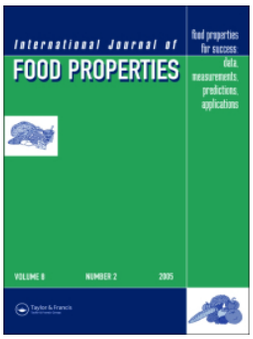

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Nutritional composition, functional and chemical characterization of Moroccan *Opuntia ficus-indica* cladode powder

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[a]Natural Resources and Sustainable Development Laboratory, Research Unit in Nutrition, Metabolism and Physiology, Department of Biology, Faculty of Sciences, Ibn Tofail, University, Kenitra, Morocco; [b]Organic Chemistry catalysis and Environment Laboratory, Department of Chemistry, Faculty of Sciences Ibn Tofail University, Kenitra, Morocco; [c]Department of Biology, Bahir Dar University, Bahir Dar, Ethiopia; [d]Laboratory of Therapeutic and Organic Chemistry, Faculty of Pharmacy, University of Montpellier, Montpellier, France; [e]Department of Pharmaceutics, College of Pharmacy, King Saud University, Riyadh, Saudi Arabia

ABSTRACT

Opuntia ficus-indica, also known as the prickly pear, is a cactus belonging to the Cactaceae family. For centuries, this remarkable plant has been valued for its medicinal, environmental, and culinary uses. The primary objective of this research is to examine and contrast the chemical composition, functional attributes, and nutritional significance of *Opuntia ficus-indica* cladodes sourced from three distinct regions in Morocco: Oulad Boubker, Imzouren, and Skoura. According to the results, moisture content differs significantly between the three sites, from 88.21 ± 0.20% to 92.11 ± 0.10%, with an acid pH value. While the ash content remained consistent across all three samples. Carbohydrate content ranging from 55.40 ± 0.08% to 55.90 ± 0.60%, fat content from 2.30 ± 0.21 to 2.62 ± 0.09, protein from 7.54 ± 0.03% to 9.07 ± 0.16%, crude fibers from 20.52 ± 1.87% to 21.00 ± 0.20%, and soluble fibers from 15.08 ± 0.16% to 16.33 ± 1.25%. Additionally, total chlorophyll content varied between 102.64 ± 8.93 and 144.80 ± 3.08 mg.100 g^{-1} DM. The functional properties showed considerable differences between the three samples: the water holding capacity ranged from 109.58 ± 0.11 to 174.95 ± 0.06 g water.100 g^{-1} DM, the oil holding capacity from 129.27 ± 0.39 to 146.51 ± 0.39 g oil.100 g^{-1} DM and the solubility index from 25.75 ± 0.60 to 33.18 ± 0.15 g solids.100 g^{-1} DM. Mineral analysis revealed significant differences based on location. The concentrations of potassium exhibited a considerable elevation compared to those of magnesium, calcium, sodium, iron, and zinc. Moreover, the existence of diverse organic functional entities, including alcohols, ketones, and acids, was authenticated by Fourier-transform infrared spectroscopy. A differential distribution of the chemical composition of cladodes according to region was confirmed by nutritional, mineral and functional characterization and functional groups of cladodes.

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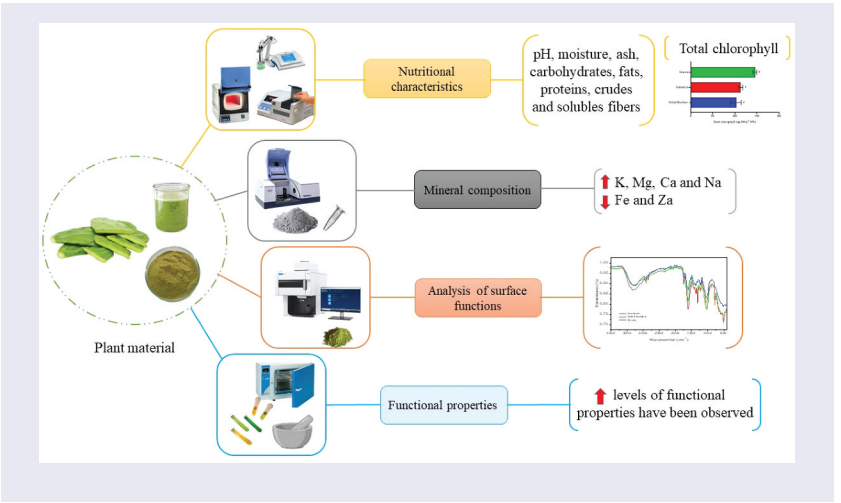
CONTACT Sara Razzak sara.razzak@uit.ac.ma Natural Resources and Sustainable Development Laboratory, Research Unit in Nutrition, Metabolism and Physiology, Department of Biology, Faculty of Sciences, Ibn Tofail, University, Kenitra, Morocco; Gezahign Fentahun Wondmie resercherfent@gmail.com Department of Biology, Bahir Dar University, Bahir Dar, Ethiopia



Introduction

Green chemistry is a relatively new concept aimed at minimizing risks throughout all stages of the life cycle to reduce environmental impacts. Additionally, it aims to be a financially viable approach.[1] Numerous research studies have shown that the use of pesticides and insecticides, which are employed to enhance and protect genetically modified and cultivated crops, may pose a direct threat to human health. These foods are often associated with health issues, such as the development of allergies due to the harmful effects of fertilizers used to boost the nutritional content of these crops and ensure their microbiological safety.[2]

Opuntia ficus-indica, commonly known as the prickly pear, belongs to the *Cactaceae* family. Over the centuries, this cactus species has been cultivated and valued for its medicinal, environmental, and culinary applications, showcasing unique characteristics and a global presence.[3] Every part of this plant is utilized, leaving no waste. The food industry was among the first to recognize the potential of *Opuntia ficus-indica*. The fruits of this cactus are prized for their high antioxidant content, including vitamin C, flavonoids, and betalains.[4] Researchers have demonstrated that using biocoagulants derived from *Opuntia ficus-indica* cladodes makes them an effective coagulant and flocculant, offering a potential solution to drinking water supply challenges.[5] In this context, the structural configuration of *Opuntia ficus-indica* cladodes makes them suitable for formulating functional food items aimed at promoting well-being.[6]

Extensive research has highlighted the remarkable health benefits of cladodes, thanks to their rich nutritional composition, including polysaccharides, vitamins, minerals, and functional compounds such as phenolic antioxidants. These attributes make cladodes an excellent choice for incorporation into food, dietary, and pharmaceutical products.[7] Epidemiological studies have shown that maintaining a consistent diet centered around plant-based foods is associated with a reduced incidence of chronic illnesses related to oxidative stress. Consequently, compounds with bioactive properties can enhance their medicinal qualities by having high concentrations of antioxidants, fiber, minerals, and vitamins, while being low in calories and lipid content, and free from artificial additives commonly found in traditional cuisine.[8] It is also well known for its ability to protect nerve cells against diseases such as Parkinson's, Alzheimer's, and cerebrovascular diseases.[9] Notably, the juice extracted from Opuntia fruits is a valuable natural source of colorants (betanin and indicaxanthin), vitamins B_1, B_2, and C, and dietary fiber.[10]

Additionally, the cladodes of *Opuntia ficus-indica* exhibit a wide range of health benefits, including antioxidant, anti-inflammatory, neuroprotective, antiviral, antiulcerative, antigenotoxic,

and hypotensive properties.[9,11] Several chemical compounds included in dietary fiber, including cellulose, hemicelluloses, pectin, lignin, and gums, are resistant to the action of digestive enzymes. The amount of fiber in a food can differ based on the plant's species and its developmental stage. The bran layers of cereal grains, berries, fruit skins, and plant seeds all often contain high levels of fiber.[12] The researchers suggest incorporating cladodes powder into milk-based drinks and breakfast cereals. It also has thickening properties, potentially reaching concentrations of up to 20% in vegetable soups and dessert gels.[13] According to earlier research, the amount of calcium (Ca) in immature prickly pear cladodes increases with the age of the cladodes.[14] It's also well known for being a significant source of minerals, pectin, and other nutrients, including mucilage.[15]

Expanding on our previous studies concerning *Opuntia ficus-indica*, this inquiry goes into further depth. The primary objective of this study is to thoroughly evaluate the nutritional and mineral content of cladode samples grown in three distinct regions of Morocco: Oulad Boubker, Imzouren, and Skoura. To accomplish this, advanced methodologies such as Inductively Coupled Plasma (ICP) and Fourier-Transform Infrared (FTIR) spectroscopy are utilized for the analysis and characterization of the extracts. Through the application of a stringent statistical analysis, our goal is to study and compare the properties of *Opuntia ficus-indica* cladodes in these various geographical areas.

Materials and methods

Chemicals and reagents

High-purity ≥ 98% chemicals used in this study were all purchased from Sigma-Aldrich.

Plant material and extract preparation

Mature cladodes of *Opuntia ficus-indica* (OFI) were collected from three geographically distinct sites in Morocco. These sites varied in both topography and climate: Imzouren, a town in the province of Al Hoceima on the northern Mediterranean coast in the Tangier-Tetouan-Al Hoceima region; Oulad Boubker, a rural commune in the Driouch subdivision of the Oriental region; and Skoura, located 40 km from Ouarzazate in the southern Souss-Massa region.

The different powders were obtained by dehydrating slices of cladodes in an oven set at 60°C for 18 to 20 h. After manually removing the spines, the cladodes were washed with distilled water and sanitized with a 10% alcohol solution. Subsequently, the dried materials were finely ground using a grinder and stored in a dark environment at room temperature. Some young cladodes are sliced into pieces for fresh, unprocessed usage.

Proximate analysis

The assessment of moisture, pH, and ash content was proficiently executed by adhering to the traditional methodologies stipulated by the Association of Analytical Chemists (AOAC).[16]

Carbohydrate content

The carbohydrate content is determined by Dubois *et al.*[17] Sugar extraction was performed following the AOAC[16] method. Briefly, 0.1 g of sample was mixed with 30 mL of 80% (v/v) ethanol and allowed to stand for 48 h at room temperature. After removing the ethanol by evaporation at 80°C, 20 mL of distilled water was added to the extract to obtain the solution for analysis. In a test tube, 1 mL of the solution to be analyzed was mixed with 1 mL of 5% (v/v) phenol and 5 mL of pure concentrated sulfuric acid (96%). After 10 min, the mixture was placed in a water bath at 25°C for 20 min and the absorbance was read at 490 nm (ZUZI spectrophotometer model 4201/20).

Fat content

Following the AOAC[18] standard, the Soxhlet method was employed to quantify lipid content. The method consists of depleting the sample with hexane, which is then removed by evaporation. Only the fat remains in the flask for quantification.

Protein content

Protein content was evaluated using the Lowry[19] method for protein quantification, which is based on the Biuret reaction and the reduction of Folin reagent. A 5% aqueous solution of young cladode powder was used as the sample after preparation of a cuprous alkaline pretreatment solution. After reaction with Folin-Ciocalteu reagent, the absorbance was measured at 750 nm. The protein content was determined extrapolating from a standard curve prepared using bovine serum albumin.

Crude fiber content

Fiber content in young cladodes was determined using a sequential acid-base digestion method.[16] 1 g of dried cladode powder (previously dried at 105°C for 3 h) was boiled with 150 mL of 1.25% sulfuric acid for 30 min. The residue was then filtered, washed with hot distilled water, and boiled again with 150 mL of 1.25% KOH solution for another 30 min. Following a series of hot and cold-water washes and acetone rinses, the residue was dried at 105°C to a constant weight. Finally, the remaining residue, containing both fibers and minerals, was incinerated at 550°C for 3 h to remove minerals, leaving behind the crude fiber content.

Soluble fiber content

The soluble fiber content of the powder was determined using the method of Khule *et al.*.[20] 2 mL of cladode puree were mixed with 6 mL of 80% ethanol in an acidic solution (pH 1.5) and centrifuged at 8000 rpm for 15 min. The resulting pellet was then dried in an oven at 50°C. Pectin content was subsequently calculated based on the difference between the initial sample weight and the weight of the dried pellet.

Total chlorophyll content

Total chlorophyll content was measured in fresh cladodes following the method of Lichtenthaler and Wellburn[21] with slight modifications. The samples were prepared using an 80% (v/v) acetone solution. After filtration, the solutions were transferred to tubes and centrifuged. The absorbance of the samples was then measured at 645 nm and 663 nm using a ZUZI spectrophotometer model 4201/20. Chlorophyll content was subsequently calculated and expressed as milligrams of chlorophyll per 100 grams of dry weight (mg.100 g^{-1} DM).

$$\text{Total chlorophyll}\,(\text{mg.100}\,\text{g}^{-1}\,\text{DM}) = 17.32\text{A}_{645} + 7.18\text{A}_{663}$$

Where: A_{645} represents the absorbance at 645 nm, and A_{663} represents the absorbance at 663 nm

Mineral composition

The mineral elements calcium (Ca), magnesium (Mn), iron (Fe), potassium (K), sodium (Na), zinc (Zn), present in the buffer powder were quantified by inductively coupled plasma optical emission spectrometry ICP-OES (Inductively Coupled Plasma-Optically Emitting Spectra, Perkin Elmer Optima 8000) according to procedure 925.10.[16] The fast sequential optical ICP spectrometer enables simultaneous peak and background measurement with dual aiming, based on the combination of a dual Scanning Charge Coupled Device (CCD) detector, with a lower resolution of the order of 6–8 pm in the UV. A spectral range from 160 to 900 nm and dual-viewing of the plasma, with axial and/or radial viewing, enable simultaneous measurement of highly concentrated elements and traces.

Analysis of surface functions by Fourier transform infrared spectroscopy (FTIR)

FTIR spectra were recorded on a Bruker Tensor II spectrometer between 4000–400 cm^{-1} with a RapidScan at over 25 spectra at 16 cm^{-1} spectral resolution. The samples were prepared with *Opuntia ficus indica* cladode powder.

Water holding capacity (WHC)

The method of Chen *et al.*[22] was used to determine the water holding capacity (WHC) of cladode powder. Briefly, 1 g of powder was mixed with 50 mL of distilled water. The mixture was centrifuged, and the supernatant was discarded. The remaining pellet was then inverted at 50°C for 25 min. WHC was expressed as the amount of bound water per 100 gram of dry sample.

Oil holding capacity (OHC)

Lin *et al.*[23] method was employed to assess the oil holding capacity (OHC) of the powdered sample. Briefly, 1 gram of powder was mixed with 20 mL of corn oil, stirred, and centrifuged. Supernatant was removed and pellet mass was determined. The weight of the remaining oil-bound material was measured. OHC was expressed as the amount of bound oil per 100 gram of dry sample.

Solubility index (SI)

The method of Anderson *et al.*[24] was used to determine the solubility index (SI) of cladode powder. This involved dispersing 1 g of powder in 30 ml of distilled water and incubating in a water bath at 90°C for 15 min. After cooling to room temperature, centrifugation at 3000 g for 10 min was performed. Subsequently, Supernatant was transferred to reweighed crucible and evaporated at 105°C overnight. The solubility index was calculated as g per 100 g of sample flour on a dry weight basis.

Statistical analysis

Results were reported as mean ± standard deviation. Each analysis was conducted in triplicate. The mean of each data item was compared between the three study sites using the ANOVA test followed by Tukey's multiple comparison test ($p < .05$) (SPSS version 26).

Results and discussion

Proximate analysis

The proximate composition of OFI pads gathered from three regions of Morocco (Skoura, Oulad Boubker, and Imzouren), encompassing moisture, pH, ash, carbohydrate, fats, proteins, and fibers is outlined in Table 1. The moisture content of OFI cladodes estimated in this study is 88.21 ± 0.20% for Skoura, 89.40 ± 0.12% for Oulad Boubker and 92.11 ± 0.10% for Imzouren. These values are similar to

Table 1. Nutritional profile of *Opuntia ficus-indica* cladodes sourced from Morocco.

Parameters	Oulad Boubker	Imzouren	Skoura
Moisture (%)	89.40 ± 0.12^{a}	92.11 ± 0.10^{c}	88.21 ± 0.20^{b}
pH	5.05 ± 0.01^{a}	4.80 ± 0.01^{b}	4.51 ± 0.01^{c}
Ash (%)	25.12 ± 0.05^{a}	25.14 ± 0.05^{a}	24.40 ± 0.14^{b}
Carbohydrates (%)	55.84 ± 0.04^{a}	55.40 ± 0.08^{a}	55.90 ± 0.60^{a}
Fats (%)	2.62 ± 0.09^{a}	2.60 ± 0.18^{a}	2.30 ± 0.21^{a}
Proteins (%)	9.07 ± 0.16^{a}	8.73 ± 0.06^{a}	7.54 ± 0.03^{b}
Crude fibers (%)	20.74 ± 0.21^{a}	21.00 ± 0.20^{a}	20.52 ± 1.87^{a}
Soluble fibers (%)	15.08 ± 0.16^{a}	15.92 ± 0.23^{a}	16.33 ± 1.25^{a}

Letters a–c indicate that there is a statistical difference ($p < .05$) between each parameter tested separately.

that found by Moussaoui,[25] with a moisture content of 87%. In another study, the moisture content of OFI cladodes varied between 90.67 and 94.95%.[26] In fact, according to Ayadi *et al.*,[27] cladodes are exceptionally rich in water, comprising 90 to 91%. A significant proportion of which is explained in part by their role in water storage.[25] Taking into account the differences between ecotypes noted by El Kharrassi,[28] the study by Stintzing and Carle[15] shows that young nopales store more water.

Acidic and insignificant pH values of 4.51 ± 0.01, 4.80 ± 0.01 and 5.05 ± 0.01 were found for Skoura, Imzouren, and Oulad Boubker, respectively. These results are in line with those of Rodríguez-Garcia *et al.*,[14] who found a pH of 4 to 4.5. This acidity contributes to the inhibition of bacterial growth.[29] Furthermore, according to Inglese *et al.*,[30] acidity increases during the night and decreases during the day, with a significant variation depending on the time of day.

Ash analysis revealed very similar, insignificant values between the two regions (Oulad Boubker and Imzouren) at 25.12 ± 0.05% and 25.14 ± 0.05%, respectively, while a significant value of 24.40 ± 0.14% was recorded in the Skoura region. Hernández *et al.*[31] reported a similar value (21.35%), whereas Astello *et al.*[32] and Mounir *et al.*[33] found lower values than ours. It has been suggested that various factors, such as pH, water availability, texture, and soil composition, influence certain elements of the chemical composition of ash in which the cladode grows. These findings are consistent with previous research indicating that the primary minerals found in prickly pear figs are in the form of carbonates, chlorides, sulfates, and phosphates.[34,35]

Regarding carbohydrates, the analysis revealed insignificant values between the three study sites, ranging from 55.40 ± 0.08% to 55.90 ± 0.60%. In contrast to our findings, Moussaoui[25] reported a carbohydrate content of 36.91%. Sadok *et al.*[36] obtained a carbohydrate content of 1.66% for a growth stage (less than three months), although the same authors suggested it could reach 8.8% for one-year-old cladodes. Carbohydrates are also the primary component of OFI.[15] The composite powder's rich carbohydrate content plays a crucial role in bread, cakes, biscuits, pastries, and pizza crusts. Carbohydrates act as the fuel source, providing the body with the energy it needs to function optimally.[37]

The fat content in OFI cladodes was observed to be low and showed insignificant difference between the three sites of Imzouren, Oulad Boubker, and Skoura, with values of 2.60 ± 0.18%, 2.62 ± 0.09%, and 2.30 ± 0.21%, respectively. These findings are in line with the study conducted by Rodríguez-Garcia *et al.*,[14] which reported values ranging from 1.96% to 3%, and are notably higher than those documented by Angulo-Bejarano *et al.*[38] (0.2%). Albergamo *et al.*[39] conducted a similar investigation on Tunisian cladodes of the same species and revealed a fat content of 1.15%, which is lower than the values observed here. Additionally, Hernández-Urbiola *et al.*[12] observed that fat content decreased with age, although no direct correlation between age and fat content was observed. The reductions observed could be the result of physiological changes or variations in climatic conditions, including rainfall or irrigation levels, in the areas where the plants were found.[40] The high fat content in flour plays a crucial role in bakery production, contributing to a flaky and tender texture. Fat acts as a barrier between water and gluten, inhibiting the formation of a strong gluten network.[41]

Regarding proteins, our study indicated insignificant values for Oulad Boubker and Imzouren of 8.73 ± 0.06% and 9.07 ± 0.16%, respectively, while the value found in the Skoura site was 7.54 ± 0.03% and statistically significant compared to the others. These low levels were also noted by Hernández-Urbiola *et al.*,[12] whereas Rodríguez-Garcia *et al.*[14] reported higher values ranging from 11.39% to 14.22%. However, the protein content of mature cladodes reported by El Kharrassi[28] ranged from 4.64% to 14.22%. Nitrogen fertilization and cladode age, along with notable variations between and within species, all contribute to protein richness.[28,42]

The crude fiber content of dried cladodes ranged from 20.52 ± 1.87% to 201.00 ± 0.20%, while in the case of soluble fiber, values of 15.08 ± 0.16% to 16.33 ± 1.25% were found. Albergamo *et al.*[39] reported a value of 28.39% for crude fiber, whereas Hernández-Urbiola *et al.*[12] found values ranging from 11% to 23.33% for soluble dietary fiber. Comparatively, the seeds of this species contain much less crude fiber (12.47%) than the cladodes.[43] Cactus dietary fiber consists of various chemical

components such as cellulose, hemicelluloses, pectin, lignin, gums, and more, which exhibit resistance to digestive enzymes.[44] According to Ramulu and Rao,[45] genetic composition, agro-climatic variables, dosing technique, and geographical location have an impact on fiber content. In summary, the results presented underscore the potential of OFI pads as a valuable source of essential nutrients, thereby making them suitable for improving individuals' dietary and overall health.

Chlorophyll content

According to the data presented in Figure 1, the Chlorophyll content showed insignificant results between the two sites, Imzouren and Oulad Boubker, with values of 102.64 ± 8.93 mg.100 g^{-1} DM and 113.22 ± 3.28 mg.100 g^{-1}DM, respectively, while Skoura showed statistical significance compared to the other sites with a value of 144.80 ± 3.08 mg.100 g^{-1} DM. Similar values to our results were reported by Ayadi *et al.*[27] (131.08 mg.100 g^{-1} DM), while a higher value was found by Msaddak[46] of 802 mg.100 g^{-1} DM. The chlorophyll content of cladodes is directly linked to the increase in photosynthesis (carbohydrate production) as they age and at the start of the fruiting process.[36] It's worth noting that, besides factors like cladode age and season, the concentration of chlorophyll can be influenced by irradiance temperature, water availability, and nutrient supply.[47]

Nutritionally, incorporating chlorophyll into the diet during early life could potentially attenuate weight gain, improve glucose tolerance, and reduce inflammation, thereby potentially acting as a preventive measure against obesity.[48]

Mineral composition

Minerals are widely recognized for their essential role in human nutrition, contributing to overall physical and mental well-being.[47] The mineral composition of cladodes from various sites is depicted in Table 2. Potassium emerges as the most abundant mineral in OFI cladodes, ranging from 2283.475 to 2278.975 mg.100 g^{-1} DM, followed by magnesium from 590.315 to 588.65 mg.100 g^{-1} DM, calcium from 503.80 to 524.30 mg.100 g^{-1} DM, sodium from 151.925 to 149.425 mg.100 g^{-1} DM, and a low content of iron and zinc, ranging from 15.9 to 15.625 mg.100 g^{-1} DM and 4.775 to 4.825 mg.100 g^{-1} DM, respectively. A notable difference in composition was observed among the three sites. Similar studies have reported potassium as the predominant mineral in cladodes.[27,49] These values remain approximate due to variations in mineral content influenced by factors such as species, tissue physiological state, and cultivation location.[15] Likewise, seeds are rich in calcium (Ca), potassium

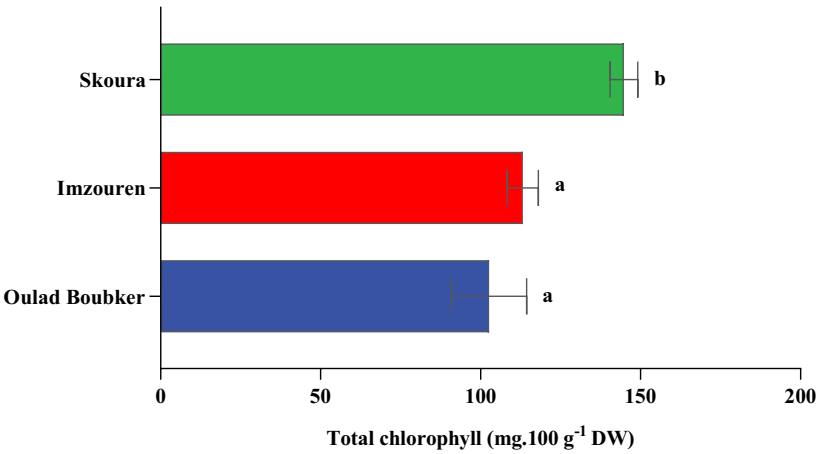


Figure 1. Total chlorophyll content of *Opuntia ficus-indica* cladodes sourced from Morocco. Letters a and b indicate that there is a statistical difference ($p < .05$) between each simple tested.

Table 2. Mineral composition of *Opuntia ficus-indica* cladodes in mg.100 g^{-1} DW.

Minerals	Oulad Boubker	Imzouren	Skoura
Ca	524.30 ± 0.03^{a}	512.30 ± 0.04^{b}	503.80 ± 0.01^{c}
Fe	15.30 ± 0.01^{a}	15.90 ± 0.02^{b}	15.60 ± 0.01^{c}
K	2271.00 ± 0.01^{a}	2283.50 ± 0.01^{b}	2281.00 ± 0.01^{c}
Mg	590.32 ± 0.02^{a}	588.15 ± 0.01^{b}	588.70 ± 0.03^{c}
Na	149.43 ± 0.01^{a}	148.70 ± 0.01^{b}	152.00 ± 0.02^{c}
Zn	4.83 ± 0.03^{a}	4.80 ± 0.04^{b}	4.78 ± 0.04^{c}

Letters a–c indicate that there is a statistical difference ($p < .05$) between each parameter tested separately.

(K), magnesium (Mg), and phosphorus (P), rendering them a valuable source of both macro and micronutrients and can be incorporated as a food ingredient to supply essential nutrients.[50] Furthermore, the mineral composition of prickly pear varies depending on its cultivation location. Assessments reveal significant differences in the levels of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), zinc (Zn), and manganese (Mn) among samples obtained from different geographical regions.[51] Minerals perform vital functions in our bodies, from strengthening our bones to aiding the transmission of nerve signals, all contributing to a healthy and extended lifespan. The presence of diverse minerals not only supports the production of various hormones but also helps regulate a steady heartbeat.[47]

Functional properties

Table 3 displays the functional properties, which include water holding capacity (WHC), oil holding capacity (OHC), and solubility index (SI), of dry cladode powder. These characteristics are primarily influenced by the fibers found in the powders.

The water holding capacity exhibited a higher value for the Skoura site, with 174.95 ± 0.06 g water.100 g^{-1} DM, 145.78 ± 0.04 g water.100 g^{-1} DM for Oulad Boubker, and 109.58 ± 0.11 g water.100 g^{-1} DM for Imzouren. These values demonstrated a significant disparity for the Skoura site compared to the other sites. In similar studies, Ayadi *et al.*[27] reported higher values (315 g g water.100 g^{-1} DM) for cladodes of the same species, while Msaddak[46] found an even higher value (795 g water.100 g^{-1} DM). Powder with a higher water holding capacity contains more hydrophilic constituents. Furthermore, researchers have observed that the functional properties of dehydrated powders are influenced by drying conditions, and the utilization of intense heat treatments during the preparation of cactus cladode flours has a detrimental effect on their water absorption capacity and green color.[52] Further, Prior studies indicate that raising the overall dry mass percentage, encompassing fibers, may enhance the capacity for water retention within the gel matrix and boost WHC.[53]

In terms of oil holding capacity, our investigation found insignificant values across all three study sites, ranging from 129.27 ± 0.39 g oil.100 g^{-1} DM to 146.51 ± 0.39 g oil.100 g^{-1} DM. These findings closely align with those reported by Ayadi *et al.*[27] and Msaddak.[46] The capacity to retain oil is primarily attributed to hydrophobic constituents. This property is instrumental in enhancing the retention of fats and flavors in food products and contributes to improving overall technological efficiency.[54] Dietary fiber demonstrates the capacity to interact with water and various compounds within the gastrointestinal system, consequently affecting the oil-holding

Table 3. Functional characteristics of *Opuntia ficus-indica* cladodes originating from Morocco.

Parameters	Oulad Boubker	Imzouren	Skoura
WHC (g water.100 g^{-1} DM)	145.78 ± 0.04^{a}	109.58 ± 0.11^{a}	174.95 ± 0.06^{b}
OHC (g oil.100 g^{-1} DM)	146.51 ± 0.39^{a}	129.27 ± 0.39^{a}	140.95 ± 0.42^{a}
SI (g solid.100 g^{-1} DM)	25.75 ± 0.60^{a}	28.93 ± 0.45^{a}	33.18 ± 0.15^{a}

Letters a–c indicate that there is a statistical difference ($p < .05$) between each parameter tested separately.

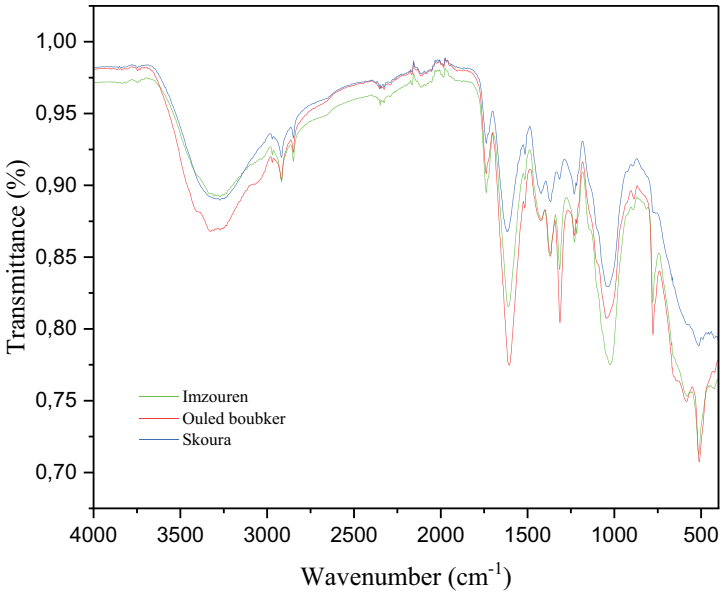


Figure 2. FTIR spectrum of dried *Opuntia ficus-indica* cladodes sourced from Morocco.

capacity parameter. Nonetheless, the oil-holding capacity exhibited by dietary fiber is subject to fluctuations based on the composition and amount of fiber inherent in a particular food product.[55]

The solubility index of the cladode powder exhibited no significant difference among the three study sites: 33.18 ± 0.15 g solid.100 g^{-1} DM for Skoura, 28.93 ± 0.45 g solid.100 g^{-1} DM for Imzouren, and 25.75 ± 0.60 g solid.100 g^{-1} DM for Oulad Boubker. These values exceed those reported by Ayadi *et al.*[27] (25.54%) and Ammar *et al.*[56] (15.5%) for the same OFI species. The water solubility index plays a significant role in dried extract powders, serving as a key parameter that reflects their capacity to dissolve quickly for subsequent application in food or pharmaceutical sectors.[57] It's important to note that the solubility index correlates with the presence of soluble molecules in the powder. Specifically, the quantity of soluble fraction provides insights into the potential for viscosity, gel formation, and/or emulsification.[58]

Analysis of surface functions

The FTIR spectrum was analyzed within the wavelength range of 4000–400 cm^{-1} to characterize the main functional groups present in OFI cladode powder. Figure 2 displays the spectra obtained from the three study sites. A broad peak was noted around 3271.71 cm^{-1} for Imzouren and Skoura, and approximately 3326.52 cm^{-1} for Oulad Boubker, attributed to —OH (hydroxyl group) bands associated with alcohols, phenols, and carboxylic acids.[59] Peaks observed in the range of 2917.16–2849.06 cm^{-1} were assigned to aliphatic C—H vibrations.[60] A peak at approximately 2114.06–2113.84 cm^{-1} indicated the presence of C≡C groups in Skoura and Imzouren. Additionally, the spectra exhibited a band between 1737.48–1618.11 cm^{-1}, characterized by C═O and phenol groups.[61] The absorption region around 1400–1350 cm^{-1} corresponded to the COO- carboxylic double bond of deprotonated carboxylate functional groups.[62] Peaks observed in the 1320–1004 cm^{-1} range indicated stretching vibrations of —COOH groups, aromatic proteins, phosphoric groups, and polysaccharides.[63] The presence of aromatic groups was confirmed by a peak around 897–673 cm^{-1}.[64] Spectra below 700 cm^{-1} potentially indicated halogen stretching.[59]

Conclusion

The physicochemical analysis of *Opuntia ficus-indica* cladode from different regions in Morocco revealed significant variations among the three study sites. Our findings underscored the cladodes' potential as a valuable source of dietary fiber, chlorophyll, essential inorganic elements (such as Mg, K, Ca, Na, Fe, and Zn), proteins, fats, and carbohydrates. High ash content, acidic pH levels, and elevated moisture content were also observed. Functional assessments highlighted the cladodes' capacity for water and oil absorption, along with a notable solubility index. Comparison of FTIR spectra indicated no discernible differences in the characteristic groups of OFI cladode powder across the studied sites. Moreover, the chemical composition of cladodes exhibited variability, influenced by geographical location. This variability suggests that environmental conditions in each region contribute to biochemical processes within the plants, resulting in differences in nutrient content and functional properties. Given their diverse nutritional and functional attributes, coupled with environmental benefits, cladodes present promising opportunities for the development of innovative biopharmaceuticals.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Author's contribution

Conceptualization, R.S, A.M, and Z.M.; methodology, R.S. and Z.M.; software, R.S and Z.M.; validation, T.Y, B.R. and I.S.; formal analysis, R.S., Z.M and B.H.; investigation, R.S., Y.B.A.J.,and G.F.W; resources, AZK. and G.F.W data curation, R.S., and M.T; writing – original draft preparation, R.S., and Z.M.; writing – review and editing, S.R., Z.M. and T.Y.; visualization, T.M., B.H, and I.S.; supervision, T.Y. All authors have read and agreed to the published version of the manuscript.

Data availability statement

Data will be available upon request from the corresponding author.

Ethical approval

Ethical Approval is not applicable to this article.

Statement of Informed consent

There are no human subjects in this article and informed consent is not applicable.

Statement of human and animal rights

This article does not contain any studies with human or animal subjects.

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