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RESEARCH ARTICLE

Cacti from Northern Chile with potential for domestication: Morphological, chemical, and functional characterization of their fruits

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ABSTRACT

Cacti are plants native to the Americas, characterized for their numerous nutritional and functional values, their multiple uses, and their unique morphology and physiology, which allow them to grow and thrive under dry environments with extreme temperatures and in poor soils. Climate Change is imposing great challenges on research and development in agriculture to maintain productivity using sustainable production systems to cope with human population increases. Several strategies are currently being developed to cope with this problem, being domesticating of new species one strategy, particularly if one uses native cacti species. Chile is particularly rich in endemic cacti species. After studying fruit and ethnobotanical characteristics six species were selected for further studies: *Corryocactus brevistylus* vernacular named "rumba"; *Leucostele atacamensis* "pasacana"; *Airampoa ayrampo* "ayrampo"; *Browningia candelaris* "sabaya"; *Eulychnia iquiquensis*, "copao de Iquique"; and *Haageocereus chilensis* "tunilla" which are native cactus species distributed mainly, but not exclusively, in Northern Chile. Their fruits are edible with functional properties or can be used as natural food colorants, characteristics that makes them suitable for domestication. Fruits of *C. brevistylus*, *H. chilensis* and *L. atacamensis* can be consumed fresh, with *L. atacamensis* having a very high antioxidant capacity. *Airampoa ayrampo*, on the other hand, has potential as a natural red-purple food colorant. This work shows specific analytical data related to the proportion of pulp in the fruit of these species, and the presence of functional compounds with antioxidant capacity, such as vitamin C and phenolics compounds.

Key words: Antioxidant capacity, arid zone fruits, Cactaceae, food colorant.

INTRODUCTION

World agricultural production is being affected by climate change, mainly because of increases in temperature, in CO_2 and other greenhouse effect gas emissions, and in changes in the patterns of rainfall, all of which are leading to a decline in food production (Eftekhari, 2022). Several strategies are being used to cope with this significant challenge for agriculture and one of them is the development of climate-resilient crops to make available plants tolerant to drought, high temperatures, and poor soils (Eftekhari, 2022).

In this context, species in the Cactaceae family stand out for their nutritional value, diverse uses, and unique morphology, which allows them to grow and thrive under stressful conditions such as dry, xeric, and low-temperature environments (Coqueiro et al., 2024).

Species of the Cactaceae family are naturally distributed in the American continent from Canada to Patagonia and from sea level to almost 4000 m a.s.l., mainly in arid and semi-arid regions. They were among the first plants taken from the Americas to Europe, and from there, they were distributed to the rest of the world, where they are extensively cultivated nowadays (Khan et al., 2024). Some species were domesticated very early in human history. *Opuntia ficus-indica*, the cactus pear, was domesticated mainly because of its edible fruit almost 9000 yr before present time (Mizrahi, 2014). Since then, several other species have been domesticated for fresh fruit consumption, like the pitahayas (*Selenicereus* spp.) Others were domesticated as animal feed, to produce cosmetics, as ornamentals, and other uses. In a climate change scenario, this family acquire strong economic relevance in agriculture, particularly for the world's arid zones (Coqueiro et al., 2024). Cacti are also well known for the functional components and other active phytochemicals present in different plant parts, like phenolics, dietary fiber, and antioxidants (Monteiro et al., 2023). In rural communities, cacti are also utilized in folk medicine, and in recent years, their consumption has been reported to produce several health benefits (Das et al., 2020).

Over 140 species and subspecies of cacti grow in the Chilean territory, of which 45% are endemic (Walter and Guerrero, 2022). In the Northernmost area of the country, 19 species have been reported (Pinto and Kirberg, 2009) of which 8 produce fruits with potential uses: *Corryocactus brevistylus* (K. Schum. ex Vaupel) Britton & Rose, *Leucostele atacamensis* (Phil.) Schlumpb., *Airampoa ayrampo* (Azara) Doweld, *Browningia candelaris* (Meyen) Britton & Rose, *Eulychnia iquiquensis* (K. Schum.) Britton & Rose, *Haageocereus chilensis* F. Ritter ex D.R. Hunt, *Lobivia ferox* Britton & Rose, and *Eulychnia acida* Phil., but only the fruit of this last one has been fully characterized regarding its chemical and functional properties (Masson et al., 2011).

This work was aimed to describe particularly their fruit morphology their chemical and functional properties and the presence of other bioactive compounds in the six species listed above, as a first step to determine the domestication potential of some of these species, as has been done with others in Chile and elsewhere (Khan et al., 2024).

MATERIALS AND METHODS

Species considered in the study

The following six species were selected based on their fruit characteristics and available ethnobotanical information (Pinto and Kirberg, 2009). Current scientific names are listed according to WFO Plant List, Snapshots of the taxonomy (https://wfoplantlist.org):

Corryocactus brevistylus (K. Schum. ex Vaupel) Britton & Rose, vernacular name "rumba", is a robust shrubby plant, 1-3 m high, branched from the base, with segmented branches, 8-15 cm in diameter, with 6-9 ribs (Figure 1A), with areoles spaced between 2-4 cm with 3-15 spines, with some short ones (1 to 3 cm) and others longer (5-24 cm), that grows in the foothills of the Andes mountains at 2400 to 3500 m a.s.l., from 18° to 21° S lat (Figure 2).

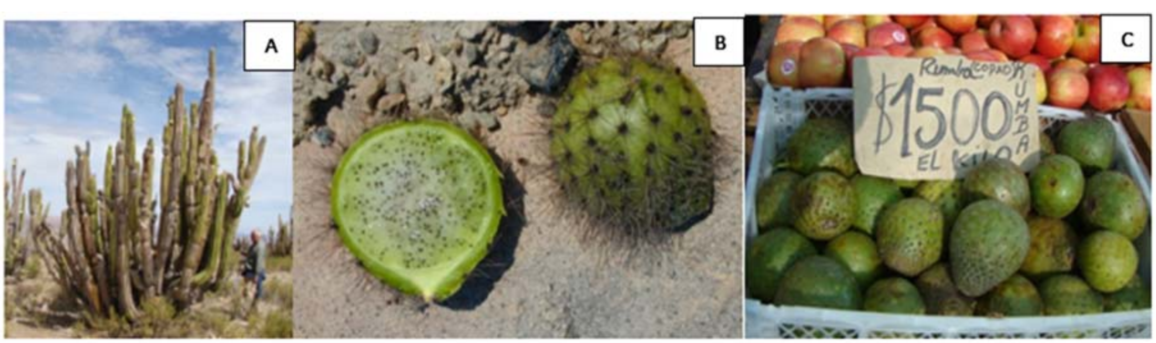

Figure 1. *Corryocactus brevistylus*: Mature plant (A), cross-section of the "rumba" fruit (B), fruits for sale at a market in Iquique (C).

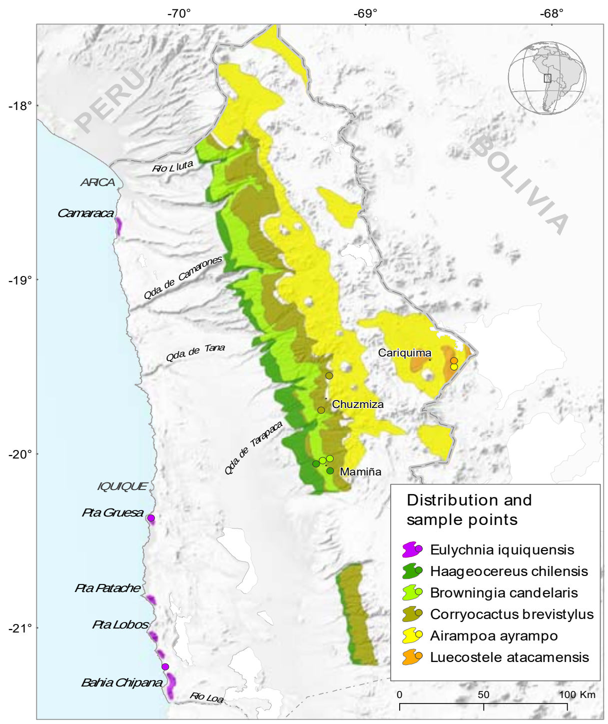

Figure 2. Areas where fruit samples were obtained in Northern Chile.

Leucostele atacamensis (Phil.) Schlumpb., "pasacana" (Synonym: *Echinopsis atacamensis* (Phil.) H. Friedrich & G.D. Rowley), is a plant that produce lateral branches that acquire the shape of a chandelier, with 20-35 ribs with large round areoles carrying 50-100 unequal spines 13-20 cm long, where it is difficult to differentiate the central from radial ones (Figure 3A), that grows in the highlands of the Andes mountains between 3600 and 4100 m a.s.l., around 19.5° S lat (Figure 2).

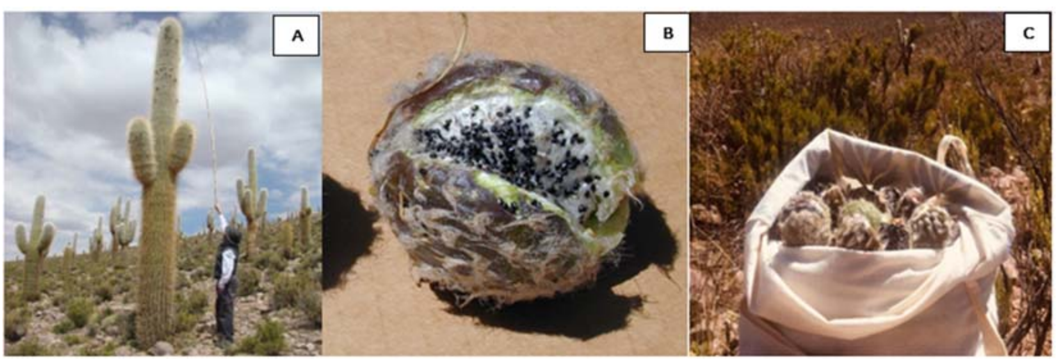

Figure 3. *Leucostele atacamensis*: Mature plant (A), "pasacana" ripe fruit (B), fruits collected by local people (C).

Airampoa ayrampo (Azara) Doweld, "ayrampo" (Synonym: *Tunilla soehrensii* (Britton & Rose) D.R. Hunt & Iliff), plant grows as a low subshrub of 30 to 60 cm in diameter and 10-20 cm height; stems, generally flattened, with segments 4 to 8 cm long, with 40-60 areolas per segment, and 2-12 acicular spines, uneven and up to 7 cm in length (Figure 4A), that grows in the high hills of the Andes mountains at 3700-4200 m a.s.l. (Figure 2), together with species of *Leucostele.*

Figure 4. *Airampoa ayrampo*: Mature plant (A), “ayrampo” ripe fruit (B), seeds fruit for sale at a market in Iquique (C).

Browningia candelaris (Meyen) Britton & Rose, “sabaya”, has a tree-like stem up to 50 cm in diameter and 3-5 m high. Thorny at the base, but when reaching a certain height, it divides into erect stems without thorns. The trunk possesses 27-33 flattened ribs; areoles are oval and quite large; thorns are numerous, up to 50 per areola and up to 15 cm long, brown and gray (Figure 5A), that grows between 2000 to 3000 m a.s.l. in the pre-Andean zone between 19° and 20° S lat (Figure 2), in very arid mountain slopes, where no other vegetation is present, except for a few *Haageocereus* spp.

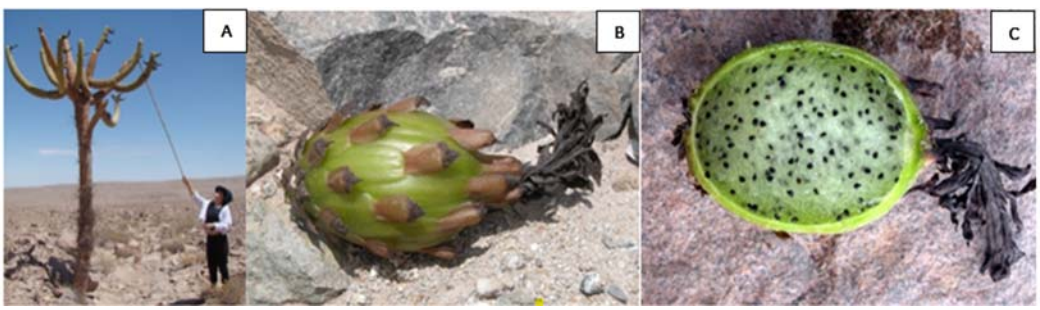

Figure 5. *Browningia candelaris*: Mature plant (A), “sabaya” ripe fruit (B), cross-section of the fruit (C).

Eulychnia iquiquensis (K. Schum.) Britton & Rose, “copao de Iquique”, plant has a branched growth of stems with 12-15 ribs that can reach a height of 2-7 m. The areoles are covered with short white “wool” from where 10-20, 2-12 cm long spines emerge that are difficult to tell if they come from the central or radial zone of the areoles (Figure 6A), that grows between 20°12’ and 23°38’ S lat (Figure 2), from 0 to 1000 m a.s.l. mainly in the fog ecosystem called “camanchaca”.

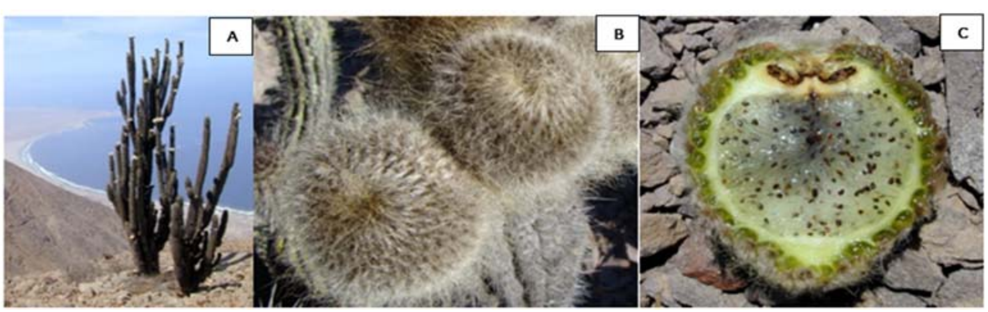

Figure 6. *Eulychnia iquiquensis*: Mature plant (A), “copao de Iquique” fruit (B), cross section of the fruit (C).

Haageocereus chilensis F. Ritter ex D.R. Hunt, common name "tunilla" (Synonym: *Haageocereus fascicularis* (Meyen) F. Ritter), plant is shrubby with stems prostrate and decumbent and cylindrical, 50-100 cm in length by 4-7 cm in diameter, with 11-18 ribs with thorns 1-4 cm long (Figure 7A), that grows between 2400 to 3500 m a.s.l. in the pre-Andean zone (Figure 2).

Figure 7. *Haageocereus chilensis*: Mature plant (A), "tunilla" fruit (B), cross-section of the fruit (C).

Area where the species were collected

Figure 2 shows where the species under study exist in their natural habitat, from 18-21° S lat, at altitudes ranging from 600 to 2000 m a.s.l. in The Andes mountains. Some of the species' growing areas was regularly visited to collect ripe fruits for their morphological, chemical, and functional characterization. Plants from where fruits were collected were georeferenced. Locations at which fruits were collected and date of collection are listed in Table 1.

Table 1. Location, date of fruit collection, and georeferentiation of the sampled specimens.

Species	Locality	Collection date	Latitude (S)	Longitude (W)	Altitude (m a.s.l.)
Eulychnia iquiquensis	Alto Chipana	2 Feb 2019	21°13'28.85"	70°04'09.96"	773
E. iquiquensis	Alto Punta Gruesa	19 Feb 2018	20°22'02.08"	70°09'07.26"	822
Haageocereus chilensis	Road to Parca	8 Jun 2019	20°03'20.85"	69°14'09.84"	2694
H. chilensis	Mamiña	8 Jun 2019	20°04'21.84"	69°12'40.34"	2817
Browningia candelaris	Quebrada Punaya	29 Jan 2018	20°01'35.55"	69°11'12.68"	2832
B. candelaris	Alto Quebrada Punaya	29 Jan 2018	20°02'00.78"	69°13'13.49"	2850
B. candelaris	Road to Parca	29 Jan 2018	20°02'32.55"	69°13'52.38"	2832
B. candelaris	Alto Quebrada Imagua	29 Jan 2018	20°05'18.28"	69°11'02.97"	2953
Corryocactus brevistylus	Alto Usmagama	7 Jun 2017	19°43'53.97"	60°13'24.73"	3238
C. brevistylus	Chuzmiza to Chiapa	17 May 2018	19°33'32.62"	60°12'00.18"	3443
Airampoa ayrampo	Panavinto	17 May 2018	19°25'46.17"	68°31'26.69"	3733
A. ayrampo	Umiña	17 May 2018	19°30'01.24"	68°42'40.98"	3844
Leucostele atacamensis	Panavinto	17 May 2018	19°25'45.55"	68°31'35.66"	3788

Management of the collected fruits

Several trips were planned and made to where these species exist to find fruit at their ripe stage. Collected fruits, about 2 kg, were bagged in plastic containers and stored in a cooler for their transportation to the laboratory for their characterization. Fruits were sent by courier in a cooler to the Laboratories of the Department of Agroindustry and Enology of the Faculty of Agricultural Sciences of the University of Chile at La Pintana, Metropolitan Region of Santiago, Chile.

Analyses

Parameters used to characterize the fruits and pulps of each species were the following: (i) For the morphology of the fruit, their weight (g), length (cm), and width (cm) were measured. Fruits were then pulped by removing the peel (exocarp), and % pulp (mesocarp) was determined based on fresh weight. (ii) For the chemical analyses, the following parameters were determined in the pulp: pH, acidity (g citric acid 100 g^{-1}), and soluble solids (expressed as °Brix). Functional analyses were also made based on pulp following the methods described by the AOAC (1996). Vitamin C (mg ascorbic acid 100 g^{-1} fw) was determined using the indophenol method (Nielsen, 2017); total phenolics using the Folin method (mg gallic acid eq. 100 g^{-1} fw) (Singleton and Rossi, 1965); total sugars by the Antrona method (g 100 g^{-1}) (Osborne and Voogt, 1986); antioxidant capacity by the oxygen radical absorption capacity (ORAC) method (μm Trolox eq. 100 g^{-1}) (Dávalos et al., 2004) and color parameters using a spectrophotometer (Model UltraScan Pro, Hunter Lab, Reston, Virginia, USA) (Jamilah et al., 2011). All these analyses were done in triplicate. Due to plant material availability in some species, it was impossible to measure all proposed variables.

RESULTS AND DISCUSSION

Corryocactus brevistylus

The fruit is large, with an average weight of 371 ± 64 g at maturity. The shape of the fruit is almost round, with a polar diameter of 8.3 ± 0.6 cm and an equatorial diameter of 8.5 ± 0.5 cm. The pulp is white when unripe and turns green when ripe. The peel is thin and remains green through the ontogenesis of the fruit. The pulp represents 62.0 ± 6.3% of the fruit's fresh weight and contains numerous seeds (Figures 1B and 1C). This fruit is like that of *Eulychnia acida*, but it weighs three times more and has a higher percentage of pulp, according to data provided by Masson et al. (2011).

The chemical and functional properties of the fruit are presented in Table 2. The pH of the pulp was 2.6 ± 0.01; acidity 2.2 ± 0.02 g citric acid 100 g^{-1}; soluble solids, 2.3 ± 0.1 °Brix; and with a soluble solid/acidity ratio of 1.0. The fruit of *C. brevistylus* is higher in acidity than *Eulychnia acida* (Masson et al., 2011). The pH and acidity of this fruit are comparable with that of 'Eureka' lemon, according to the data provided by Martí et al. (2009). Essential attributes of the fruit, both as juice and as fresh fruit, are the soluble solid/acidity ratio since this ratio determines the flavor of the fruits, with those with higher acidity tasting better than those with lower acidity, therefore, better acceptance by consumers.

Table 2. Chemical composition and functional properties of fruits of *Corryocactus brevistylus* from Northern Chile, based on fresh weight.

Parameter	Value
pH	2.6 ± 0.01
Acidity, g citric acid 100 g^{-1}	2.2 ± 0.02
Soluble solids, °Brix	2.3 ± 0.10
Total phenolics, gallic acid equivalent in mg 100 g^{-1}	16.0 ± 2.10
Vitamin C, mg ascorbic acid 100 g^{-1}	35.9 ± 1.10
Total sugars, g 100 g^{-1}	0.2 ± 0.01
Antioxidant capacity, μm Trolox eq. 100 g^{-1}	654.0 ± 6.00

Corryocactus brevistylus fruit also exhibits a higher content of vitamin C (35.9-57.1 mg 100 g^{-1}) compared with *E. acida,* which, according to Romero-Orejón et al. (2022), has only 18-33 mg 100 g^{-1}. Higher also than *Opuntia joconostle* and *Opuntia matudae* according with López-Martínez et al. (2015) which reported 6.80-13.46 mg 100 g^{-1}).

The total phenolic content of *C. brevistylus* was 16 ± 2.1 mg gallic acid equivalents (GAE) 100 g^{-1}, somewhat lower than the one reported by Matos-Chamorro et al. (2010), which using a different extraction method, reported 0.259-1012 mg GAE mL^{-1}; by Areche et al. (2020), who reported 24.34 mg GAE g^{-1} dw; and, by Romero-Orejón et al. (2022) who reported 24.24 mg GAE g^{-1} dw.

The antioxidant capacity of the pulp of the fruit of *C. brevistylus* was 654 µm Trolox eq. 100 g^{-1}, different from the values reported by Matos-Chamorro et al. (2010) and Areche et al. (2020), who using a different method of extraction, reported values in the range of 266.32-439.11 µg Trolox g^{-1} in fruits from Perú.

Leucostele atacamensis

Fruits are slightly oblong with a polar diameter of 4.1 ± 0.56 cm and an equatorial diameter of 3.77 ± 0.38 cm; they weigh 43.8 ± 11.2 g and are covered with whitish hairs, with scarce white pulp and many conspicuous seeds distributed throughout the pulp. Fruits shows a green external color when unripe and yellow-greenish when ripe (L* = 42.8 ± 4.9, C* = 14.4 ± 2.6, h° = 86.2 ± 6.8) (Figures 3B and 3C). The pulp yield was 42.6 ± 4.49% when ripe. In Table 3, we show this fruit's chemical composition and functional properties. The soluble solid content of the fruit was 12.3 ± 2.4 °Brix. The antioxidant capacity was 16 716 ± 64 µm Trolox eq. 100 g^{-1}, and the total phenols were 952 ± 2.8 mg GAE 100 g^{-1}, among the highest found in the fruits of any cacti. There are no previous studies on the characteristics of this fruit. However, if we compare these values with those of the fruit of *Opuntia ficus-indica*, the most consumed cactaceous fruit, these values are higher. Phenolic compounds are one of the most studied phytochemicals in cacti species, reported, besides *Opuntia* species, also in *Hylocereus, Pereskia, Ariocarpus*, and *Coryphantha* genera (Das et al., 2020). *Opuntia ficus-indica* has an antioxidant capacity measured as ORAC value of 54.5 (µm Trolox eq. 100 mL^{-1} fw and total phenols 24.2 mg GAE 100 mL^{-1} fw (Stintzing et al., 2005). The higher the score of the ORAC value, the more capable is a particular fruit of destroying free radicals. Therefore, only 50 g fruit of *L. atacamensis* would comply with the per day ORAC values suggested by the U.S. Department of Agriculture in the human diet (Apak et al., 2013) (3000-5000 Trolox equivalent antioxidant capacity). However, the large number of seeds and the poor juiciness of the pulp make the fruit not very palatable. Therefore, it can only be used as a source of antioxidants. The phenolics compound is highly related to the antioxidant capacity of this fruit, so these components can be extracted from the fruit to generate a dietary supplement.

Table 3. Chemical composition and functional properties of fruits of *Leucostele atacamensis* from Northern Chile, based on fresh weight.

Parameter	Value
Soluble solids, °Brix	12.3 ± 2.37
Total phenolics, gallic acid equivalent in mg 100 g^{-1}	952.0 ± 2.77
Antioxidant capacity, µm Trolox eq. 100 g^{-1}	16 716 ± 64

Airampoa ayrampo

The fruit is 2-3 cm in diameter, with a purple-rose peel and dark purple pulp (L* = 6.21 ± 0.8, C* = 27.5 ± 1.3 and h° = 11.3 ± 0.9) with many seeds distributed within the pulp (Figure 4B).

The chemical and functional properties of the fruit are presented in Table 4. This species has an unusual class of pigments known as betalains, which are water-soluble, tyrosine-derived pigments that contain the chromophore betalamic acid of yellow-orange color (Stintzing et al., 2005). The betalains are divided into betacyanin (red purple) and betaxanthin (yellow); the former has a betalamic acid condensed with a cyclo-DOPA (3,4-dihydroxyphenylalanine) or its glycosylated derivatives and the betaxanthins are composed of a betalamic acid condensed with amines or amino acids (Gengatharan et al., 2015). The betalains content of the ayrampo fruit was 81.04 ± 31.0 mg betanin 100 mL^{-1} of red color (Table 4).

There is a great interest in finding new sources of natural colorants that are safe for human consumption. The ayrampo, whose seeds have been traditionally used for centuries by the Andean inhabitants as a food and textile colorant, has been little studied scientifically, and it can be considered a source of red pigments to be used as natural colorants (Figure 4C). In this sense, Caldas-Cueva et al. (2016) found in an aqueous extract of ayrampo in Peru, 230 mg betacyanins 100 g^{-1} (db) and color parameters in a diluted extract of 96 µg betacyanin 100 g^{-1} db of L* = 80.91 ± 0.34, C* = 5.12 ± 0.22 and h° = 18.07 ± 0.75, while the ayrampo pulp from Chile was darker and more purple. Justo (2018) extracted betalains from ayrampo seeds in Peru, finding 177.927 mg betacyanins 100 g^{-1}. Morales et al. (2009) reported for the purple cactus pear (*Opuntia ficus-indica*) betacyanins contents of 111.01 mg 100 g^{-1}, and Navarro et al. (2022) found contents of 40.15 mg betanin 100 g^{-1} in *Opuntia robusta* (Table 5).

Table 4. Chemical composition and functional properties of fruits of *Airampoa ayrampo* from Northern Chile, based on fresh weight.

Parameter	Value
Soluble solids, °Brix	11.9 ± 2.1
Total phenolics, gallic acid equivalent in mg 100 g^{-1}	67.9 ± 0.5
Antioxidant capacity, µm Trolox eq. 100 g^{-1}	2906.0 ± 43.0
Betalain, mg betanin 100 g^{-1}	81.0 ± 31.0

Table 5. Betacyanin content of different fruits in the Cactaceae family. *db: Dry base.

Species	Total content	Reference
	mg 100 g^{-1}	
Selenicereus costaricensis (red pitahaya)	39.0	Wybraniec and Mizrahi, 2002
S. undatus (white pitahaya)	29.0	Wybraniec and Mizrahi, 2002
Opuntia ficus-indica (purple cactus pear)	28.1	Sáenz et al., 2009
O. ficus-indica (purple cactus pear)	41.1	Stintzing et al., 2005
O. ficus-indica (purple cactus pear)	11.1	Morales et al., 2009
O. robusta (purple cactus pear)	40.2	Navarro et al., 2022
Airampoa ayrampo (230 mg 100 g^{-1}, db*)	~ 46.0	Caldas-Cueva et al., 2016
A. ayrampo (694 mg 100 g^{-1} db*)	~ 138.0	Apaza, 2017

The antioxidant capacity of the fruit pulp was 2906 ± 43 µm eq. Trolox 100 g^{-1} with a phenolic content of 67.9 ± 0.50 mg GAE 100 g^{-1}. Jorge and Troncoso (2016) found a phenolic content of 107.3 ± 10.6 mg GAE eq. 100 g^{-1} fw and an antioxidant capacity determined by the FRAP method of 1.1 ± 0.1 (mmol Fe-II 100 g^{-1} fw); the authors compared with the same method the antioxidant capacity of red cactus pear finding a value 1.5 times greater in the ayrampo. Sáenz et al. (2009) in *O. ficus-indica* pulp found a total phenolic content of 90.95 mg GAE 100 mL^{-1}, higher than that reported for the same species by Stintzing et al. (2005) of 66.0 mg 100 mL^{-1} and by Morales et al. (2009) of 77.74 mg 100 mL^{-1}. Arivalagan et al. (2021), reported in red pitahaya (*Selenicereus* spp.), total phenolics of 44.8 mg GAE 100 g^{-1} and Hernández-Fuentes et al. (2015) in some *Opuntia joconostle* accessions, values of 108-118 mg GAE 100 g^{-1}.

Differences among the results in betalains and phenolic content could be attributed to the cultivar, stage of maturity of the fruit, and climate at the site of production (Stintzing et al., 2005), to the extraction methodology (solvent used and pH) (Apaza, 2017) and to the different methods used to determine antioxidant capacity. Despite these differences, the betalains concentration in ayrampo are relatively high compared with other cacti, making this species a good candidate to produce a natural food colorant.

Table 5 shows the betacyanin content of different cacti fruits, where the "ayrampo" values show large variability, that Apaza (2017) attributes to the extraction methods used.

Caldas-Cueva et al. (2016) tested an "ayrampo" seed extract as a colorant for yogurt compared to a red beet colorant. Color retention of dyed yogurts was not influenced by fat content (0.1% or 3,0%), but ayrampo extract showed better color retention (∼ 95%) after 4 wk cold storage (4 °C) compared with red beet extract (∼ 91%).

Browningia candelaris

The fruit is elliptic with black bracts like pitahaya fruit. The pulp is fleshy, somewhat acidic with many tiny black seeds that do not diminish the palatability of the fruit. "Sabaya" fruit shows an average size of 7.8 ± 0.5 by 4.9 ± 0.4 cm and a weight of 104 ± 19 g, with a greenish-yellow peel color (L* = 38.3 ± 2.3, C* = 32.4 ± 2.9, h° = 91.3 ± 2.2). Its pulp is whitish, with a gelatinous texture. The pulp yield is high (64.0 ± 1.9 %), the highest value among the fruits we studied (Figures 5B and 5C).

The chemical composition and the functional properties of the fruits are presented in Table 6. The pulp is highly acidic (1.9% citric acid). It has a low soluble solid content of 6.0 °Brix (Table 6), making the soluble solids/acidity ratio of 3.5 relatively low to make this fruit palatable as a fresh fruit.

Table 6. Chemical composition and functional properties of fruits of *Browningia candelaris* from Northern Chile, based on fresh weight.

Parameter	Value
pH	2.96 ± 0.01
Acidity, g citric acid 100 g^{-1}	1.90 ± 0.02
Soluble solids, °Brix	6.00 ± 0.10
Total phenolics, gallic acid equivalent in mg 100 g^{-1}	128.00 ± 14.00
Vitamin C, mg ascorbic acid 100 g^{-1}	30.90 ± 1.40
Total sugars, g 100 g^{-1}	4.69 ± 0.36
Antioxidant capacity, µm Trolox eq. 100 g^{-1}	2556.00 ± 146.00

The antioxidant capacity of the pulp was 2556 ± 146 µm Trolox eq. 100 g^{-1}, and the total phenolic content was 128 ± 14 mg GAE 100 g^{-1}, similar value to that of some *Opuntia joconostle* (xoconostle) accessions (Hernández-Fuentes et al., 2015). Compared with the yellow pitaya or dragon fruit (*Selenicereus undatus*), the "sabaya" is smaller, with similar pulp yield (65%-77%), higher acidity, and phenolic content and antioxidant capacity, but lower soluble solids content (Ochoa-Velasco et al., 2012). An alternative for consumption could be in preparations with other fruits to balance the high acidity and low sugar content and thus take advantage of its chemical characteristics, such as its antioxidant capacity.

Eulychnia iquiquensis

The fruit is globose, 6-7 cm in diameter, with a peel with brown, persistent hair (Figure 6B) and a transparent greenish pulp, even when ripe, where many black seeds are dispersed (Figure 6C).

The chemical and functional properties of the fruit are shown in Table 7. The fruits of *Eulychnia iquiquensis* had an average size of 7.4 ± 0.9 by 6.6 ± 0.5 cm, a weight of 157 ± 44 g, and most had an almost spherical shape. The pulp has high acid content (3.0 ± 0.07% citric acid), very low sugar content (0.39 g 100 g^{-1}), and a low pulp yield of 33.4 ± 10.2%. Because of these characteristics, it does not seem attractive to humans; however, it was observed that birds consume it. Therefore, its preservation is essential to protect the ecosystem. This fruit is different from that of *E. acida*. The copao from Iquique is similar in weight and size to the copao of Coquimbo (Masson et al., 2011), but copao from Coquimbo is much more acidic, which is probably where its name comes from. Total phenolic in *E. iquiquensis* (57.00 ± 11.0 mg GAE 100 g^{-1}) is in the same range of *E. acida* (Masson et al., 2011), but lower than some *Opuntia joconostle* (xoconostle) genotypes (López-Martínez, 2015). The vitamin C content of 26.00 ± 1.3 mg 100 g^{-1} is like that of some *Opuntia* cultivars (Monroy-Gutierrez et al., 2017). It would be interesting to cultivate this species, considering the few specimens that remain in very few locations.

Table 7. Chemical composition and functional properties of fruits of *Eulychnia iquiquensis* from Northern Chile, based on fresh weight.

Parameter	Value
pH	2.41 ± 0.0
Acidity, g citric acid 100 g^{-1}	3.00 ± 0.1
Soluble solids, °Brix	4.00 ± 0.1
Total phenolics, gallic acid equivalent in mg 100 g^{-1}	57.00 ± 11.0
Vitamin C, mg ascorbic acid 100 g^{-1}	26.00 ± 1.3
Total sugars, g 100 g^{-1}	0.39 ± 0.2
Antioxidant capacity, μm Trolox eq. 100 g^{-1}	1366.00 ± 201.0

Haageocereus chilensis

The fruit is small but attractive, round or slightly elongated, with 4.2 ± 0.3 cm of polar diameter and 3.3 ± 0.3 cm of equatorial diameter; that weighs 21 ± 6 g (Figure 7B). The pulp yield is 59.3 ± 3.4%; the fruit's skin is bright pinkish-red or yellow green. The pulp is translucent white, with many black seeds distributed throughout the pulp (Figure 7C).

The chemical and functional properties of the fruit are presented in Table 8. The acidity and soluble solids content give this fruit a balanced flavor in addition to a high vitamin C content of 35.43 ± 1.82 mg ascorbic acid 100 mL^{-1}, values that are close to the content found in this study in *Corryocactus brevistylus* and *Browningia candelaris* and like the content reported in some citrus species like orange and lemon (Martí et al., 2009).

These characteristics of the fruit make it a good candidate for human consumption as a fresh fruit. As was mentioned before, ORAC values in the order of 3000 to 5000 TEAC (Trolox equivalent antioxidant capacity) per day are suggested for human intake by the U.S. Department of Agriculture (Apak et al., 2013). The recommended "five servings of fruit and vegetables per day" has an approximate ORAC score of 3500. This amount can be achieved by consuming 100 to 200 mL juice of this fruit per day.

Table 8. Chemical composition and functional properties of fruits of *Haageocereus chilensis* from Northern Chile, based on fresh weight.

Parameter	Value
pH	2.8 ± 0.0
Acidity, g citric acid 100 g^{-1}	0.9 ± 0.0
Soluble solids, °Brix	7.7 ± 0.1
Total phenolics, gallic acid equivalent in mg 100 g^{-1}	80.0 ± 5.0
Vitamin C, mg ascorbic acid 100 g^{-1}	35.4 ± 1.8
Total sugar, g 100 g^{-1}	7.31 ± 0.8
Antioxidant capacity, μm Trolox eq. 100 g^{-1}	3167.0 ± 153.0

A preliminary sensory test reveals a transparent pulp with low aromatic intensity, quite acid and low sweetness, highly juicy, and with conspicuous seeds. The pulp reached high acceptability, up to 12 on a continuing scale from 0 to 15, which could be generically described as juicy with a harmonious, pleasant, and balanced taste. These characteristics and functional attributes could make this native wild cactus a new alternative crop for arid regions.

Table 9 show the differences among the different species studies, in relation to their fruit characteristics and the different parameters measured in the pulp of the fruit. Fruit shape ranged from rounded to oblong, but the weight of the fruit ranged from 21 to 371, with large differences also in relation to percent pulp. Regarding the chemical characteristics of the pulp, great variability was observed. For example, acidity ranged from 1 to 3 g citric acid 100 g^{-1} pulp, whereas soluble solid content ranged from 2 to 12 °Brix, which make the ratio of soluble solid content and acidity range from 1 in *C. brevistylus* to 8.5 in *H. chilensis*. Total phenolics and the antioxidant capacity also showed great variability, ranging in the first case from 16 to 952 mg GAE 100 g^{-1} and for the antioxidant capacity, from 600 to 16000 µm Trolox eq. 100 g^{-1}.

Table 9. Comparison between the different species studies in relation to their fruit and pulp main characteristics.

Character	*Corryocactus brevistylus*	*Leucostele atacamensis*	*Airampoa ayrampo*	*Browningia candelaris*	*Eulychnia iquiquensis*	*Haageocereus chilensis*
Fruit						
Weight, g	371.0 ± 64.0	43.8 ± 11.2	-	104.0 ± 19.0	157.0 ± 44.0	21.0 ± 60.0
Shape	Rounded	Oblong	-	Oblong	Rounded	Rounded
Pulp, %	62.0 ± 6.3	42.6 ± 4.5	-	-	33.4 ± 10.2	59.3 ± 3.4
Pulp						
pH	2.6 ± 0.0	-	-	3.0 ± 0.0	2.4 ± 0.0	2.8 ± 0.0
Acidity, g citric acid 100 g^{-1}	2.2 ± 0.0	-	-	1.9 ± 0.0	3.0 ± 0.1	0.9 ± 0.0
Soluble solids, °Brix	2.3 ± 0.1	12.3 ± 2.4	11.9 ± 2.1	6.0 ± 0.1	4.0 ± 0.1	7.7 ± 0.1
Soluble solids acidity ratio	1.0	-	-	3.2	1.3	8.5
Vitamin C, mg ascorbic acid 100 g^{-1}	46.5	-	-	-	26.0 ± 1.3	35.43 ± 1.84
Total phenolics, mg gallic acid equivalents 100 g^{-1}	16.0 ± 2.1	952.0 ± 2.8	67.9 ± 0.5	128.0 ± 14.0	57.0 ± 11.0	80.0 ± 5.0
Antioxidant capacity, µm Trolox eq. 100 g^{-1}	654 ± 6.0	16716 ± 64.0	2906 ± 43.0	2556 ± 146.0	1366 ± 201.0	3167 ± 153.0
Belatain, mg betanin 100 g^{-1}	-	-	81.0 ± 31.0	-	-	-

CONCLUSIONS

The characteristics of the species studied show that some could be domesticated for consumption as fresh fruit, others for industrial use as natural food colorants, and others for pharmaceutical use. For instance, *Leucostele atacamensis* has a high antioxidant capacity; *Corryocactus brevistylus* and *Haageocereus chilensis*, for human consumption as a fresh fruit; and *Airampoa ayrampo,* for its potential as a source of a natural red-purple natural food colorant.

Author contribution

Conceptualization: L.P., C.S., C.M. Project administration: L.P., D.A. Acquisition of field data, including photographs: R.P., D.A. Methodology: L.P., R.P., C.S., C.M. Draft preparation a subsequent review: L.P., C.M., C.S., R.P. Plant and fruit characterization: D.A., R.P. Chemical and functional analyses: E.A., J.C.C., C.S. All co-authors reviewed the final version and approved the manuscript before submission.

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