

CHEMICAL COMPOSITION OF PEAR CACTUS MUCILAGE AT DIFFERENT MATURITY STAGES

Silvia Viridiana Vargas-Solano¹, Francisco Rodríguez-González^{1*}, Rita Martínez-Velarde¹, Roberto Campos-Mendiola¹, Marco Antonio Hurtado-Salgado¹, Jonathan Muthuswamy Ponniah²

¹ Instituto Politécnico Nacional (IPN). Centro de Desarrollo de Productos Bióticos (CEPROBI). Carretera Yautepec-Jojutla km 6, Calle CEPROBI, No. 8, Colonia San Isidro, Yautepec, Morelos, Mexico. C. P. 62731.

² Instituto Politécnico Nacional (IPN). Centro Interdisciplinario de Investigaciones y Estudios sobre Medio Ambiente y Desarrollo (CIIEMAD). Calle 30 de junio de 1520 s/n, Colonia Barrio la Laguna Ticomán, Gustavo A. Madero, Mexico City, Mexico. C. P. 07340.

* Corresponding author: frrodriguez@ipn.mx

ABSTRACT

The pear cactus (nopal, *Opuntia ficus-indica*) mucilage is a hydrocolloid that it helps to regulate the cellular water content in the plant for survive during long periods drought, is composed mainly of neutral and acidic sugars and the concentration of those can change due to the maturity stages of the cladodes or pear cactus. For this reason, the hypothesis of this work was that the maturity stages of pear cactus mucilage produce change in the chemical composition and the aim of this work was to characterize pear cactus mucilage of three different stages of maturity, namely, tender, young, mature according to their proximal chemical composition, analysis of functional groups, identification, and quantification of sugars as well as the elemental microanalysis of the respective pear cactus. The results showed that the mature pear cactus mucilage exhibited the highest content of ash, fiber, and total sugars, with 34.8, 47.5 and 14.32 g 100 g⁻¹, respectively, and uronic acid with 34.5 %, with respect to the other mucilage. The functional groups identified in the three mucilage (O-H, C-H of methylene, C=O of carboxylic, C-N of amines, and C-O bonds of primary and secondary alcohol) were same, however did show differences in the band intensity between the three mucilage. Chemical elements (minerals) such as potassium, magnesium, calcium, phosphorus, sulfur, silicon, and chlorine were identified in the different pear cactus samples. The content of total sugars, fiber, ash, calcium crystals and uronic acids showed an increase with the increase in the maturity stage of the pear cactus. The results generated could be a potential and relevant for its application in removal of heavy metals present in bodies of water.

Keywords: *Opuntia ficus-indica*, pear cactus, mucilage, maturity stages, chemical composition.

INTRODUCTION

Pear cactus (*Opuntia ficus-indica*) is a plant of the Cactaceae family, cultivated in arid and semi-arid zones and called nopal in Mexico (Contreras *et al.*, 2015), the plant has Crassulacean acid metabolism (CAM), which allows it to be resistant to drought during long periods and growing in arid and semi-arid regions by storing water in

Citation: Vargas-Solano SV, Rodríguez-González F, Martínez-Velarde R, Campos-Mendiola R, Hurtado-Salgado MA, Muthuswamy Ponniah J. 2022. Chemical composition of pear cactus mucilage at different maturity stages. Agrociencia <https://doi.org/10.47163/agrociencia.v56i2.2726>

Editor in Chief:
Dr. Fernando C. Gómez Merino

Received: June 11, 2021
Approved: March 07, 2022.

Estimated publication date:
March 09, 2022.

This work is licensed under a Creative Commons Attribution-Non-Commercial 4.0 International license.



the parenchyma of their cladodes (Nuzhyna *et al.*, 2018). For it produce mucilage in their interior (specialized cells) which secrete it into apoplast where it helps to regulate the cellular water content in the plant. Other possible function of mucilage can be relationated with the Ca^{2+} (Goycoolea and Cardenas 2003). On the other hand, the cladodes or pseudo stems in the adulthood stage accumulate calcium in the form of drusen (calcium oxalate crystals), which helps the flow of calcium inside them (Contreras *et al.*, 2015), whereas in the young stage are active for synthesis of proteins, lipids, polysaccharides, and oxalic acid.

The mucilage from pear cactus is a hydrocolloid composed mainly of different sugars such as arabinose, galactose, rhamnose, xylose, galacturonic acid which are present in polymeric form as polygalacturonic acid and others pectic compounds. The presence of polymeric compounds is formed by two or more sugars with different molecular weights varying from 2.3×10^4 to 13×10^6 g mol⁻¹ (Medina-Torres *et al.*, 2013). Moreover, the chemical composition of the mucilage varies depending on factors such as temperature, season, soil, region, light/dark periods, and availability of water as well as age of maturation (Contreras *et al.*, 2015; Ribeiro *et al.*, 2010). Previous studies by different authors with reference to the chemical composition and maturity stage of pear cactus are very limited. The hypothesis of this work was that the maturity stages of pear cactus mucilage produce change in the chemical composition. To test it, the aim was characterize the pear cactus mucilage during the three different stages of maturity (tender, young and mature), which is done based on chemical composition, analysis of functional groups, identification, and quantification of sugars as well as the elemental microanalysis of the respective pear cactus.

MATERIALS AND METHODS

Cladodes from *Opuntia ficus-indica* were cultivated and harvested by producers in a crop of field of Tepoztlan, Morelos, Mexico (18°58'29.3"N; 99°08'10.1"W). The selection and collection of the cladodes was random from different plants in March 2019, during early morning (06:00 am) for not affect the acidity and the taste produced by the malic acid and other acids on the cladode (during the night) and that are reduced in the day due to its metabolic cycle (formation of other compounds), the cladodes were divided in three stages [average in days – tender (T): 20; young (Y): 40; mature (M): 600]. Thorns in the samples were removed with the help of a stainless-steel knife and cladodes were brushed and washed with distilled water and liquid soap to remove all external particles. Extraction of mucilage from different samples of pear cactus was carried out following the method used by Rivera-Corona *et al.* (2014) which was modified during the extraction and purification process. The modification from the previous method was from 1:7 (pear cactus: water) to 1:1 (pear cactus: deionized water) during the extraction, and the purification stage was opted out. The cleaned-up pear cactus was sliced and agitated constantly at 40 °C for 4 h during the leaching process. The leached product was filtered using a 425 µm mesh and stored at 4 °C for 14 h. This was subsequently dried by lyophilization kit (Virtis Consol 25 SL, EUA) at -25 °C with high vacuum for 7 d approximately and the powders were stored in hermetic containers.

Chemical analysis of pear cactus mucilage

Moisture content, ashes, proteins, lipids, and total dietary fiber of dried mucilage (T, Y and M) were determined using the oven drying method (14.004), incineration (32.10), digestion and distillation by the Kjeldahl method (14.026). Likewise, extraction of lipids was done based on Goldfish method (70.56) and enzymatic-gravimetric method (992.16) respectively (AOAC, 2010). In addition, the total sugar content was determined using the phenol-sulfuric colorimetric method (Feitosa *et al.*, 2021).

Fourier Transform Infrared Spectroscopy analysis (FTIR)

The FTIR spectra of the different mucilage powder samples (T, Y and M) were identified to determine the functional groups in an IR-Affinity 1 spectrophotometer (Shimadzu, Japan) which is operated within a range of 600-4000 cm^{-1} with a resolution of 4 cm^{-1} using an ATR plate.

Identification of sugars

The identification of sugars was carried out by High-performance thin layer chromatography HPTLC (Singh *et al.*, 2021). Three microliters of the standard solutions of arabinose, fructose, galactose, glucose, sucrose, rhamnose, xylose, galacturonic acid, glucuronic acid and polygalacturonic acid (3 mg mL^{-1} of deionized water) (Purity \geq 98 %, Sigma-Aldrich, Germany) and 15 μL of the mucilage solutions (6 mg mL^{-1}) was applied semi-automatically (CAMAG Linomat 5, Switzerland) to a silica gel plate F_{254} with aluminum support (20 $\text{cm} \times 10 \text{ cm}$) (Merck, Germany). The plate was developed twice with butanol-propanol-water (3:12:4 v/v/v) and then heated at 180 $^{\circ}\text{C}$ for 20 min, subsequently derivatized with diphenylamine-aniline-acetone-phosphoric acid (1:1:40:7.5 w/v/v/v) and heated for 5 min at 120 $^{\circ}\text{C}$, finally was exposed to visible light and UV (wavelength of 254 and 366 nm) to obtain images by means of Visualizer 2 (CAMAG, Switzerland). The sugars identified by HPTLC of T, Y and M mucilage solutions were detected with the retention factor (Rf) of the bands present in the standard solutions.

Quantification of sugars

The quantification of the water-soluble sugars of the mucilage studied was performed by HPLC, using LC-MS 2020 (Shimadzu, Japan). It is controlled by the CBM-20A system with 2 dual LC-20AD pumps, DDU-20A degasser, SIL-20AC auto-sampler, CTO-20A column furnace, RID-10A refractive index detector. The Prevail™ carbohydrates ES 5u column (250 \times 4.6 mm) (Alltech, EUA) was operated at 30 $^{\circ}\text{C}$ with acetonitrile-ultrapure water (8:2 v/v) as the mobile phase in an isocratic elution with a flow rate of 1 mL min^{-1} to sample volume of 20 μL (software lab solution version 5.0). The detection of these sugars was done at a wavelength of 195 nm and was quantified using a standard curve of arabinose, fructose, galactose, glucose, rhamnose and xylose.

Quantification of uronic acids

The quantification of uronic acid of the different mucilage in solution (2 mg mL^{-1} of distilled water) was analyzed by the colorimetric method with carbazole (Feitosa *et al.*,

2021). Then 100 μL of mucilage in solution was mixed with 6 mL of concentrated H_2SO_4 in a cold and was placed in a boiling water bath for 10 min. The mixture was cooled to room temperature and then 0.4 mL of alcoholic carbazole solution (0.1 %) was added. The absorbance was measured in a UV-160A spectrophotometer (Shimadzu, Japan) at 530 nm (after 30 min) and the concentration was determined with a calibration curve used a galacturonic acid standard (solutions of 0.25 to 1 mg mL^{-1} distilled water) and was made an adjustment of linear regression model with R^2 of 0.998.

Scanning Electron Microscopy (SEM) and micro elemental analysis

A microanalysis of the minerals was carried out in different sections of the fresh pear cactus studied (T, Y and M). The samples were observed in a scanning electron microscope (CARL ZEISS EVO LS 10, Germany) and analyzed with a scattered energy detector (EDX) coupled to the microscope to determine the elemental composition.

Statistical analysis

The experiments of chemical composition, quantification of sugars as well as quantification of uronic acids were carried out in triplicate, for which the results of these are expressed in mean values with a standard deviation \pm . Statistical analyzes were performed using SigmaPlot version 14.0 (Systat Software Inc., 2017). The mean values of the variables studied in the different groups were compared using a one-way analysis of variance followed by a Tukey's multiple range tests assuming a significant difference at $p \leq 0.05$.

RESULTS AND DISCUSSION

Chemical composition of mucilage

Table 1 shows the chemical composition analysis of the mucilage extracted from the *O. ficus-indica* of different maturity stages of growth used in this study were coded as tender (T), young (Y) and mature (M) mucilage. The moisture content in the three mucilage types varied from 4.2 to 5.9 $\text{g } 100 \text{ g}^{-1}$ with differences between M and the other mucilage, these results are close with studies conducted on cactus mucilage (Rivera-

Table 1. Chemical composition of pear cactus (*Opuntia ficus-indica*) mucilage of different maturity stages.

Composition ($\text{g } 100 \text{ g}^{-1}$)	Tender	Young	Mature
Moisture [†]	5.9 \pm 0.4 a	5.3 \pm 0.2 a	4.2 \pm 0.1 b
Protein [†]	15.0 \pm 0.3 a	14.7 \pm 0.2 a	10.1 \pm 0.1 b
Fat [†]	4.4 \pm 0.2 a	4.1 \pm 0.1 a	2.3 \pm 0.1 b
Ash [†]	29.8 \pm 1.3 b	30.1 \pm 0.8 b	34.8 \pm 0.6 a
Total sugars [†]	45.4 \pm 0.3 b	45.3 \pm 0.3 b	47.5 \pm 0.5 a
Fiber [‡]	8.61 \pm 0.1 c	8.97 \pm 0.1 b	13.7 \pm 0.1 a

[†]Mean \pm standard deviation (n = 3). [‡]Mean \pm standard deviation (n = 2). Means in a row with different letters indicate significant difference ($p \leq 0.05$).

Corona *et al.*, 2014). This low moisture content is due to the drying process of the samples. However, in none of these cases there was the total elimination of the water due the water bound to the material produces interactions between the dipole charges of the water and the negative charges of the functional groups of the macromolecules present in the mucilage (Goycoolea and Cardenas 2003).

The highest protein content of mucilage was observed in T and Y (15 g 100 g⁻¹ and 14.7 g 100 g⁻¹, respectively), which showed difference with the M mucilage. Likewise, the same behavior was observed in the fat content for T and Y of 4.4 g 100 g⁻¹ and 4.1 g 100 g⁻¹, respectively. The content of proteins decreased as a function of development due to the variations attributed to the thickening of the cuticle and to the parenchyma expansion in matured pear cactus (Astello-García *et al.*, 2015).

The total sugar content observed in mucilage in our study was 45.4 g 100 g⁻¹ at 47.5 g 100 g⁻¹, with differences between the mature mucilage and the other two mucilage ($p \leq 0.05$). These results are consistent with the necessary requirements for the development and protection of the pear cactus during the dry season (Carpita *et al.*, 2015). Moreover, it was observed that the total sugars are present as the major component in the mucilage with no regard to the age of maturation, which is mainly due to the presence of complex neutral and acidic sugars that form the hydrocolloid. In addition, with reference to the fiber content, the same behavior was observed that sugars by increasing as a function of the age of maturation were different between the T and Y with respect to M mucilage.

The ash content in M mucilage was the highest (34.8 g 100 g⁻¹), indicating a clear difference with the Y and T mucilage (30.1 g 100 g⁻¹ and 29.8 g 100 g⁻¹). The ash content in the mucilage was mainly hard minerals and was a tendency to increase as a function of the maturity stage as reported by Messina *et al.* (2021) for fresh mucilage of *O. ficus-indica* during the seasonal growth period (dormancy to post-fruiting); however, had a lower ash content than the obtained for the mucilage studied.

FTIR analysis

The FTIR spectrum of the three mucilage studied showed spectral bands between the region of 3270-3217 cm⁻¹ (Figure 1), which are due to the stretching (extension) of the O-H bond (hydroxyl group). However, in mature stage mucilage, there is a greater intensity of these bands compared to young and tender mucilage. A similar result is observed in the bands present in the 2932-2926 cm⁻¹ region, which are related to the asymmetric stretching (extension) of the C-H bond of the methylene group (-CH₂). Likewise, the bands observed in the regions of 1714-1709 cm⁻¹, 1599-1595 cm⁻¹ and 1400 cm⁻¹ are related to the vibration of the stretching (extension) of the C=O of the carboxylic acid (RCOOH), these bands showed an intensity higher in the mature mucilage with respect to T and Y mucilages.

Bands detected in 1328-1312 cm⁻¹ and 1256-1250 cm⁻¹ correspond to C-N stretch of amines, were a higher intensity in the bands of T mucilage, while bands identified in 1080 cm⁻¹ and 1040 cm⁻¹ correspond to the vibrations of the stretching (extension) of

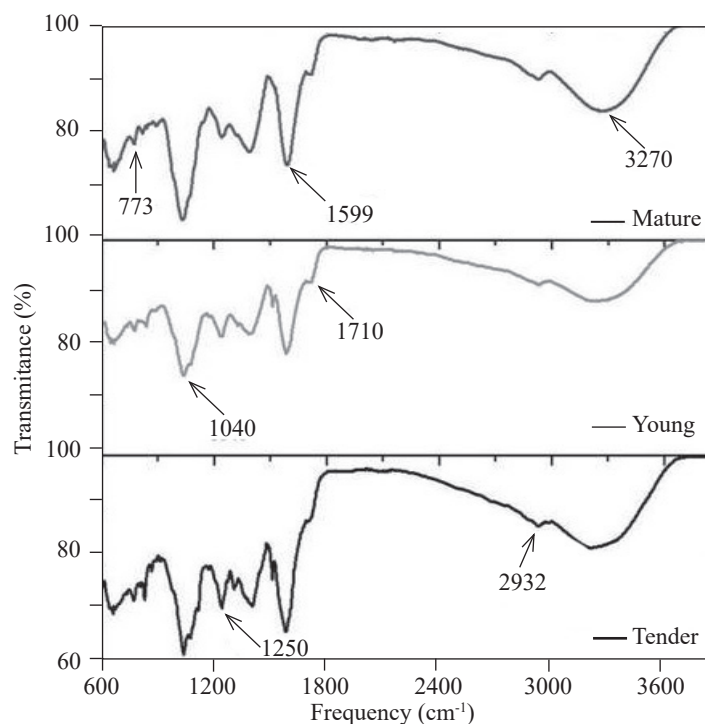


Figure 1. FT-IR spectra of tender, young and mature mucilage of pear cactus (*Opuntia ficus-indica*).

the C-O bonds of primary and secondary alcohol of the pyranose ring were a higher intensity in the bands of mature mucilage, and bands observed in the region of 916-773 cm^{-1} are due to C-H out of plane bend and to monosubstitution (phenyl) on phenolics compounds. The groups identified in this study (O-H, C-H, C=O, C-N, C-O) were also observed by Rivera-Corona *et al.* (2014) for lyophilized pear cactus mucilage, powders and gels of mixtures sorghum starch-mucilage; they observed an increase in the intensity of the bands by increasing the concentration of mucilage in the mixtures, this result was attributed to the increase in functional groups due to the increase in the concentration of mucilage. Therefore, a greater intensity of the bands of the functional groups C=O, C-H and O-H of the mature mucilage could be due to the higher content of uronic compounds.

Identification of sugars

The T, Y and M mucilage by HPTLC had glucose and fructose in their composition (Figure 2), as expected because these sugars are generated by the biochemical reactions of the plant, derived from the metabolic pathway called glycolysis (Carpita *et al.*, 2015). In addition, xylose, galacturonic acid and polygalacturonic acid were also identified in the mucilage. This last compound was detected near the application line, that is, it interacted with the silica gel on the plate. This result indicates that the compound is

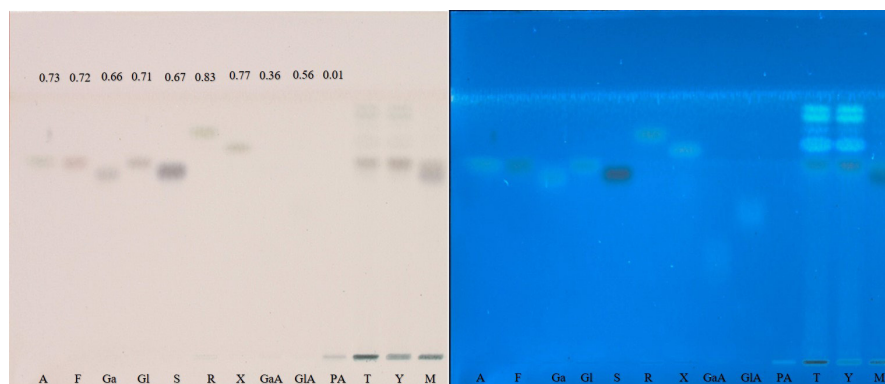


Figure 2. Typical HPTLC chromatograms of sugars of pear cactus mucilage of different maturity stages. Arabinose (A), fructose (F), galactose (Ga), glucose (Gl), sucrose (S), rhamnose (R), xylose (X), galacturonic acid (GaA), glucuronic acid (GLA) and polygalacturonic acid (PA), tender (T), young (Y) and mature (M).

polar due to the high content of hydroxyl groups (-OH) that it presents in its molecules. Likewise, in the M mucilage was identified galactose while rhamnose was detected for Y and T mucilage.

Quantification of sugars

The identification of the different sugars was done by comparing the retention time of the standards with those of the mucilage studied (T, Y and M) and quantified using the standard curve of the sugars; the results of the quantification of sugars of the three mucilages are shown in Figure 3. The highest content of arabinose, glucose and fructose was observed in Y mucilage with 0.55, 168.3 and 4.2 mg g⁻¹, respectively, while the first sugars mentioned was not detected in T mucilage (Figure 3). The presence and variations in the concentration of glucose and arabinose in the different mucilage is consistent with the reported by Ribeiro *et al.* (2010) for a fraction of high weight of peeled pear cactus aged between six and twelve months, they obtained different concentrations of the sugars and compounds of different molecular weight.

However, the highest content of galactose, rhamnose and xylose was present in the T mucilage with 86.4, 84.9 and 193.8 mg g⁻¹ respectively, indicating differences with Y and M mucilage, the decreasing of galactose with the maturity stages could be attributed to the oxidation of C6 for the formation of galacturonic acid. The higher galactose content in Y mucilage and decreasing in mature mucilage was reported for *O. ficus-indica* of the Giant palm variety by Ribeiro *et al.* (2010), it was also observed that the T mucilage had the highest content of neutral sugars and these compounds decreased as a function of the maturation age. Therefore, variations in the content of these sugars in pear cactus mucilage at different maturation ages were due to the variety and requirements of the plant for the formation of other primary or secondary metabolites necessary for the maturation stages of the cactus. For example, the reduction of the

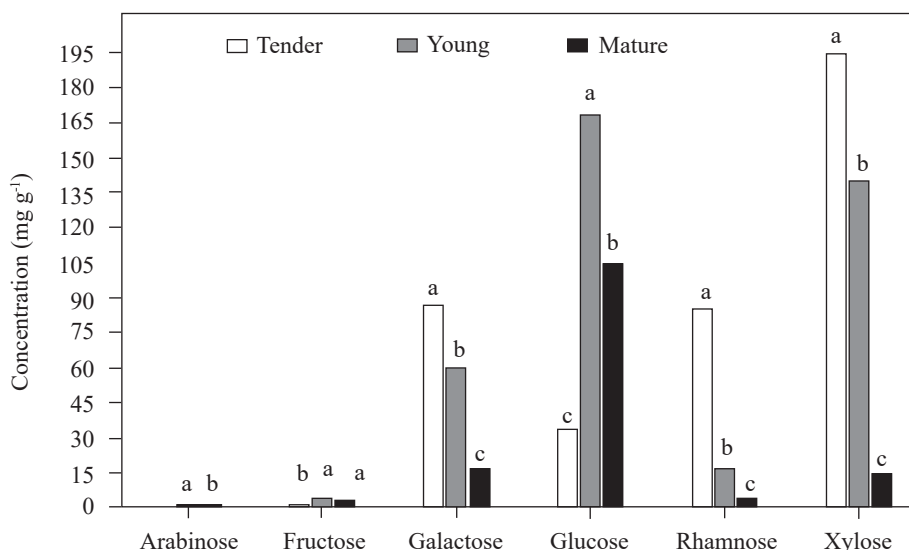


Figure 3. Concentration of sugars of mucilage of pear cactus (*Opuntia ficus-indica*) at different maturity stages. Means in a row with different letters indicate statistical difference ($p \leq 0.05$).

simple sugars content in the M mucilage could be due to the metabolism in the plant for reproduction, which after 360 d of maturation is specialized in the production of flowers and fruits. The cladodes with more than 600 d of maturation often form and develop new cladodes in the plant (Nuzhyna *et al.*, 2018). According to the results of Di Lorenzo *et al.* (2017) for the case of pear cactus mucilage, these sugars form polymeric components of high molecular weight, a linear one called β -(1 \rightarrow 4)-galactans (galactopyranose) and a branched one called xyloarabinane composed of α -(1 \rightarrow 5) Arabinofuranosyl skeleton linked with additional arabinofuranosyl residues and the presence of xylose units as protecting groups for the plant.

Uronic acids

The content of uronic acids is higher in the M mucilage (345.8 mg g⁻¹) and it showed differences in the content of these compounds with Y and T mucilage (112.9 and 100.7 mg g⁻¹, respectively). In addition, the concentration of uronic acids was quantified in the mucilage which increases with the maturity stages of the pear cactus. On the other hand, the uronic acid content for the three mucilage studied was between the interval for the pear cactus mucilage purified with isopropanol (11.64 %) and total pectin fraction (60.66 %) (Bayar *et al.*, 2016). The result of the increase in the uronic acids content with maturity stage is like the reported for the purified mucilage of young and mature age of different *O. ficus-indica* variety (Ribeiro *et al.*, 2010).

The increasing tendency in the uronic acids content and decreasing in the content of galactose, rhamnose and xylose as a function of the maturity stage of *O. ficus-indica* can be related to the requirements of the plant for other functions. For example, in the

synthesis of sugars forming polysaccharides of rhamnogalacturonanes type that form the mucilaginous substances or also called pectics in the primary cell wall (Vriesmann and de Oliveira, 2017), have the main function of retaining or storing the water to survive in drought conditions for long periods (Bayar *et al.*, 2016).

However, after a short, elapsed period the developed plant has other requirements (after 37 d) like reducing the synthesis of pectin substances, the increasing in the concentration of acidic sugars for the formation of hemicellulose (composed of neutral and acidic sugars). Those are deposited together with the cellulose and lignin in the secondary cell wall, generating a thickening of the wall that results in greater support and rigidity in the mature plant (Nuzhyna *et al.*, 2018).

SEM and elemental microanalysis

The images obtained with SEM of the pear cactus in different maturation stages showed that the crystals are immersed in the interior of the cactus samples, and they present a cubic shape (Figure 4 a-c). The size of the crystals varies between 1.6 to 5.8 μm and it was mainly observed in the M pear cactus samples; followed by the Y and finally the T (Figure 4c). Based on the above differences in crystals identified as calcium carbonate salt (CaCO_3) (Contreras *et al.*, 2015), it is considered that the quantity of crystals increased as a function of the maturity age of this pear cactus and was related to the increase of ash content. In addition, it can be observed the morphology of fragments of calcium oxalate crystals and structures formed by the union of drusen that corresponds to a star or rosette shape with sharp peaks which have sizes between 10 and 30 μm and decreased as the cactus matures.

The decrease in oxalates and the increase in CaCO_3 suggests that the plant had a bidirectional calcium regulation mechanism. Which consisted in the fragmentation of druses by enzymatic action when the plant needed carbon dioxide or calcium available. This process was stopped when the plant had an excess of calcium (CaCO_3) and these crystals were added to generate again oxalates as a reserve of calcium. Therefore, the increase of the crystals of cubic shape and the reduction of druses in plants with around 100 d of maturation suggest that this behavior is due to the plant biochemical process for the opening and closing events of the stomata, which

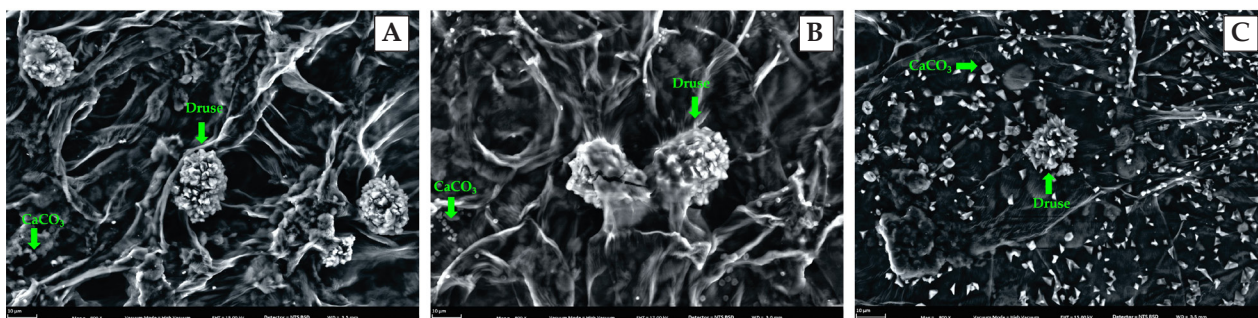


Figure 4. SEM images of calcium structures of pear cactus (*Opuntia ficus-indica*). A) Tender pear cactus; B) Young pear cactus; C) Mature pear cactus.

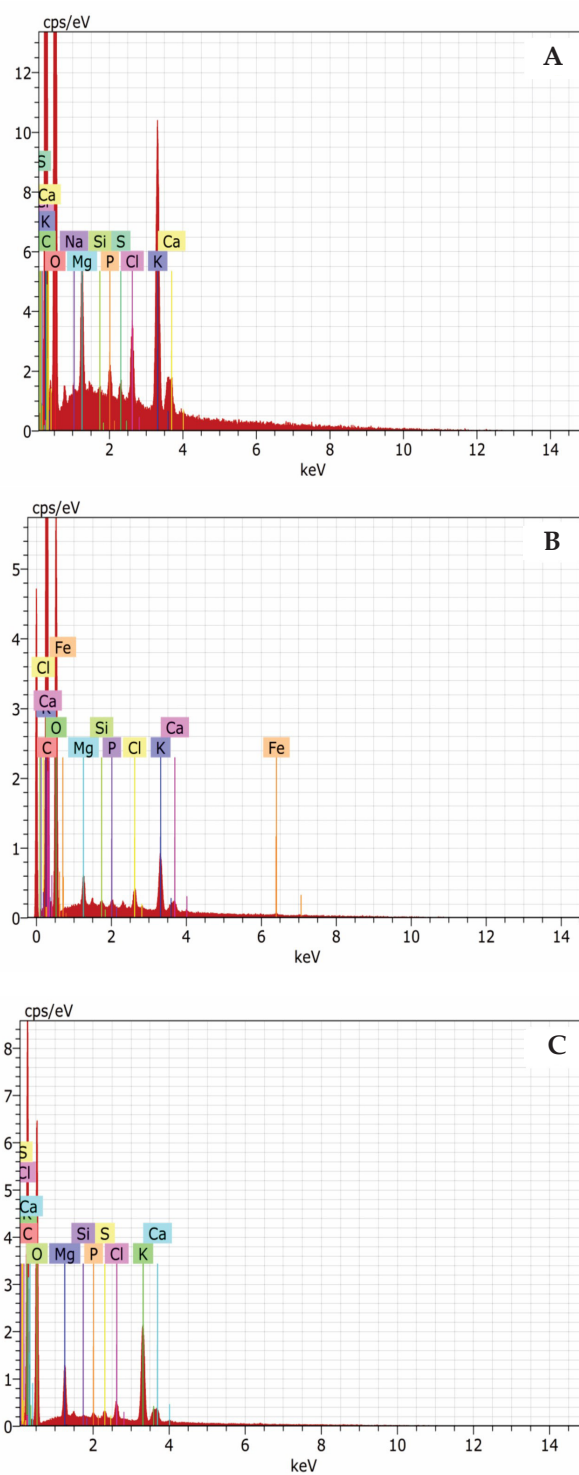


Figure 5. Elemental microanalyses of pear cactus (*Opuntia ficus-indica*) at different maturity stages. A) Tender pear cactus; B) Young pear cactus; C) Mature pear cactus.

must be closed during the day for avoiding gas exchange and water loss, due to the Crassulacean acid metabolism (CAM) (Nuzhyna *et al.*, 2018).

The images of the elemental microanalysis of cactus samples at different maturity stages confirmed the presence of potassium, magnesium, calcium, phosphorus, sulfur, silicon and chlorine (T, Y and M pear cactus in Figure 5a, b and c, respectively). In addition, presence of sodium in the T pear cactus and iron in the Y pear cactus is also observed. These identified elements, except sulfur, silicon and chlorine are the main minerals identified in the analyzed *Opuntia* species (*O. ficus-indica*, *O. hyptiacantha*, *O. megacantha*) (Astello-García *et al.*, 2015). The presence of calcium in pear cactus is related with the calcium oxalates observed in figure 4 and which act as a response to various abiotic and biotic factors, while magnesium is an essential element for the composition of chlorophyll, which is essential for the photosynthesis process.

CONCLUSIONS

The study of pear cactus mucilage of different maturity stage showed change in the chemical composition, decreasing the protein content, ether extract and sugars such as galactose, rhamnose and xylose, and increasing the content of total sugars, fiber, ash, calcium crystals and uronic acids as a function of maturity stages (tender mucilage to mature mucilage) due to the requirements biochemical of the plant.

The mucilage extracted from mature pear cactus exhibited the higher content of galacturonic acids and was confirmed with the FT-IR technique, which showed qualitatively with the intensity in the bands that the mature mucilage contained more functional groups related to uronic acids.

The element potassium, magnesium, and calcium were identified in prickly pear cactus *O. ficus-indica*.

The study the composition of pear cactus mucilage at different maturity stages is important to exploit its use in the industry according to the properties given by its compounds and required in each product.

ACKNOWLEDGMENTS

To Secretaría de Investigación y Posgrado of Instituto Politécnico Nacional (IPN), for the financial support of the research allowed to F. Rodríguez-González through the projects SIP-IPN No. 20210224. To Sistema Nacional de Investigadores (SNI) under the Consejo Nacional de Ciencia y Tecnología (CONACyT), and COFAA & EDI of IPN, Mexico.

REFERENCES

- AOAC (Association of Official Analytical Chemists). 2010. Official Methods of analysis. 15th ed. AOAC International: Arlington, VA, USA. 1298 p.
- Astello-García MG, Cervantes I, Nair V, Santos D MS, Reyes-Agüero A, Guéraud F, Negre-Salvayre A, Rossignol M, Cisneros-Zevallos L, Barba de la Rosa AP. 2015. Chemical composition and phenolic compounds profile of cladodes from *Opuntia* spp. cultivars with different domestication gradient. *Journal of Food Composition and Analysis* 43: 119–130. <https://doi.org/10.1016/j.jfca.2015.04.016>
- Bayar N, Kriaa M, Kammoun R. 2016. Extraction and characterization of three polysaccharides extracted from *Opuntia ficus indica* cladodes. *International Journal of Biological Macromolecules* 92: 441–450. <https://doi.org/10.1016/j.ijbiomac.2016.07.042>

- Carpita N, Ralph CJ, McCann MC. 2015. The cell wall. *In*: Buchanan BB, Gruissem W, Jones RL. (eds). *Biochemistry & Molecular Biology of Plants*. The American Society of Plant Physiologists. Maryland. pp: 45–110.
- Contreras-Padilla M, Rivera-Muñoz EM, Gutiérrez-Cortez E, del Real-López A, Rodríguez-García ME. 2015. Characterization of crystalline structures in *Opuntia ficus-indica*. *Journal of Biological Physics* 41: 99–112. <https://doi.org/10.1007/s10867-014-9368-6>
- Di Lorenzo F, Silipo A, Molinaro A, Parrilli M, Schiraldi C, D'Agostino A, Izzo E, Rizza L, Bonina A, Bonina F, Lanzetta R. 2017. The polysaccharide and low molecular weight components of *Opuntia ficus indica* cladodes: Structure and skin repairing properties. *Carbohydrate Polymers* 157: 128–136. <https://doi.org/10.1016/j.carbpol.2016.09.073>
- Feitosa B, Freitas DA, da Silva JNR, Gonçalves M. de Freitas A, Assreuy AM. 2021. Polysaccharide-rich extract of *Caesalpinia férrea* stem barks attenuates mice acute inflammation induced by zymosan: Oxidative stress modulation. *Journal of Ethnopharmacology* 267: 113501. <https://doi.org/10.1016/j.jep.2020.113501>.
- Goycoolea FM, Cárdenas A. 2003. Pectins from *Opuntia spp.*: A short Review. *Journal of the Professional Association for Cactus Development* 5: 17–29. <https://www.jpacd.org/jpacd/article/view/302/261>
- Medina-Torres L, García-Cruz EE, Calderas F, González-Laredo RF, Sánchez-Olivares G, Gallegos-Infante JA, Rocha-Guzmán NE, Rodríguez-Ramírez J. 2013. Microencapsulation by spray drying of gallic acid with nopal mucilage (*Opuntia ficus-indica*). *LWT - Food Science and Technology* 50: 642–650. <https://doi.org/10.1016/j.lwt.2012.07.038>
- Messina CM, Arena R, Morghese M, Santulli A, Liguori G, Inglese P. 2021. Seasonal characterization of nutritional and antioxidant properties of *Opuntia ficus-indica* [(L.) Mill.] mucilage. *Food Hydrocolloids* 111: 106398. <https://doi.org/10.1016/j.foodhyd.2020.106398>
- Nuzhyna N, Baglay K, Golubenko A, Lushchak O. 2018. Anatomically distinct representatives of Cactaceae Juss. family have different response to acute heat shock stress. *Flora*. 242: 137–145. <https://doi.org/10.1016/j.flora.2018.03.014>
- Ribeiro EM, da Silva NE, de Lima JL, de Brito JZ, Carvalho da Silva MP. 2010. Study of carbohydrates present in the cladodes of *Opuntia ficus-indica* (fodder palm), according to age and season. *Ciência e Tecnologia de Alimentos* 30: 933–939. <https://doi.org/10.1590/S0101-20612010000400015>
- Rivera-Corona JL, Rodríguez-González F, Rendón-Villalobos R, García-Hernández E, Solorza-Feria J. 2014. Thermal, structural and rheological properties of sorghum starch with cactus mucilage addition. *LWT - Food Science and Technology* 59: 806–812. <https://doi.org/10.1016/j.lwt.2014.06.011>
- Systat Software Inc. 2017. Procedure Guide, SigmaPlot version 14.0 (computer program). Systat Software Inc, San Jose, California.
- Singh RS, Singh T, Singh D, Kennedy JF. 2021. HPTLC-densitometry quantification of fructooligosaccharides from inulin hydrolysate. *International Journal of Biological Macromolecules* 177: 221–228. <https://doi.org/10.1016/j.ijbiomac.2021.02.116>
- Vriesmann LC, de Oliveira CL. 2017. Cacao pod husks as a source of low-methoxyl, highly acetylated pectins able to gel in acid media. *International Journal of Biological Macromolecules* 101: 146–152. <https://doi.org/10.1016/j.ijbiomac.2017.03.082>