) showed a slight recovery in OHC. Values similar to the means reported in this study (1.22 ml/g) were reported for spiny and spineless cladode flour (1.29 and 1.21 g fat/g) (Ayadi et al. 2009). A positive correlation ($r = 0.87$) between OHC and OAC values were observed. Thus, mucilage powders from cladodes harvested in the early post-harvest or late dormant (warmer) months may demonstrate better hydrophobic properties.

Protein content

Protein is indispensable for the formation of foams and emulsions as it acts on the air–water or oil–water interface (surfactant) to form a highly viscoelastic film, which can withstand mechanical shock and gravity (Fenema 1996). The protein content in mucilage powders ranged from 3.28 to 3.64 g/100 g and did not differ significantly over the 6 months of harvest (Table 3). The protein content of Robusta (4.8/100 g) was significantly ($p < 0.001$) higher than the three *O. ficus-indica* (2.7–3.2/100 g) cultivars (Du Toit et al. 2018).

Foaming capacity and stability

Foaming capacity is the amount of foam formed immediately after agitation while foam stability is determined over predetermined time intervals. After 10 s of agitation, only 18.65% of all the samples were foamy (Table 3). Of all the samples tested, only the August Robusta mucilage sample had 100% foam volume (significantly different) 10 s after agitation, yet the foam bubbles were large, unstable and disappeared instantly (data not shown). After 2 and 12 min of agitation, the average foam volume decreased to 5.42% and 2.4% respectively (Table 3). June mucilage (highest solids content) (Table 1) had significantly higher foaming ability after 12 min (8.13%) than February (0%), July (0%) and August (0%) mucilage while May (4.38%) and April (1.88%) showed very little foaming abilities. It was concluded that overall, the 5% RM did not have foaming stability.

Emulsifying capacity and stability

The protein detected in mucilage powders may provide the ability for emulsifying activity (Du Toit et al. 2018). According to Du Toit (2017) and Du Toit et al. (2019a in press), Robusta was named the best, of the four tested cultivars, for emulsification capacity and stability as emulsifying ability and stability results showed 93.24% emulsified layer in relation to the original volume after 24 h. Of the four cultivars tested, Robusta mucilage had the

Table 4 Technological properties: sensory panel evaluation of the application of mucilage powder as emulsifying (replace egg yolk 25%, 50% and 100%) and fat-replacing (replace sunflower oil 15% and 30%) agent in mayonnaise-type products

Sample replacement	Control	Egg yolk 25%	Egg yolk 50%	Egg yolk 100%	Oil 15%	Oil 30%
Appearance	6.38 ^c ± 1.66	7.34 ^d ± 1.08	6.84 ^{cd} ± 1.35	2.76 ^a ± 1.72	6.26 ^c ± 1.59	5.28 ^b ± 1.98
Taste	5.68 ^{bc} ± 2.04	7.00 ^d ± 1.32	6.28 ^c ± 1.68	4.20 ^a ± 1.87	4.98 ^b ± 2.00	5.90 ^c ± 1.67
Overall acceptability	5.98 ^{bc} ± 1.87	7.18 ^d ± 1.10	6.46 ^c ± 1.47	3.74 ^a ± 1.99	5.40 ^b ± 1.86	5.80 ^{bc} ± 1.70

Significance level $p < 0001$. Means with different superscripts in the same row differ significantly

highest protein content (4.79 g/100 g). The good emulsification ability and stability observed in Robusta mucilage was attributed to the higher viscosity and higher protein content compared to the other three cultivars.

In terms of harvest month (Table 3), after 20 s, mucilage from February and April (94.29 and 95.67%) had significantly lower emulsifying capacities than the other months (May to August), possibly because of the lower viscosity mucilage. The overall average emulsifying capacity was 98.31% after 20 s (Table 3). Five minutes after homogenization, April samples had significantly ($p = 0.002$) lower emulsification capacity (90.35%) than May (99.75%), June (99.62%), July (99.82%) and August (100%). After 60 min, May to August samples had significantly higher ($p = 0.013$) emulsifying capacity (97.70–98.21%) than April samples (74.69%), but not significantly higher ($p = 0.013$) than the February samples (86.81%) (Table 3). After 24 h, the means of the samples which contained the highest protein content in May (3.94 g/100 g) and August (3.39 g/100 g), also demonstrated significantly high emulsifying capacity (May 93.40% and August 92.27%). In comparison, April powders had the lowest emulsifying stability (78.59%) as well as the lowest protein content (3.30 g/100 g) (Table 3). Iturriaga et al. (2009) showed that mucilage had potentially good emulsification properties. Native mucilage (2% solution) reportedly had 90.77% emulsion capability and 90% stability while freeze-dried mucilage (10% solution) had 100% capacity.

Technological properties: application of mucilage as an emulsifying and fat-replacing agent in mayonnaise-type products

Egg (25%, 50% and 100%) or sunflower oil (15% and 30%) were replaced with Robusta mucilage, harvested in August, in mayonnaise-type products which were served to a sensory panel in potato salads to determine the emulsifying and fat-replacing capacity and consumer acceptability of mucilage. According to a previous study, Robusta mucilage has been successfully applied before in

mayonnaise-like products (Bernardino-Nicanor et al. 2015) using 26.79% oil, 62.50% mucilage and 10.71% whey protein.

In the sensory evaluation tests, 25% egg replacement mayonnaise received significantly higher scores from panellists than the control in terms of all attributes (Table 4). The appearance of 25% egg replacement mayonnaise was significantly higher than the control, while 50% and 15% egg replacement mayonnaise were comparable with the control. The appearance of 100% egg replacement mayonnaise was rated significantly lower than all the other samples. The 25% egg replacement mayonnaise tasted significantly better than all the other samples. Therefore, panellists experienced the acidity of the products positively and rated the products higher. The 100% egg replacement mayonnaise was rated significantly lower (“dislike slightly”). The sensory panellists perceived the 15% oil replacement mayonnaise and 30% oil replacement mayonnaise positively. The 30% oil replacement mayonnaise received slightly higher ratings for taste than the control, while the 15% oil replacement mayonnaise was comparable to the control in terms of appearance. In terms of taste (Table 4), a surprising result was observed with the 30% oil replacement mayonnaise which was rated significantly better than 15% oil replacement mayonnaise as well as the control.

Conclusion

The cultivar and harvest month significantly influenced the physicochemical and technological properties of cactus pear mucilage. High and low viscosity mucilage have the potential to stabilize, thicken, emulsify and restore textural properties in functional food products. High viscosity *Opuntia robusta* mucilage is recommended for highly viscous emulsified products such as mayonnaise while the low viscosity mucilage obtained from *Opuntia ficus-indica* (Algerian, Morado and Gymno-Carpo) cladodes harvested in high summer is recommended for low-viscosity, emulsified liquid products. Thus, the specification of the product

predetermines the cultivar and the harvest time for optimal mucilage viscosity. Demand for mucilage powders could stimulate the commercial cultivation of the cactus pear as a crop, which could be a valuable prospect for regions with limited farming opportunities.

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References

- Association of Official Analytical Chemists (AOAC) (2000) Official methods of analysis of AOAC International, 17th edn. AOAC, Washington
- ASTM Manual Series: MNL 13 (1992) Manual on descriptive analysis testing for sensory evaluation. Library in Congress Cataloging-in-Publication Data, Philadelphia
- Ayadi MA, Abdelmaksoud W, Ennouri M, Attia H (2009) Cladodes from *Opuntia ficus-indica* as a source of dietary fiber: effect on dough characteristics and cake making. *Ind Crops Prod* 30:40–47. <https://doi.org/10.1016/j.indcrop.2009.01.003>
- Bernardino-Nicanor A, Hinojosa-Hernandez E, Juarez-Goiz JMS et al (2015) Quality of *Opuntia robusta* and its use in development of mayonnaise-like product. *J Food Sci Technol* 52:343–350. <https://doi.org/10.1007/s13197-013-0989-8>
- Brown AC (2007) Understanding food: principles and preparation, 3rd edn. Thomson Wadsworth, Manao
- ColorMine.org (2014) Convert lab to lch. <http://colormine.org/convert/lab-to-lch>. Accessed 7 Dec 2016
- Cui SW, Roberts KT (2009) Dietary fiber—fulfilling the promise of added-value formulation. In: Kasapis S, Norton IT, Ubbink JB (eds) Modern biopolymer science—bridging the divide between fundamental treatise and industrial application, 1st edn. Academic Press Limited, London, pp 399–448
- Dhingra D, Michael M, Rajput H, Patil RT (2012) Dietary fibre in foods: a review. *J Food Sci Technol* 49:255–266. <https://doi.org/10.1007/s13197-011-0365-5>
- Dickinson E (2003) Hydrocolloids at interfaces and the influence on the properties of dispersed systems. *Food Hydrocoll* 17:25–39. [https://doi.org/10.1016/S0268-005X\(01\)00120-5](https://doi.org/10.1016/S0268-005X(01)00120-5)
- Du Toit A (2017) Selection, extraction, characterization and application of mucilage from cactus pear (*Opuntia ficus-indica* and *Opuntia robusta*) cladodes. Ph.D. Thesis. University of the Free State, Bloemfontein, South Africa
- Du Toit A, De Wit M (2011) A process for extracting mucilage from *Opuntia ficus-indica* and *Aloe barbadensis*. South Africa Patent No. PA153178/P
- Du Toit A, De Wit M, Hugo A (2018) Cultivar and harvest month influence the nutrient content of *Opuntia* spp. cactus pear cladode mucilage extracts. *Molecules* 23:916. <https://doi.org/10.3390/molecules23040916>
- Du Toit A, De Wit M, Naudé S et al (2019a) Determination of the functional properties of cactus pear mucilage from cladodes of four South African cultivars. In: Acta horticulture proceedings 9th IC Cactus Cochineal (accepted)
- Du Toit A, De Wit M, Seroto KD et al (2019b) Rheological characterization of cactus pear mucilage for application in nutraceutical food products. In: Acta horticulture proceedings 9th IC Cactus Cochineal (accepted)
- Elleuch M, Bedigian D, Roiseux O et al (2011) Dietary fibre and fibre-rich by-products of food processing: characterisation, technological functionality and commercial applications: a review. *Food Chem* 124:411–421. <https://doi.org/10.1016/j.foodchem.2010.06.077>
- Fenema OR (1996) Food Chemistry, 3rd edn. Marcel Dekker, Madison
- Food and Cookery (1991) Food and cookery, 2nd edn. Government Printer, Pretoria
- Gebresamuel N, Gebre-Mariam T (2012) Comparative physico-chemical characterization of the mucilages of two cactus pears (*Opuntia* spp.) obtained from Mekelle, Northern Ethiopia. *J Biomater Nanobiotechnol* 3:79–86
- Glauert AM (ed) (1974) Practical methods in electron microscopy, 3rd edn. North Holland Publishing Company, Amsterdam
- Iturriaga L, Quinzio C, Corvalan M, Mishima B (2009) Study of the stability at coalescence in mucilage emulsions. In: Acta horticulture proceedings 9th IC Cactus Cochineal, vol 811, pp 427–431
- Kaur M, Singh N (2005) Studies on functional, thermal and pasting properties of flours from different chickpea (*Cicer arietinum* L.) cultivars. *Food Chem* 91:403–411. <https://doi.org/10.1016/j.foodchem.2004.06.015>
- León-Martínez FM, Méndez-Lagunas LL, Rodríguez-Ramírez J (2010) Spray drying of nopal mucilage (*Opuntia ficus-indica*): effects on powder properties and characterization. *Carbohydr Polym* 81:864–870. <https://doi.org/10.1016/j.carbpol.2010.03.061>
- López-Cervantes J, Sánchez-Machado DI, Campas-Baypoli ON, Bueno-Solano C (2011) Functional properties and proximate composition of cactus pear cladodes flours. *Food Sci Technol* 31:654–659. <https://doi.org/10.1590/S0101-20612011000300016>
- Nazareno MA (2013) New insights about medicinal uses and health-beneficial properties of cactus products. In: Acta horticulture proceedings 9th IC Cactus Cochineal, vol 995, pp 237–250
- NCSS 11 Statistical Software (2016) NCSS, LLC. Kaysville, Utah, USA. ncss.com/software/ncss
- Ojeda-Pérez ZZ, Jiménez-Bremont JF, Delgado-Sánchez P (2017) Continuous high and low temperature induced a decrease of photosynthetic activity and changes in the diurnal fluctuations of organic acids in *Opuntia streptacantha*. *PLoS ONE* 12:1–19. <https://doi.org/10.1371/journal.pone.0186540>
- Particle Analytical (2007) Bulk and tapped density. In: Usp30-Nf25. <http://particle.dk/about-particle-analytical/>. Accessed 28 June 2016
- Reeb J, Milota M (1999) Moisture content by the oven-dry method for the industrial testing weight of water. In: West Kiln Association proceedings, pp 66–74
- Rodríguez-García ME, De Lira C, Hernández-Becerra E et al (2007) Physicochemical characterization of nopal pads (*Opuntia ficus-indica*) and dry vacuum nopal powders as a function of the maturation. *Plant Foods Hum Nutr* 62:107–112. <https://doi.org/10.1007/s11130-007-0049-5>
- Sáenz C, Yoong M, Figuerola F et al (2012) Cactus pear cladodes powders as a source of dietary fibre: purification and properties. *Int J Food Sci Nutr* 63:283–289. <https://doi.org/10.3109/09637486.2011.624492>
- Salisbury FB, Ross CW (1992) Plant physiology, 4th edn. Wadsworth Publishing Company, Belmont-California
- Sepúlveda E, Sáenz C, Aliaga E, Aceituno C (2007) Extraction and characterization of mucilage in *Opuntia* spp. *J Arid Environ* 68:534–545
- Sepúlveda E, Gorena T, Chiffelle I, Sáenz C (2013) Effect of the cactus cladodes peeling in the functional, technological and chemical characteristics and bioactive compounds in cactus cladodes powders. In: Acta horticulture proceedings 7th IC Cactus Pear Cochineal, vol 995, pp 269–272

- Smith J, Charter E (2010) Functional food product development. Wiley-Blackwell, Charlottetown
- Trachtenberg S, Mayer AM (1981) Composition and properties of *Opuntia ficus-indica* mucilage. Phytochemistry 20:2665–2668
- World Weather and Climate Information (2016) Bloemfontein, South Africa. <https://weather-and-climate.com/average-monthly->

[Rainfall-Temperature-Sunshine,bloemfontein,South-Africa.](#)

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