



Mineral profile determination by ICP-MS and physicochemical evaluation of cultivated and wild Algerian *Opuntia* species

Fares Boudjouan^{1,2} · Walid Zeghibib^{3,4} · Graciliana Lopes⁴ · Edgar Pinto⁵ · Agostinho Almeida⁶ · Vítor Vasconcelos^{4,7}

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Abstract

Opuntia is a well-known plant for its folkloric use and nutritional composition. This work aimed to evaluate the physicochemical characteristics, as well as the mineral composition realized by inductively coupled plasma-mass spectrometry (ICP-MS) for cultivated and wild Algerian *Opuntia* species. The results showed a significant difference in length, diameter, and weight between both *Opuntia* fruits. The highest pH, brix°, and total sugar content were found in the pulp of cultivated fruit compared to the wild one. Moisture was found to be higher in pulp of both species with more than 90% compared to their seeds (33%); however, ashes content was more determined in seeds with 1.04%. Moreover, high protein content was found in wild *Opuntia* parts (more than 200 mg bovine serum albumin equivalent/100 g dry matter), which also presented higher ascorbic acid and betalain contents, particularly in the pulp with 211.45 mg EAA/100 g DM and 312.91 mg/100 g DM, respectively, compared to the cultivated *Opuntia*. Finally, the mineral profile revealed a significant countenance of all species' fractions in many important minerals for human organism functioning, like iron, magnesium, zinc, and potassium.

Keywords *Opuntia* species · Fruit fractions · Physicochemical characteristic · Nutritional composition · Mineral profile

Introduction

Natural products have received a lot of attention from health professionals for an overall well-being improvement and prevention of diseases. Accordingly, all kinds of fruits and vegetables have been reevaluated and recognized as rich and valuable sources of nutrients, endowed with potential multi-functional properties.

The *Cactaceae* family is constituted by a group of plants growing generally in warm arid regions (Zeghibib et al.

2022a). Among its almost 150 genera, the *Opuntia* genus, commonly known as prickly pear cactus, regroups almost 300 species that produce pleasant-tasting fruits and edible cladodes consumed as vegetables (Santos-Zea et al. 2011; Boudjouan et al. 2022). The *Opuntia* species are not newly known plants; on the contrary, evidence has shown their long-term relationship with human culture (Zeghibib et al. 2022b). Their cultivation was not only practiced for domestic purposes, consumption, or to prevent soil erosion, but also in folk medication, as a powerful antidiarrheal and

✉ Fares Boudjouan
fares.boudjouan@univ-bejaia.dz

¹ Université de Bejaia, Faculté de Technologie, Laboratoire de Génie de l'Environnement, Université de Bejaia, 06000 Bejaia, Algeria

² Université de Bejaia, Faculté des Sciences de la Nature et de la Vie, Département de Biotechnologie, Université de Bejaia, 06000 Bejaia, Algeria

³ Laboratoire de Biochimie Appliquée, Faculté des Sciences de la Nature et de la Vie, Université de Bejaia, 06000 Bejaia, Algeria

⁴ CIIMAR – Interdisciplinary Centre of Marine and Environmental Research, Terminal de Cruzeiros

de Leixões, Avenida General Norton de Matos s/n, 4450-208 Matosinhos, Portugal

⁵ Department of Environmental Health, School of Health, REQUIMTE/LAQV, Escola Superior de Saúde, Instituto Politécnico do Porto, Rua Dr. António Bernardino de Almeida, 4200-072 Porto, Portugal

⁶ V/REQUIMTE – Laboratory of Applied Chemistry, Department of Chemical Sciences, Faculty of Pharmacy, University of Porto, R. Jorge de Viterbo Ferreira 228, 4050-313 Porto, Portugal

⁷ Department of Biology, Faculty of Sciences, University of Porto, Rua do Campo Alegre s/n, 4169-007 Porto, Portugal

constipating cure, as well as for treating ulcers, burns, gonorrhoea, asthma, wounds, obesity, inflammatory diseases, and indigestion (Baldassano et al. 2010; Boudjouan et al. 2021; Zeghibib et al. 2024). These beneficial properties that can be provided for human health are mainly due to many biological compounds found in *Opuntia* plants, like vitamins, polyphenols, carotenoids, and betalains, as well as to many mineral elements including magnesium, calcium, iron, and so forth (García et al. 2020; Boudjouan et al. 2021; Bellumori et al. 2023).

Cactus pear fruits had a short shelf life from 3 to 4 weeks, limiting thus long-term storage and worldwide distribution (Feugang et al. 2006), that is why they are mainly consumed as fresh fruits and very few countries have made industrial transformations from it. Moreover, compared to cladodes, the fruits display many distinguishable differences like size, shape, color, flavor, as well as in seed quantity, size, and hardness. These parameters, accompanied by a difference in bioactive compounds and nutrients contents, are strongly influenced by the environment and vary from one cultivar to another (Mazari et al. 2018), making the fruits an interesting part from cactus to investigate.

Few reports were undertaken about the physicochemical parameters of *Opuntia* species fruits in Algeria, and to the best of our knowledge, none had reported the mineral composition that could be found in fruits. Thus, this work constitutes a pioneer study on the physicochemical parameters, some bioactive compounds, and mineral content evaluations from cultivated and wild *Opuntia* species fruits, grown in Bejaia (Algeria). Otherwise, no reports were found about the wild species investigated in this paper.

Experimental

Materials

Chemicals

2,6-Dichloroindophenol sodium salt hydrate (DCPIP, $C_{12}H_7NCl_2O_2$), ethanol (C_2H_6O , 99.8% purity), bovine serum albumin (BSA), ascorbic acid ($C_6H_8O_6$), D-(+)-Glucose ($C_6H_{12}O_6$), and sulfuric acid (H_2SO_4) were purchased from Sigma Chemical (Sigma–Aldrich GmbH, Germany), phenol (C_6H_6O) is from Biochem Chemopharma (Montreal, Canada) and L-(+)-Oxalic acid ($C_2H_2O_4$) is purchased from Panreac (Barcelona, Spain), nitric acid (HNO_3) ($\geq 69\%$, w/w) was purchased from Fluka (France), hydrogen peroxide (H_2O_2) (30–32%, w/w) was from Fisher Chemical (Loughborough, UK), and multi-element commercial standard solution PlasmaCAL

SCP-33-MS was acquired from (SCP Science, Quebec, Canada).

Plant material

This study was conducted on cactus fruits, also named by the Algerian population as takeṛmust (ⵜⴰⴷⵓⴷⵉⴳⴰⴷⵉⴳⴰ) in Tamazight (and as الهندي in Arabic), using two kinds of *Opuntia* sp. trees: a cultivated and a wild one. The fruits in adult stage were harvested in Bejaia city (Algeria) during their respective periods of maturity (August for the cultivated fruit and October of the same year for the wild one). The cultivated cactus tree is the only one producing fruits which are commercialized and consumed by the population. This plant is from the region of Bouzoulam at a latitude of 36.69164, a longitude of 4.81969, and an altitude of 85 m, whereas the wild tree is situated near the city's coast at a latitude of 36.76649, a longitude of 5.10310, and an altitude of 235 m (at approximately 27 km from the cultivated species).

Fruits from each species with the same ripening and no physical damages were selected, washed with tap water, and manually peeled. After blending, 50% of the amount was passed through a strainer to separate seeds from pulp (obtaining seed and pulp fractions), while the other part was blended using an ULTRA-TURRAX (IKA T18 Basic ULTRA-TURRAX, Germany) during 5 min, to allow a complete homogenization, producing a fruit mixture between pulp and seeds (entire fruit fractions).

For a good conservation of plant material, the different fruit parts were lyophilized using a freeze dryer (Christ, alpha 1–4 LD plus, Germany). The seeds were crushed (Retsch RM200, Germany), and all dehydrated samples (seeds, pulps, and entire fruit) were stored at $-20\text{ }^\circ\text{C}$ until use.

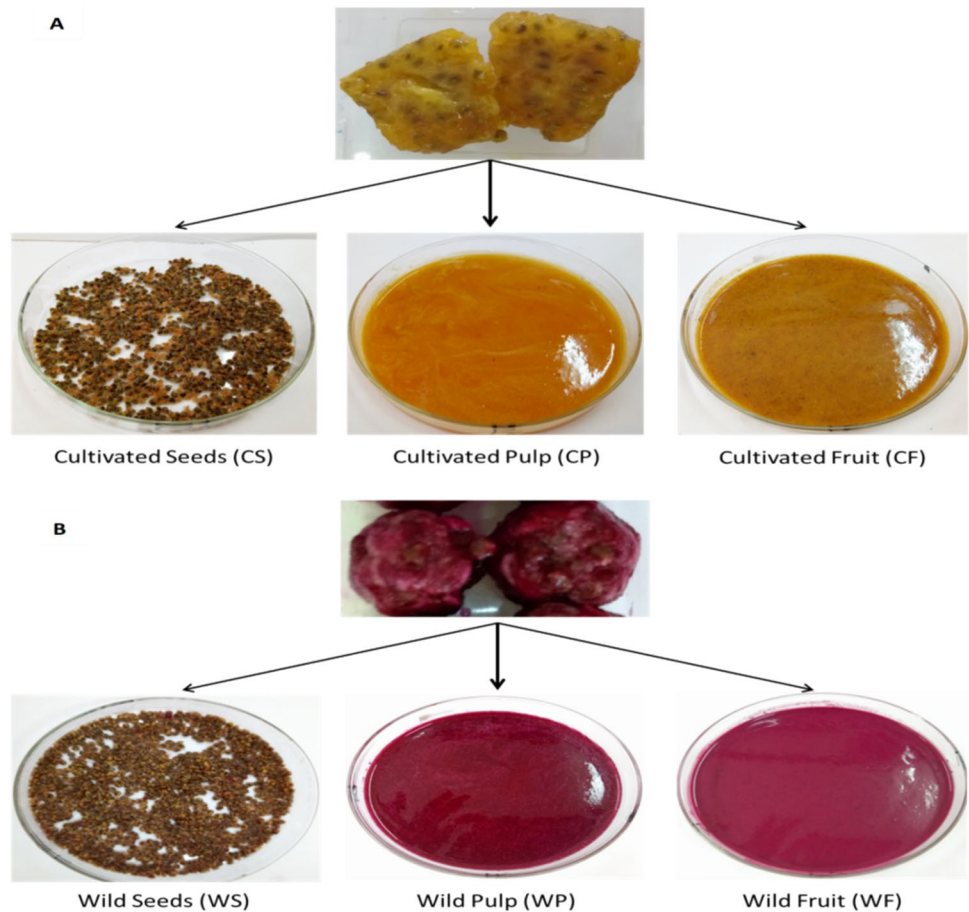
Morphological characterization of the fruits

The diameters (measured at fruit middle part) and length (measured from the fruit attachment point to its end pad) of ten entire fruits were determined using a digital caliper. After washing the fruits under running tap water and drained, their weights were recorded with and without the peel. Then, the peeled fruits were separated into three parts: seeds, pulp, and entire fruits (mix between pulp and seed), as shown in Fig. 1.

Chemical characterization of the fruits

Evaluation of the pH and the brix The hydrogen potential (pH) and soluble solids (brix $^\circ$) of pulps were measured using a pH meter (Bante model 920, UK) and an Abbe-type

Fig. 1 The fruit parts investigated: **A** cultivated fruit, **B** wild fruit



refractometer (AR12 Schmidt and Haensch Co., Germany), respectively.

Moisture content The moisture content of the different fruit parts from each species was carried out by drying at 105 °C using a ventilated oven (WTB Blinde, 120 Tuttlingen, Germany), until weight stabilization. The ash content was determined by combustion of the samples in a muffle furnace (Nabertherm GmbH, Germany) at 550 °C for 4 h.

Total sugars content An acid hydrolysis of samples was performed following a modified procedure of Benchikh et al. (2016), which consists on incubating 0.1 g of lyophilized samples and 10 mL of sulfuric acid (0.5 M) in a ventilated oven at 105 °C for 3 h. Then, total sugars content was analyzed by phenol–sulfuric acid method (DuBois et al. 1956), by adding 1.5 mL of concentrated sulfuric acid and 0.3 mL of phenol (5%, v/v) to 0.3 mL of the precedent solution, and subsequently incubated for 5 min in the ventilated oven. After cooling to room temperature, the absorbances were measured at 490 nm with a spectrophotometer (Uviline 9400, France), and the results were expressed as g glucose equivalent/100 g of dry matter (g GE/100g DM).

Total protein content The proteins were extracted from samples according to Landi-Librandi et al. (2007), by shaking 0.4 g of lyophilized samples with 10 mL of ethanol (70%) during 24 h. Then total protein content was measured according to Bradford protein measurement assay (Bradford 1976), by mixing 200 µL of extracts with 2.5 mL of Bradford reagent. After incubation for 5 min in darkness, absorbance was measured at 595 nm. The results were expressed as mg bovine serum albumin equivalent/100 g of dry matter (mg BSAE/100g DM).

Ascorbic acid content Ascorbic acid content was determined following the method described by Klein and Perry (1982), with some modifications. Briefly, 2 g of lyophilized samples were mixed with 10 mL of oxalic acid (3%, w/v) using an ULTRA-TURRAX (IKA T18 Basic ULTRA-TURRAX, Germany) for 20 min. Then, 100 µL of the solution was added to 1 mL of 2,6-dichlorophenolindophenol (DCPIP) and absorbances were measured at 515 nm. The results were expressed as mg ascorbic acid equivalent/100 g dry matter (mg AAE/100 g of DM).

Betalains content The betalains content was determined according to Yahia and Mondragon-Jacobo (2011), with

slight modifications. Briefly, 0.1 g of lyophilized sample was added to 20 mL of distilled water and the mix was shaken 10 min in darkness. The betalains content (BC) expressed in (mg/g) was calculated according to the following equation:

$$BC = A(DF)(MW)(Vd)/(L)(Wd)$$

where A is the absorbance at maximum absorption of 535 nm and 483 nm for betacyanins and betaxanthins, respectively, DF is the dilution factor (mL), Vd is the dried sample solution volume (mL), L is the path length of the cuvette (1 cm), Wd is the dried pulp weight (g). MW and ϵ were the molecular weight and molar extinction coefficient of betanin [$MW = 550$ g/mol; $\epsilon = 60,000$ L/(mol cm) in H_2O] and indicaxanthin [$MW = 308$ g/mol; $\epsilon = 48,000$ L/(mol cm) in H_2O] for betacyanins and betaxanthins measurement, respectively.

Mineral content analysis

Prior analytical determination, 400 mg of sample was placed in microwave PTFE vessels, to which 3 mL of high purity HNO_3 (67–70%, w/w, TraceMetal™ Grade, Fisher Chemical, Loughborough, UK) and 1 mL of H_2O_2 (30–32%, w/w, Primar™, for trace metal analysis, Fisher Chemical, Loughborough, UK) were added. The vessels were closed and placed in a microwave oven MLS-1200 Mega high-performance microwave digestion (Milestone, Sorisole, Italy) unit, equipped with an HPR-1000/10 S rotor. Then, the following program was applied: 250 W for 1 min, 0 W for 2 min, 250 W for 5 min, 400 W for 5 min, and 600 W for 5 min. After cooling, samples were diluted to 25 mL with ultrapure water (> 18.2 M Ω ·cm at 25 °C, obtained with an arium® pro system (Sartorius, Goettingen, Germany).

Elemental analysis was carried out using inductively coupled plasma-mass spectrometry (ICP-MS) using an iCAP™ Q (Thermo Fisher Scientific, Bremen, Germany) instrument. Calibration standards ranging from 0.5 to 200 μ g/L were prepared from a 10 mg/L multi-element commercial standard solution (Periodic table mix 1, Sigma-Aldrich, Buchs, Switzerland). Samples solutions were diluted at least 10 times before analysis with a solution composed of 10 μ g/L of Sc, Y, Tb, Pr, and Lu in 2% HNO_3 (v/v). Limits of detection

(LOD) and limits of quantification (LOQ) were estimated from the analysis of 10 digestion blanks.

Statistical analysis

All data of each experiment were reported as a mean of three replicates \pm standard deviation. The results were compared using Statistica 8 software, through the analysis of the variance (ANOVA / MANOVA), and the differences among means were determined using the LSD (least significant difference) test. The level of significance was set at $p \leq 0.05$.

Results and discussion

Plant description

According to a previous study conducted by our research group, the taxonomic study confirmed the belonging of the species investigated herein in the genus *Opuntia* (Boudjouan et al. 2022). The cultivated species is a very popular plant in the region; its cultivation was conducted traditionally by receiving scarce attention from farmers, its growth is dependent on weather conditions, providing consequently a lower fruit yield compared to its real potential. This cultivar plant is a big cactus that can grow up to 2 m in height and produce big, elongated, and spiny orange–yellow fruits during the summer season (July–August).

The wild species grows on a rocky slope with an estimated height lower than 1 m; this species produces small, ovoid, and spiny purple fruits during the autumn season (October–November).

Morphological characterization

The morphological characteristics of both species are shown in Table 1. The cultivated prickly pear fruits are orange–yellow, with an elongated shape and glochids on their surface. Their approximate length and diameter were recorded to be approximately 68.70 mm and 42.23 mm, respectively. The statistical analysis confirmed that they were significantly larger than the wild fruits (approximately 40.06 mm and 30.57 mm for length and diameter, respectively), which had a purple color, smaller, and more rounded shape with

Table 1 Morphological characterization for cactus fruits

Fruits variety	Length (mm)	Diameter (mm)	Weight (g)	Weight without peel (g)
Cultivated <i>Opuntia</i>	68.70 \pm 8.40 ^a	42.23 \pm 4.90 ^a	65.62 \pm 18.09 ^a	32.63 \pm 10.12 ^a
Wild <i>Opuntia</i>	40.06 \pm 2.99 ^b	30.57 \pm 0.87 ^b	21.93 \pm 1.93 ^b	11.13 \pm 1.05 ^b

Differences between the samples were designed with different letters from the most significant (letter a) to the lowest significant (letter b) ($p \leq 0.05$, ANOVA)

glochids on their surface. The average size of the cultivated fruits was closer to the values recorded by Bargougui et al. (2019) on different varieties of *Opuntia ficus-indica* (OFI) cultivated in Morocco, Italy, and Algeria (between 66.20 and 72.90 mm and between 41.30 and 47.70 mm for length and diameter, respectively). The average total weight for the cultivated fruits was approximately 65.62 g, which is three times more than those recorded for the wild ones (approximately 21.93 g). After peeling, the weight recorded was 32.63 g and 11.13 g, which represented a peel percentage of 50.27% and 49.32% from the whole weight of cultivated and wild fruits, respectively, and seeds constituted approximately 12.83% and 28.90% of the weight of the edible part of cultivated and wild fruits, respectively. This significant variation could be related to the different species and could also depend on the size, age, and number of flowers produced by the *Cactaceae* plants (Feugang et al. 2006). The peel and pulp percentage were found to be per Jana's (2012) study, reporting that the percentage distribution of each part of *Opuntia* sp. fruits varied from 33.00 to 55.00% for peels and from 43.00 to 57.00% for pulp. In addition, Reis et al. (2017) reported that the morphological characteristic of different *Opuntia* fruits varied according to the species studied, where they found the highest weight recorded for a variety of OFI with 132.50 g, and the lightest for *Opuntia elata* with 19.50 g, this latter fruit was reported also to be the smallest in terms of length and diameter; but had the highest percentage of seeds (with 22.80%) compared to other species.

Chemical composition

pH and brix° measurement

The results for pH measurement (Table 2) revealed a statistical significance between both pulps, with a high pH value found for the cultivated pulp (pH = 5.90) compared to the wild one which presented a more acidic juice (pH = 2.13). The pH values recorded from the pulp of the cultivated species were found to be in correlation with Mazari et al. (2018), who found a pH variation between 5.91 and 6.25 for the pulp of OFI grown in different sites of Souk Ahras in Algeria. Besides, it has been reported that cactus fruits were classified as low acidity foods (pH ≥ 4.50), most of them have a pH between 5.30 and 7.10, but only some varieties have a very acidic pH like *Opuntia xocconostle* (Sáenz 2017).

The brix° is generally defined as the percentage of total soluble solids present in fruits. The brix° measurements (Table 2) were significantly higher for the cultivated pulp and fruit with 11.20% and 11.48%, respectively, compared to the wild variety which had an approximate estimation of 10%. The results obtained herein were in accordance with De Wit et al. (2010) study, recording between 8.00 and 14.67% for prickly pears fruits; they also deduced that the

Table 2 Physicochemical results for cactus fruits

Variety of <i>Opuntia</i>	Part	pH	Brix°	Moisture content (%)	Ash content (%)	Total sugars (g GE/100 g DM)	Total proteins (mg BSAE/100 g DM)	Ascorbic acid (mg AAE/100 g DM)	Betainins (mg/100 g DM)		
									Betaxanthins	Betacyanins	Total
Cultivated	Seeds	–	–	33.13 ± 0.84 ^e	1.04 ± 0.02 ^a	14.16 ± 0.51 ^e	190.60 ± 2.31 ^c	78.31 ± 2.11 ^d	–	–	–
	Pulp	5.90 ± 0.02 ^a	11.20 ± 0.00 ^b	90.54 ± 0.07 ^b	0.25 ± 0.05 ^d	92.88 ± 2.14 ^a	30.98 ± 1.91 ^e	53.95 ± 3.22 ^e	37.09 ± 0.26 ^b	11.67 ± 0.38 ^b	48.76 ± 0.27 ^b
	Fruit	–	11.48 ± 0.03 ^a	86.48 ± 0.10 ^c	0.32 ± 0.05 ^d	75.96 ± 1.42 ^b	89.08 ± 0.92 ^d	40.15 ± 2.54 ^f	–	–	–
Wild	Seeds	–	–	33.77 ± 0.65 ^e	1.04 ± 0.05 ^a	12.65 ± 0.21 ^e	226.08 ± 5.05 ^b	91.70 ± 5.58 ^e	–	–	–
	Pulp	2.13 ± 0.05 ^b	10.02 ± 0.18 ^c	91.26 ± 0.14 ^a	0.43 ± 0.06 ^c	41.90 ± 0.34 ^d	280.48 ± 9.23 ^a	211.45 ± 6.71 ^a	88.51 ± 0.74 ^a	224.40 ± 0.37 ^a	312.91 ± 1.07 ^a
	Fruit	–	10.10 ± 0.10 ^c	83.14 ± 0.14 ^d	0.53 ± 0.09 ^b	44.78 ± 1.18 ^c	278.03 ± 9.23 ^a	125.80 ± 4.39 ^b	–	–	–

Each parameter was done in triplicate. Differences between the samples were designed with different letters from the most significant (letter a) to the lowest significant (letter f) ($p \leq 0.05$, ANOVA)

brix° may be influenced by the variety, as well as from the location, where lower values were measured for fruits collected from regions with a higher intensity of rainfall, which is mainly observed in high altitude.

Moisture and ash contents

The results showed a significant difference in moisture between fruit species and their fractions (Table 2), with pulps having higher moisture content (91.26% for wild pulp and 90.54% for the cultivated one), followed by fruits (86.48% and 83.14% for the cultivated and wild species, respectively), then seeds of both varieties with an approximate value of 33%. These results agreed with already published studies, which reported moisture contents between 28.60 and 37.40% and from 89.13 to 91.18%, respectively, for seeds and pulps of different varieties of *Opuntia ficus-indica* (Dehbi et al. 2014; Jiménez-Aguilar et al. 2015). Moreover, Morales et al. (2012) found that the moisture contents for pulp from two *Opuntia* species cultivated in Mexico (*Opuntia joconostle* and *Opuntia matudae*) were approximately estimated at 93%; however, for their seeds, the moisture content was estimated at 73.95% and 60.44% for *O. joconostle* and *O. matudae*, respectively; thus, the moisture content could be different according to the *Opuntia* species studied and the regions where they grew.

The statistical analysis confirmed a difference in ash content between both fruit species and fractions, with the highest values recorded for seeds of both varieties (approximately 1.04%). These results are similar to those obtained by Morales et al. (2012), who found a higher ash content in seeds compared to pulps of the fruits studied. However, the results obtained were slightly lower compared to the values found by Özcan and Al Juhaimi (2011) in OFI seeds cultivated in Turkey (1.27%) that may be due to the region and more particularly the soil where the plant is cultivated. On another side, other fractions from the wild *Opuntia* demonstrated a significant high content of ash compared to the cultivated one (0.53 and 0.43% found in wild fruit and pulp, respectively, vs 0.33 and 0.26% in the cultivated fruit and pulp, respectively). This is quite similar to Dehbi et al. (2014) results, with an ash content ranging from 0.27 to 0.41% for the pulp of different varieties of OFI.

Total sugar content

The total sugar results showed high content for pulps of both varieties, followed by fruits and lastly seeds. Total sugar content in cultivated pulp was 92.88 g GE/100 g DM, which was 2 times more than recorded for the wild pulp (41.90 g GE/100 g DM), while seeds of both species demonstrated statistically the same amount sugar less than found from all fractions (nearly 14.16 g GE/100 g DM). From the literature,

no reports about sugar content on *Opuntia* seeds were found since most studies on sugar evaluation were undertaken on pulp. While the results obtained herein for the cultivated pulp were slightly higher than the values published by El-Samahy et al. (2006) on different Egyptian orange–yellow cactus pears pulps (85.49–88.02 g/100 g DM), these differences could be due to the climatic conditions, region, age of the plant, and stage of ripening of the fruit.

Total protein content

The Fisher test showed an elevated protein content in the wild *Opuntia*, especially in pulp and fruit fractions, containing almost 280 mg BSAE/100 g DM, which is higher than found in the cultivated one (30.98 and 89.08 mg BSAE/100 g DM for pulp and fruit, respectively). Otherwise, seeds of both species possessed a good amount of proteins, with higher values recorded for the wild seeds (226.08 mg BSAE/100 g DM) compared to the cultivated one (190.60 mg BSAE/100 g DM). No reports for protein content of *Opuntia* seeds were found, while Dehbi et al. (2014) reported that the total proteins content for the pulp of different varieties of Moroccan prickly pears (OFI) varied from 114.00 to 353.00 mg/100 g.

Ascorbic acid content

The statistical analysis showed a significant difference in ascorbic acid (AA) content between the species studied and their fractions. The highest content was found in wild species (211.45 and 125.80 mg AAE/100 g DM in wild pulp and fruit fractions, respectively, vs 53.90 and 40.15 mg AAE/100 g DM in cultivated pulp and fruit fractions, respectively). Wild seeds were also found richer with 91.70 mg AAE/100 g DM compared to the cultivated one (78.31 mg AAE/100 g DM). Regarding some studies, Chaalal et al. (2013) reported an AA content ranging from 16.99 and 24.00 mg AAE/100 g DM in seeds of three varieties of OFI, while Reis et al. (2017) found for pulps of different *Opuntia* sp. a value ranging from 18.00 to 89.70 mg/100 g fresh weight (FW). According to Potgieter and D'Aquino (2017), the AA content of harvested *Opuntia* fruits varies according to the year of harvest but also depending on the cultivar and stage of ripening.

Betalains content

The results obtained for betalains content and confirmed by fisher test, revealed about the wild *Opuntia* richness for betalains, compared to the cultivated one, with 2 times higher content for betaxanthins (88.51 and 37.09 mg/100 g DM for the wild and cultivated pulp, respectively) and almost 20 times higher recorded for betacyanins (224.40 and

11.69 mg/100 g DM for the wild and cultivated pulp, respectively). These results were higher than the ones reported on two varieties of OFI: purple-skinned pelota (186.09 and 26.12 mg/100 g of dry pulp (DP) for betacyanins and indicaxanthins, respectively), and red-skinned Sanguinos (13.65 and 6.02 mg/100 g DP for betacyanins and indicaxanthin, respectively) (Gómez-Maqueo et al. 2019). Moreover, Jiménez-Aguilar et al. (2015) found that betalains content of OFI pulps varied from 41.10 to 344.40 mg/100 g DM and from 104.40 to 595.40 mg/100 g DM for betaxanthins and betacyanins, respectively.

The *Cactaceae* are known by the presence of a particular type of pigments called betalains, which are rarely found in other plants. These compounds are reported to be more correlated in cactus fruit color, than phenols and carotenoids (Yahia and Mondragon-Jacobo 2011). This characteristic gives cactus a potential food application as a natural colorant, as well as a potential health benefit due to their high antioxidant properties with an effect considered to be 3 to 4 times more powerful than ascorbic acid, rutin, and catechin (Sanchez-Gonzalez et al. 2013; Sáenz 2017). These pigments can be classified as betacyanins (responsible for red coloration) and betaxanthins (responsible for yellow coloration) (Gandía-Herrero et al. 2010).

According to the results obtained herein and those from the literature, it can be concluded that the difference in betalains content between species can be attributed to the mineral composition. Indeed, the biosynthesis of betalains is carried out by a process including various enzymatic and chemical reactions, with a particular and crucial role for 4,5-DOPA dioxygenase estradiol (DOD) which leads to the formation of betalamic acid; a chromophore molecule of betacyanins and betaxanthins (Tanaka et al. 2008). Furthermore, Sasaki et al. (2009) reported that DOD needs iron ions and ascorbic acid for its enzymatic activity, iron would then play a role of cofactor of the enzyme, whereas ascorbic acid would act as a necessary component for the maintenance of the redox state of iron.

Mineral content analysis

Minerals are important inorganic micronutrients present in every living system in charge of the maintenance of certain essential processes to life. Thus, an excess, a deficiency, or disturbance in the absorption of these chemical constituents leads to the development of a variety of diseases, which could occur in various ways depending on the function of each element (Soetan et al. 2010; Heffernan et al. 2019). The daily requirement in minerals is smaller when compared with other nutrients (like: proteins, carbohydrates, and fats), and must be regularly provided for a proper structure and normal function of human body (Quintaes and Diez-García 2015). Minerals can be divided in two main groups:

macro-minerals, including calcium (Ca), phosphorus (P), magnesium (Mg), sulfur (S), sodium (Na), chloride (Cl), and potassium (K), which are daily required with relatively high amount: more than 100 mg, while the remaining minerals belong to the micro-minerals (or trace elements) group, such as iron (Fe), zinc (Zn), iodine (I), selenium (Se), manganese (Mn), lithium (Li), nickel (Ni), and others, which are generally needed with less than 100 mg per day (Spada et al. 2010).

The minerals profile analysis conducted herein were focused on the most important ones, taking into account their high nutritional values for the body. As shown in Table 3, both *Opuntia* species constituted a good source of minerals, revealing elsewhere through the statistics that the amount of each element was significantly different for both *Opuntia* and between their fractions. It was particularly noticed that seeds of both species contained high amounts of phosphorus (P) and calcium (Ca) (more than 3000 and 2000 µg/g for calcium and phosphorus, respectively). The amount found for P was in accordance with Reda and Atspha (2019) in Ethiopian OFI seeds, which contain nevertheless high content of Ca more than recorded herein with 3901.40 µg/g. These minerals are important for bone and teeth formations, whereas P is a constituent of adenosine triphosphate (ATP), and Ca is implicated in blood coagulation, nerves, and muscle functions (Soetan et al. 2010; Quintaes and Diez-García 2015).

Zinc (Zn) was more present in seeds of both species but with high values for the cultivated one (CS) (76.36 and 27.55 µg/g for CS and WS, respectively). Similarly, El Kosori et al. (1998) reported as well that OFI seeds contain higher amount of Zn with 41.60 µg/g than compared to the peels and pulp (with 17.00 and 15.50 µg/g, respectively). This element is a cofactor of many enzymes and is an implicated element in immune system function, growth, and development processes (Ryan-Harshman and Aldoori 2005).

As for copper (Cu), wild *Opuntia* contained almost 2 time more content compared to the cultivated one, with wild seeds (WS) having almost 7.78 µg/g. The values of Cu obtained for both seeds species were higher than recorded by Özcan and Al Juhaimi (2011) in Turkish OFI seeds with 3.20 µg/g. Copper has a crucial role in human body, as it is a constituent of many enzymes, including cytochrome c oxidase, superoxide dismutase, and tyrosinase, it is also necessary for bone formation, growth, production of myelin sheaths around nerves, and it is also implicated in the hematologic system by helping the incorporation of iron in hemoglobins (Soetan et al. 2010).

Likewise, some other minerals were found significantly more in wild species compared to the cultivated one, especially in wild pulp (WP) which contained higher values for potassium (K), sodium (Na), magnesium (Mg), and manganese (Mn) with 10,889.67, 1106.67, 2432.67, and 114.23 µg/g, respectively. These values were much higher

Table 3 Mineral content analyses (expressed as µg/g)

	Li	Mg	P	Ca	Cr	Mn	Fe	Co	Ni
CS	< LOD	1335.00 ± 28.00 ^e	2200.67 ± 19.86 ^a	3170.00 ± 86.63 ^b	0.27 ± 0.03 ^d	45.43 ± 1.88 ^c	21.37 ± 0.59 ^d	0.05 ± 0.00 ^e	2.30 ± 0.07 ^c
CP	< LOD	1065.00 ± 64.55 ^d	1785.67 ± 106.01 ^c	1890.33 ± 93.52 ^d	0.85 ± 0.16 ^b	35.57 ± 2.00 ^e	18.17 ± 0.72 ^d	0.07 ± 0.00 ^d	3.40 ± 0.20 ^b
CF	< LOD	883.00 ± 13.86 ^e	1242.33 ± 35.53 ^e	1576.33 ± 56.52 ^e	0.09 ± 0.01 ^e	34.93 ± 0.45 ^e	46.67 ± 2.74 ^c	0.08 ± 0.01 ^c	2.37 ± 0.18 ^c
WS	< LOD	1314.33 ± 26.84 ^e	2038.33 ± 134.28 ^b	3365.00 ± 169.00 ^a	0.57 ± 0.05 ^c	41.87 ± 1.00 ^d	33.50 ± 1.57 ^{c,d}	0.07 ± 0.00 ^{c,d}	1.70 ± 0.13 ^d
WP	0.08 ± 0.00	2432.67 ± 59.38 ^a	371.00 ± 26.89 ^f	2837.33 ± 15.95 ^c	0.65 ± 0.01 ^c	114.23 ± 2.75 ^a	597.83 ± 23.88 ^a	0.24 ± 0.01 ^a	3.29 ± 0.05 ^b
WF	< LOD	1677.33 ± 15.01 ^b	1455.67 ± 15.63 ^d	2968.67 ± 67.89 ^e	2.79 ± 0.08 ^a	62.47 ± 2.14 ^b	350.60 ± 7.28 ^b	0.18 ± 0.01 ^b	5.82 ± 0.23 ^a
LOD	0.02	0.68	2.98	2.07	0.03	0.02	3.10	0.002	0.002
	Cu	Zn	As	Se	Cd	Pb	Na	K	
CS	3.60 ± 0.15 ^d	76.36 ± 1.94 ^a	< LOD	< LOD	0.03 ± 0.01 ^c	0.06 ± 0.01 ^b	66.00 ± 1.00 ^c	2269.67 ± 95.19 ^e	
CP	2.94 ± 0.11 ^e	14.08 ± 0.47 ^c	< LOD	< LOD	< LOD	0.02 ± 0.01 ^c	3.33 ± 0.12 ^d	8473.33 ± 117.51 ^c	
CF	2.46 ± 0.06 ^f	9.31 ± 0.41 ^d	< LOD	< LOD	< LOD	0.03 ± 0.01 ^c	6.23 ± 0.25 ^d	10,176.67 ± 129.51 ^b	
WS	7.78 ± 0.38 ^a	27.55 ± 1.51 ^b	< LOD	< LOD	0.10 ± 0.01 ^a	0.09 ± 0.01 ^a	63.33 ± 0.58 ^c	1544.67 ± 54.37 ^f	
WP	5.38 ± 0.12 ^c	9.06 ± 0.29 ^d	< LOD	< LOD	0.05 ± 0.01 ^b	0.06 ± 0.00 ^b	1106.67 ± 52.48 ^a	10,889.67 ± 437.40 ^a	
WF	7.06 ± 0.24 ^b	14.01 ± 0.10 ^c	< LOD	< LOD	0.02 ± 0.00 ^d	0.06 ± 0.01 ^b	455.67 ± 13.50 ^b	5577.67 ± 101.32 ^d	
LOD	0.04	0.16	0.05	0.03	0.002	0.003	0.81	4.47	

Each parameter was done in triplicate. Differences between the samples were designed with different letters from the most significant (letter a) to the lowest significant (letter f) ($p \leq 0.05$, ANOVA). CS, cultivated seeds; CP, cultivated pulp; CF, cultivated fruit; WS, wild seeds; WP, wild pulp; WF, wild fruit; LOD, limit of detection

Table 4 Estimated daily requirement and tolerable upper intake level for the mineral elements studied (adapted from: (Meyers et al. 2006; García-Rico et al. 2007; Quintaes and Diez-Garcia 2015; Szklarska and Rzymiski 2019))

Mineral element	Type of mineral	Daily requirements for minerals (EAR or AI)	Tolerable upper intake level (UL)	Additional information for UL
Magnesium (Mg)	Macro-mineral	EAR: Children ≤ 13 years: 30.00 – 200.00 mg Men ≥ 14 years: 330.00 – 350.00 mg Women ≥ 14 years: 255.00 – 300.00 mg In case of pregnancy: 290.00–335.00 mg In case of lactation: 255.00–300.00 mg	65.00–350.00 mg 350.00 mg	Magnesium ingested naturally from food has not shown any toxic effect, contrary to nonfood source particularly from pharmacological products, where an excessive magnesium ingestion shown toxic effects on health. Thus, the UL for magnesium represents acute intake from pharmacological agents and it is based on diarrhea as the critical endpoint
Phosphorus (P)	Macro-mineral	EAR: Children ≤ 13 years: 380.00–1055.00 mg Men and women ≥ 14 years: 580.00–1055.00 mg	100.00–4000.00 mg 3000.00–4000.00 mg	UL was derived from data on the normal range of serum inorganic phosphate concentration in adults
Calcium (Ca)	Macro-mineral	AI: Children ≤ 13 years: 210.00 – 1300.00 mg Men and women ≥ 14 years: 1000.00–1300.00 mg	2500.00 mg	UL estimation was based on milk-alkali syndrome, which is characterized by a hypercalcemia and renal insufficiency, as a critical endpoint
Sodium (Na)	Macro-mineral	AI: Children ≤ 13 years: 0.12–1.50 g Men and women ≥ 14 years: 1.20–1.50 g In case of pregnancy and lactation: 1.50 g	1.50 – 2.20 g 2.30 g	UL was based on scientific rational of the impact of sodium to increase blood pressure
Potassium (K)	Macro-mineral	AI: Children ≤ 13 years: 0.40 – 4.50 g Men and women ≥ 14 years: 4.70 g In case of pregnancy: 4.70 g In case of lactation: 5.10 g	ND	UL for potassium ingested from foods has not been set, due to an absence of evidence showing toxicity in healthy individuals; however, a supplementation of potassium can lead to acute toxicity, as well as adverse effects due to chronic consumption. Thus, magnesium supplementation should only be provided under medical supervision, to prevent a cardiac arrhythmia caused by a hyperkalemia
Chromium (Cr)	Micro-mineral	AI: Children ≤ 13 years: 0.20 – 25.00 µg Men ≥ 14 years: 30.00 – 35.00 µg Women ≥ 14 years: 20.00 – 25.00 µg In case of pregnancy: 29.00 – 30.00 µg In case of lactation: 44.00 – 45.00 µg	ND	

Table 4 (continued)

Mineral element	Type of mineral	Daily requirements for minerals (EAR or AI)	Tolerable upper intake level (UL)	Additional information for UL
Manganese (Mn)	Micro-mineral	AI: Children \leq 13 years: 0.003 – 1.60 mg Men \geq 14 years: 1.90 – 2.30 mg Women \geq 14 years: 1.60 – 1.80 mg In case of pregnancy: 2.00 mg In case of lactation: 2.60 mg	2.00–6.00 mg 9.00 – 11.00 mg	UL was based on elevated blood manganese and its relation with neurotoxicity as the critical adverse effects
Iron (Fe)	Micro-mineral	EAR: Children \leq 13 years: 3.00 – 6.90 mg Men \geq 14 years: 5.90 – 7.70 mg Women \geq 14 years: 5.00 – 8.10 mg In case of pregnancy: 22.00 – 23.00 mg In case of lactation: 6.50–7.00 mg	40.00 mg 45.00 mg	UL was based on gastrointestinal distress as the critical adverse effect
Cobalt (Co)	Micro-mineral	ND	ND	
Nickel (Ni)	Micro-mineral	Children \leq 13 years: ND Men and women \geq 14 years: ND	0.20–0.60 mg 1.00 mg	UL was based on general systemic toxicity (decreased body-weight gain reported in rat studies) as the critical endpoint; otherwise, increased risks are likely to occur from a contaminated water consumption or from environmental exposures
Copper (Cu)	Micro-mineral	EAR: Children \leq 13 years: 200.00 – 540.00 μ g Men and women \geq 14 years: 685.00 – 700.00 μ g In case of pregnancy: 785.00 – 800.00 μ g In case of lactation: 985.00 – 1000.00 μ g	1000.00–5000.00 μ g 8000.00–10,000.00 μ g	UL was based on liver damage as the critical endpoint
Zinc (Zn)	Micro-mineral	EAR: Children \leq 13 years: 2.00 – 7.00 mg Men \geq 14 years: 8.50 – 9.40 mg women \geq 14 years: 6.80 – 7.30 mg In case of pregnancy: 9.50 – 10.50 mg In case of lactation: 10.40 – 10.90 mg	4.00–23.00 mg 34.00–40.00 mg	UL was established according to the adverse effect caused by an excess of zinc ingestion on copper metabolism (reduced copper status)
Selenium (Se)	Micro-mineral	EAR: Children \leq 13 years: 15.00 – 35.00 μ g Men and women \geq 14 years: 45.00 μ g • In case of pregnancy: 49.00 μ g • In case of lactation: 59.00 μ g	45.00–280.00 μ g 400.00 μ g	UL was based on selenosis as an adverse effect, which leads to hair and nail brittleness and loss

Table 4 (continued)

Mineral element	Type of mineral	Daily requirements for minerals (EAR or AI)	Tolerable upper intake level (UL)	Additional information for UL
Lithium (Li)	Micro-mineral	Provisional AI estimated at: 1.00 mg (for adults with 70 kg body weight)	ND	
Cadmium (Cd)	Micro-mineral	ND	62.00 µg	
Lead (Pb)	Micro-mineral	ND	240.00 µg (For a body weight 68 kg)	
Arsenic (As)	Micro-mineral	ND	ND	

EAR: Estimated average requirement (EAR) corresponding to an average of daily nutrient intake level estimated to meet the requirements of 50% of the healthy people in particular gender and life stage. AI: Adequate intake is set when sufficient scientific evidence was lacking to set an EAR, it is based on observed or experimentally determined approximations assumed to be adequate for a group of healthy people. UL: Tolerable upper intake level is considered as the highest element intake level that can be tolerated without the possibility of causing ill effects; this value varies according to the age. ND: Not determined (The data were insufficient to set estimation, otherwise for UL; an extra caution should be taken when consuming levels above the recommended intake)

than recorded by Belviranlı et al. (2019) in pulp of different varieties of OFI growing Turkey. For these elements, magnesium and manganese are known to be cofactors of numerous enzymes; while sodium and potassium are important for the generation and transmission of nerve impulses, they are also implicated in the maintenance of osmotic balance between cells and interstitial fluid (Soetan et al. 2010; Quintaes and Diez-Garcia 2015).

The same observation for iron (Fe), which was in great amount in wild pulp, with almost 30 times more than pulp and seeds of the cultivated species. The content of iron in WP (with almost 597.83 µg/g) was higher than the values recorded by Dehbi et al. (2014) in different varieties of Moroccan OFI pulps (ranging from 7.58 to 10.62 µg/g), as well as from Turkish OFI pulps with a content going from 13.80 to 30.48 µg/g (Belviranlı et al. 2019); this difference could possibly due to the species of *Opuntia* on which the study was undertaken. In the body, most of Fe is found in hemoglobin playing the role of oxygen transporter (Fairweather-Tait and Cashman 2015). Besides having a crucial role in cellular respiration by being an electron transporter and an important component of cytochromes, iron is also required in brain, for a proper myelination of the spinal cord and the white matter of cerebellar folds; otherwise, this element is also a cofactor of several enzymes involved in synthesis, packaging, uptake, and degradation of neurotransmitters (Soetan et al. 2010). Meanwhile, from a plant point of view, this high content of iron would also confirm Sasaki's et al. (2009) assumption on the existence of a relationship between the iron content and the betalain content, since wild pulp was the most rich for this compounds. Furthermore, a folk medicine from the region of Bejaia (Algeria) was based on the consumption of this wild fruit to supposedly treat people with anemia; consequently, the results obtained in this study come to prove the benefit of this traditional use.

However, further studies would be required to confirm the safely use of this wild fruit.

Other mineral elements were found in few amounts in both *Opuntia* plants, like chromium (Cr) (between 0.57 and 2.79 µg/g and 0.09–0.85 µg/g for wild and cultivated *Opuntia* parts, respectively) which could allow maintaining normal blood glucose levels (Quintaes and Diez-Garcia 2015), as well as for cobalt (Co) (0.07–0.24 µg/g and 0.05–0.08 µg/g for wild and cultivated *Opuntia* parts, respectively) which is required as a constituent of vitamin B12 (Prashanth et al. 2015). The amount found for chromium was higher than Medina et al. (2007), who reported values ranging from 0.102 to 0.144 µg/g in pulp of *O. diillenii* and *O. ficus-indica* species, while no report for Cobalt content was reported in *Opuntia* fruits.

Otherwise, there was a presence of cadmium (Cd) in all wild fruit parts (0.02–0.10 µg/g), but only in seeds of the cultivated species (CS) with 0.03 µg/g. In addition, lithium (Li) was only found in wild pulp (WP) with 0.08 µg/g, this later present in trace amounts in the human body (0.16–8.60 µmol/L of blood serum) could play an essential role in the physiological regulation of mood. Indeed, a psychiatric medication of lithium salts had shown antimanic properties and prophylactic effects in depressive and bipolar disorders (Demling et al. 2001). According to another work, this normothymic action of Li for bipolar disorders resulted directly from its interaction with the intracellular neurotransmission of the central nervous system (Szklarska and Rzymiski 2019). Finally, nickel (Ni) and lead (Pb) were also found in few amounts in both species and neither selenium (Se) nor arsenic (As) were found in both collected species.

From these micronutrients analysis, almost all minerals have been confirmed, and few of them in case of cadmium, nickel, arsenic, and lead were thought to exhibit adequate biological functions (Quintaes and Diez-Garcia

2015). Furthermore, besides of the body mineral requirement differing with the gender, age, body size, and genetic factor, the amounts needed for all normal people are included approximately in the same range values; thus, amount of micronutrients below normal leads to a mineral deficiency, and an excess (more than the daily high tolerable amount, known as a tolerable upper intake level (UL)) leads eventually to toxicity. Through the comparison between the amount of minerals present in both fruits and the information resumed in Table 4, concerning the daily requirements and the daily upper intake for minerals (Meyers et al. 2006; García-Rico et al. 2007; Quintaes and Diez-Garcia 2015; Szklarska and Rzym-ski 2019), both *Opuntia* fruits could be a good source of micronutrients without presenting any toxicity risk by any minerals, except for Fe and Mn, which could exceed the upper tolerable amounts in case of consuming higher quantity of wild fruits (above 100 g of dry fruits). Moreover, when comparing to other elements known more for their toxicity than their probable benefic effect, such as Pb, Ni, and As, from which human could be exposed from various sources either environmental or food, the amounts found in both fruits were extremely lower than the higher acceptable values, this could also indicate a poor contamination of soil by these toxic chemical elements.

Finally, the difference recorded in mineral content for both fruits, could be due to the difference between both species but also due to the soil of the region where plants grow. In fact the mineral composition of plants is changing according to complex interactions occurring between endogenous plant processes and the environment, while even the present knowledge about these interactions is incomplete and limited especially because of the big variation in soil composition (Stein et al. 2017).

Conclusions

Overall, this paper provided insights on the mineral composition determined by ICP-MS and nutritional value of different fruit parts from cultivated and wild species belonging to the *Opuntia* genera. Regarding the results, both species studied showed not only a significant difference in their morphology but also in their composition. Indeed, it was revealed that fruits of both species, and especially the wild one could be considered as an essential nutrient and a rich food with a great potential for health benefits. The fruits demonstrated also a high content in biological compounds (like ascorbic acid and betalains), as well as in many interesting mineral elements which are essential for the proper functioning of the human organism (like Mg, Zn, Co, and Fe), this can emphasize a potential exploitation of *Opuntia* fruits in many economic areas, particularly in nutraceuticals

and food industries, which would have a great impact on the evolution of the economy of Algeria, where these species are very abundant but remains scarcely valorized.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

References

- Baldassano S, Tesoriere L, Rotondo A, Serio R, Livrea MA, Mulè F (2010) Inhibition of the mechanical activity of mouse ileum by cactus pear (*Opuntia ficus indica* L. Mill.) fruit extract and its pigment indicaxanthin. *J Agric Food Chem* 58:7565–7571. <https://doi.org/10.1021/jf100434e>
- Bargougui A, Tag HM, Bouaziz M, Triki S (2019) Antimicrobial, antioxidant, total phenols and flavonoids content of four cactus (*Opuntia ficus-indica*) cultivars. *Biomed Pharmacol J* 12:1353–1368. <https://doi.org/10.13005/bpj/1764>
- Bellumori M, Innocenti M, Andrenelli L, Melani F, Cecchi L, Pandino G, Mauromicale G, La Malfa S, Mulinacci N (2023) Composition of discarded Sicilian fruits of *Opuntia ficus indica* L: Phenolic content, mineral profile and antioxidant activity in peel, seeds and whole fruit. *Food Chem* 428:136756. <https://doi.org/10.1016/j.foodchem.2023.136756>
- Belviranlı B, Al-Juhaimi F, Özcan MM, Ghafoor K, Babiker EE, Alsawmahi ON (2019) Effect of location on some physico-chemical properties of prickly pear (*Opuntia ficus-indica* L.) fruit and seeds. *J Food Process Preserv* 43:e13896. <https://doi.org/10.1111/jfpp.13896>
- Benchikh Y, Paris C, Louaileche H, Charbonnel C, Ghoul M, Chebil L (2016) Comparative characterization of green and ripe carob (*Ceratonia siliqua* L.): physicochemical attributes and phenolic profile. *J Food Sci Technol*. <https://doi.org/10.25177/JFST.1.3.1>
- Boudjouan F, Zeghib W, Bachir Bey M, Djaoudene O, Elothmani D, Bououdina M, Louaileche H (2021) Extraction methods comparison for polyphenols recovery and antioxidant activity from *Opuntia ficus indica*'s seeds. *Studia Universitatis Vasile Goldis Arad, Seria Stiintele Vietii* 31:164–171
- Boudjouan F, Zeghib W, Carneiro J, Silva R, Morais J, Vasconcelos V, Lopes G (2022) Comparison study on wild and cultivated *Opuntia* sp.: chemical, taxonomic, and antioxidant evaluations. *Agriculture* 12:1755. <https://doi.org/10.3390/agriculture12111755>
- Bradford MM (1976) A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Anal Biochem* 72:248–254. <https://doi.org/10.1006/abio.1976.9999>
- Chaalal M, Louaileche H, Touati N, Bachir Bey M (2013) Phytochemicals, *in vitro* antioxidant capacity and antiradical potential of whole and ground seeds of three prickly pear varieties: a comparative study. *Ind Crops Prod* 49:386–391. <https://doi.org/10.1016/j.indcrop.2013.05.010>

- De Wit M, Nel P, Osthoff G, Labuschagne MT (2010) The effect of variety and location on cactus pear (*Opuntia ficus-indica*) fruit quality. *Plant Foods Hum Nutr* 65:136–145. <https://doi.org/10.1007/s11130-010-0163-7>
- Dehbi F, Hasib A, Ouattmane A, Elbatal H, Jaouad A (2014) Physico-chemical characteristics of Moroccan prickly pear juice (*Opuntia ficus indica* L.). *Int J Em Technol Adv Eng* 4:300–306
- Demling JH, Eglau MC, Autenrieth T (2001) On the physiological function of lithium from a psychiatric view point. *Med Hypotheses* 57:506–509. <https://doi.org/10.1054/mehy.2001.1375>
- El Kossori RL, Villaume C, El Boustani E, Sauvaire Y, Méjean L (1998) Composition of pulp, skin and seeds of prickly pears fruit (*Opuntia ficus indica* sp.). *Plant Foods Hum Nutr* 52:263–270. <https://doi.org/10.1023/A:1008000232406>
- El-Samahy SK, El-Hady EAA, Habiba RA, Moussa TE (2006) Chemical and rheological characteristics of orange-yellow cactus-pear pulp from Egypt. *J Prof Assoc Cactus Dev* 8:39–51
- Fairweather-Tait SJ, Cashman K (2015) Minerals and trace elements. *World Rev Nutr Diet* 111:45–52. <https://doi.org/10.1159/000362296>
- Feugang JM, Konarski P, Zou D, Stintzing FC, Zou C (2006) Nutritional and medicinal use of Cactus pear (*Opuntia* spp.) cladodes and fruits. *Front Biosci* 11:2574–2589. <https://doi.org/10.2741/1992>
- Gandía-Herrero F, Jiménez-Atiénzar M, Cabanes J, García-Carmona F, Escribano J (2010) Stabilization of the bioactive pigment of *Opuntia* fruits through maltodextrin encapsulation. *J Agric Food Chem* 58:10646–10652. <https://doi.org/10.1021/jf101695f>
- García FH, Coll LA, Cano-Lamadrid M, Lluch DL, Barrachina AA, Murcia PL (2020) Valorization of prickly pear [*Opuntia ficus-indica* (L.) Mill]: nutritional composition, functional properties and economic aspects. In: El-Shafie HAF (ed) *Invasive species—Introduction pathways, economic impact, and possible management options*. IntechOpen, London, pp 127–142
- García-Rico L, Leyva-Perez J, Jara-Marini ME (2007) Content and daily intake of copper, zinc, lead, cadmium, and mercury from dietary supplements in Mexico. *Food Chem Toxicol* 45:1599–1605. <https://doi.org/10.1016/j.fct.2007.02.027>
- Gómez-Maqueo A, García-Cayuela T, Weltri-Chanes J, Cano MP (2019) Enhancement of anti-inflammatory and antioxidant activities of prickly pear fruits by high hydrostatic pressure: a chemical and microstructural approach. *Innov Food Sci Emerg Technol* 54:132–142. <https://doi.org/10.1016/j.ifset.2019.04.002>
- Heffernan SM, Horner K, De Vito G, Conway GE (2019) The role of mineral and trace element supplementation in exercise and athletic performance: a systematic review. *Nutrients* 11:696. <https://doi.org/10.3390/nu11030696>
- Jana S (2012) Nutraceutical and functional properties of cactus pear (*Opuntia* spp.) and its utilization for food applications. *J Eng Res Stud* 3:60–66
- Jiménez-Aguilar DM, López-Martínez JM, Hernández-Brenes C, Gutiérrez-Urbe JA, Weltri-Chanes J (2015) Dietary fiber, phytochemical composition and antioxidant activity of Mexican commercial varieties of cactus pear. *J Food Compos Anal* 41:66–73. <https://doi.org/10.1016/j.jfca.2015.01.017>
- Klein BP, Perry AK (1982) Ascorbic acid and vitamin A activity in selected vegetables from different geographical areas of the united states. *J Food Sci* 47:941–945. <https://doi.org/10.1111/j.1365-2621.1982.tb12750.x>
- Landi-Librandi AP, Chrysóstomo TN, Azzolini AECS, Recchia CGV, Uyemura SA, de Assis-Pandochi AI (2007) Effect of the extract of the tamarind (*Tamarindus indica*) fruit on the complement system: studies *in vitro* and in hamsters submitted to a cholesterol-enriched diet. *Food Chem Toxicol* 45:1487–1495. <https://doi.org/10.1016/j.fct.2007.02.008>
- Mazari A, Yahiaoui K, Fedjer Z, Mahdeb A (2018) Physical characteristics, phytochemical content and antioxidant activity of cactus pear fruits growing in northeast Algeria. *J Prof Assoc Cactus Dev* 20:178–188
- Medina EMD, Rodríguez EMR, Romero CD (2007) Chemical characterization of *Opuntia dillenii* and *Opuntia ficus indica* fruits. *Food Chem* 103:38–45. <https://doi.org/10.1016/j.foodchem.2006.06.064>
- Meyers LD, Hellwig JP, Otten JJ (2006) *Dietary reference intakes: the essential guide to nutrient requirements*. National Academies Press, United State
- Michel DuBois, Gilles KA, Hamilton JK, Rebers PA, Smith F (1956) Colorimetric method for determination of sugars and related substances. *Anal Chem* 28:350–356. <https://doi.org/10.1021/ac60111a017>
- Morales P, Ramírez-Moreno E, De Cortes S-M, Carvalho AM, Ferreira ICFR (2012) Nutritional and antioxidant properties of pulp and seeds of two xocostle cultivars (*Opuntia joconostle* F.A.C. Weber ex Diguét and *Opuntia matudae* Scheinvar) of high consumption in Mexico. *Food Res Int* 46:279–285. <https://doi.org/10.1016/j.foodres.2011.12.031>
- Özcan MM, Al Juhaimi FY (2011) Nutritive value and chemical composition of prickly pear seeds (*Opuntia ficus indica* L.) growing in Turkey. *Int J Food Sci Nutr* 62:533–536. <https://doi.org/10.3109/09637486.2011.552569>
- Potgieter J, D'Aquino S (2017) Fruit production and post-harvest management. In: Inglese P, Mondragón C, Nefzaoui A, et al. (eds) *Crop ecology, cultivation and uses of cactus pear*. FAO of the UN and ICARDA, Roma, Italy, pp 51–69
- Prashanth L, Kattapagari KK, Chitturi RT, Baddam VRR, Prasad LK (2015) A review on role of essential trace elements in health and disease. *J Dr Ntr Univ Health Sci* 4:75
- Quintaes KD, Diez-Garcia RW (2015) The importance of minerals in the human diet. In: de la Guardia M, Garrigues S (eds) *Handbook of mineral elements in food*. Wiley, United Kingdome, pp 1–21
- Reda TH, Atspha MK (2019) Nutritional composition, antinutritional factors, antioxidant activities, functional properties, and sensory evaluation of cactus pear (*Opuntia ficus-indica*) seeds grown in Tigray region. *Ethiop Int J Food Sci* 2019:e5697052. <https://doi.org/10.1155/2019/5697052>
- Reis C, Gouveia C, Vitorino C, Gazarini L, Ribeiro M, Peres F (2017) Bioactive compounds and morphology in *Opuntia* spp. fruits from Portuguese ecotypes. *Bulgarian J Agr Sci* 23:929–938
- Ryan-Harshman M, Aldoori W (2005) Health benefits of selected minerals. *Can Fam Physician* 51:673–675
- Sáenz C (2017) Processing and utilization of fruit cladodes and seeds. In: Inglese P, Mondragon C, Nefzaoui A, et al. (eds) *Crop ecology, cultivation and uses of cactus pear*. FAO of the UN and ICARDA, Roma, pp 135–149
- Sanchez-Gonzalez N, Jaime-Fonseca MR, San Martín-Martínez E, Zepeda LG (2013) Extraction, stability, and separation of betalains from *Opuntia joconostle* cv. using response surface methodology. *J Agric Food Chem* 61:11995–12004. <https://doi.org/10.1021/jf401705h>
- Santos-Zea L, Gutiérrez-Urbe JA, Serna-Saldivar SO (2011) Comparative analyses of total phenols, antioxidant activity, and flavonol glycoside profile of cladode flours from different varieties of *Opuntia* spp. *J Agric Food Chem* 59:7054–7061. <https://doi.org/10.1021/jf200944y>
- Sasaki N, Abe Y, Goda Y, Adachi T, Kasahara K, Ozeki Y (2009) Detection of DOPA 4,5-dioxygenase (DOD) activity using recombinant protein prepared from *Escherichia coli* cells harboring cDNA encoding DOD from *Mirabilis jalapa*. *Plant Cell Physiol* 50:1012–1016. <https://doi.org/10.1093/pcp/pcp053>

- Soetan K, Olaiya C, Oyewole O (2010) The importance of mineral elements for humans, domestic animals and plants: a review. *African J Food Sci* 4:200–222
- Spada PD, Bortolin GV, Prá D, Santos CE, Dias JF, Henriques JA, Salvador M (2010) Macro and micro minerals: are frozen fruits a good source? *An Acad Bras Ciênc* 82:861–867
- Stein RJ, Höreth S, de Melo JRF, Syllwasschy L, Lee G, Garbin ML, Clemens S, Krämer U (2017) Relationships between soil and leaf mineral composition are element-specific, environment-dependent and geographically structured in the emerging model *Arabidopsis halleri*. *New Phytol* 213:1274–1286. <https://doi.org/10.1111/nph.14219>
- Szklarska D, Rzymiski P (2019) Is Lithium a micronutrient? from biological activity and epidemiological observation to food fortification. *Biol Trace Elem Res* 189:18–27. <https://doi.org/10.1007/s12011-018-1455-2>
- Tanaka Y, Sasaki N, Ohmiya A (2008) Biosynthesis of plant pigments: anthocyanins, betalains and carotenoids. *Plant J* 54:733–749. <https://doi.org/10.1111/j.1365-313X.2008.03447.x>
- Yahia EM, Mondragon-Jacobo C (2011) Nutritional components and anti-oxidant capacity of ten cultivars and lines of cactus pear fruit (*Opuntia* spp.). *Food Res Int* 44:2311–2318. <https://doi.org/10.1016/j.foodres.2011.02.042>
- Zeghib W, Boudjouan F, Bachir-bey M (2022a) Optimization of phenolic compounds recovery and antioxidant activity evaluation from *Opuntia ficus indica* using response surface methodology. *J Food Meas Charact* 16:1354–1366. <https://doi.org/10.1007/s11694-021-01241-w>
- Zeghib W, Boudjouan F, Vasconcelos V, Lopes G (2022b) Phenolic compounds' occurrence in *Opuntia* species and their role in the inflammatory process: A review. *Molecules* 27:4763. <https://doi.org/10.3390/molecules27154763>
- Zeghib W, Boudjouan F, Carneiro J, Oliveira AL, Sousa SF, Pintado ME, Ourabah A, Vasconcelos V, Lopes G (2024) LC-ESI-UHR-QqTOF-MS/MS profiling and anti-inflammatory potential of the cultivated *Opuntia ficus-indica* (L.) Mill. and the wild *Opuntia stricta* (Haw.) Haw. fruits from the Algerian region. *Food Chem* 460:140414. <https://doi.org/10.1016/j.foodchem.2024.140414>

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