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Review

Maqui (*Aristotelia chilensis* [Molina] Stuntz): the most antioxidant wild berry towards agricultural production

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Summary

Maqui (*Aristotelia chilensis* [Molina] Stuntz) is an endemic tree species widely distributed in Chile and Argentina. Its fruit is a berry that is known worldwide as having the highest antioxidant capacity of any marketed fruit. Its production to date has been based on gathering fruit from wild forest plants, which are used for food products, pharmaceuticals, and cosmetics, or exported in bulk to several countries. Growing international demand has increased pressure on the natural maqui berry populations. Consequently, projects are underway to develop the commercial production of maqui berry to meet market demand, and new orchards are under development. Therefore, a comprehensive review scoping information about its ecological, genetic and chemical characteristics, plus the new research on agronomical culture, is necessary, in order to understand the potential future of the species as an important commercial fruit.

Several sources of information were reviewed, from international journals to local thesis and research projects results in Chile. Considering that the main research of the species is going in Chile, the present review aims to access local information and to put it at the disposition of a wider community of researchers.

The work reviews knowledge to date about natural distribution, ecology, propagation and management of the species, as its chemical, medicinal and nutraceutical properties. The novelty of the review is its broad view of all the different aspects that characterize the species, contributing to update the information about the species to support further research on agronomical production.

Recent national and international demand for maqui berry makes it necessary to improve propagation, management, harvest and fruit storage techniques. Maqui berry production will soon go from harvesting natural populations to agricultural production involving current techniques like selection, cloning and shortly genetic improvement.

Significance of this study

What is already known on this subject?

- Wild maqui fruit is known as having the highest antioxidant capacity of any marketed fruit, used for food, pharmaceuticals and cosmetics products.

What are the new findings?

- Today its production is based on wild populations, from a broad geographical distribution, and with high genetic variability; but it shows plasticity to be cultivated and breed.

What is the expected impact on horticulture?

- The production will expand considerably by moving towards horticultural culture, including genetic breeding accessing wild populations.

Keywords

Aristotelia chilensis, cultivation, compounds, antioxidant capacity, ecology, market, botany

Introduction

Non-wood forest products (NWFP) are extracted from forests other than lumber, pulp and paper, firewood and charcoal (Broekhoven, 1996). In the case of Latin America, tropical and subtropical forests provide a rich variety of flora and fauna, representing an important store of a wide variety of non-wood forest products (González, 2003) and potential crops.

Among NWFP species, maqui berry, *Aristotelia chilensis* [Molina] Stuntz, has generated considerable interest internationally owing to the extraordinary antioxidant capacity of its fruit (Céspedes *et al.*, 2008), as well as the medicinal properties of its leaves (Urban, 1934; Farías, 2009).

Increasing international demand for maqui berry is placing pressure on natural populations, given that production is currently based on gathering wild fruit by local, mainly rural peoples (Valdebenito, 2012). Exports have increased steadily, mainly to the United States of America and Japan (Salinas *et al.*, 2012; Soto *et al.*, 2014).

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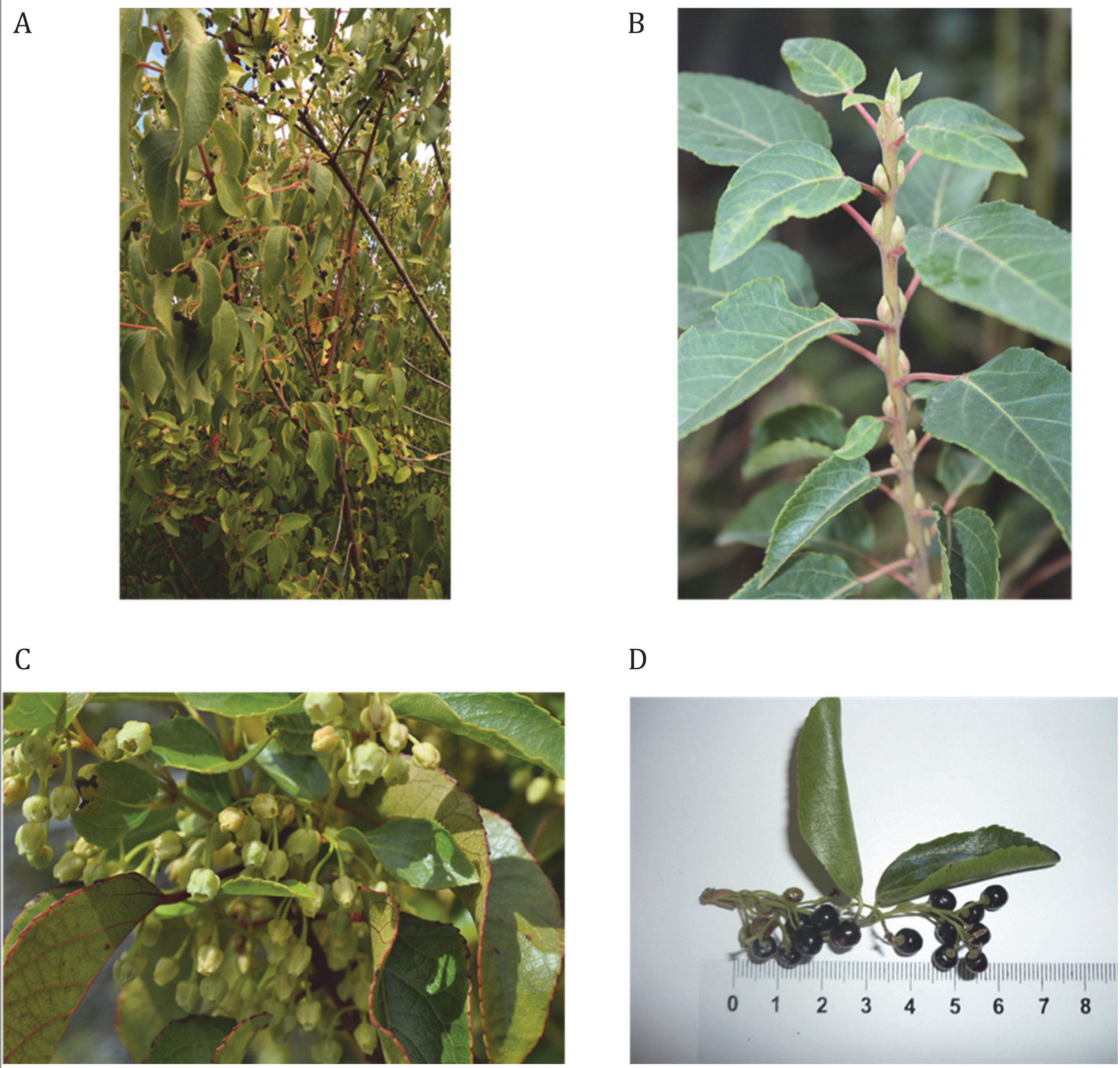

FIGURE 1. Adult plant of maqui with the characteristic reddish petiole (A); detail of leaves, petiole and emerging buds (B); flower clusters in umbels (C); mature fruits (D).

The expansion of this market makes it necessary to conduct more in-depth studies on maqui berry and the management of natural and cultivated populations to increase the supply and quality of the fruit and to reduce the pressure on natural populations during harvest periods. Misle *et al.* (2011) recommended adding a label to marketed maqui berry products to ensure that future production is based entirely on cultivated plants, to safeguard the survival of natural populations of the species, which play an essential role in the trophic chain of the ecosystems in which they are found.

The following review has the objective of characterizing the species, bringing together available information to date about its botanic and physiological characteristics, natural distribution, ecology, chemical properties, uses and market conditions, and approaches to agricultural and forestry management.

Materials and methods

Several sources of information were reviewed, from international journals to local thesis and research projects results. Considering that the main research of the species is going in Chile, and much initial research were written in Spanish, in local peer-reviewed journals, or as graduate and postgraduate theses, the present review permits access to local information and to put it at the disposition of a wider community of researchers.

The review is organized in the following sections: i) Botanic and physiological characteristics; ii) Geographic distribution and associated vegetation; iii) Chemical properties of maqui berry; iv) Uses as edible product; v) Medicinal products from the fruit; vi) Medicinal products from the leaves; vii) Cosmetic products; viii) Innovative uses; ix) Productive management; x) Methods of propagation; xi) Methods of cultivation; xii) Harvest; xiii) The market.

Results and discussion

Botanic and physiological characteristics

Aristotelia chilensis (Family Elaeocarpaceae) belongs to a genus with five species (*A. australasica*, *A. chilensis*, *A. fruticosa*, *A. peduncularis*, *A. serrata*), found in temperate regions of the southern Pacific (Australia, New Zealand, Chile, and Argentina) (Coode, 1985; Quirion *et al*., 1987). Known commonly as maqui berry, it is an evergreen species with a high degree of morphological plasticity. It grows as a bush or tree, reaching a height of between 3 and 10 m (Rodríguez *et al*., 1983; Zevallos and Matthei, 1992). Its bark is smooth and ranges in color from dark red to violet (Urban, 1934) (Figure 1A).

Its leaves are perennials, lanceolate-oval shaped and light green, with serrated edges. They have a coriaceous texture with a reddish petiole (Rodríguez *et al*., 1983) (Figure 1B).

The species produces two growth flushes of shoot and leaves per year, the first in spring, with senescence in autumn, and the second in summer, with senescence in mid-spring (Damascos and Prado, 2001).

Maqui berry plant is dioecious, with unisexual flowers (with a low percentage of hermaphroditic flowers) that are similar externally, but with the apparatus of the opposite sex atrophied, giving rise to male and female flowers. Fruit sometimes forms from male flowers (Coode, 1985), which indicates that the evolutionary process toward dioecy is still not complete throughout the species (Cárdenas, 1998; Bonometti, 2000).

Flowers cluster in umbels that develop in leaf axils. The flower, which is pale yellow, has five sepals alternating with five petals. The female flowers have an ovary with a stigma divided into three parts surrounded by numerous sterile stamens, while the male flowers have a rudimentary style surrounded by 10 to 15 fertile stamens (Cárdenas, 1998; Coode, 1985; Urban, 1934) (Figure 1C).

Flowering in temperate Mediterranean climates in central southern Chile lasts from the beginning of October until the end of November (spring in the Southern Hemisphere) (Cárdenas, 1998), while it is later in colder climates, beginning in November and ending at the end of December (Riveros and Smith-Ramírez, 1995).

Although the maqui berry plant does not present any evident nectar producing structures, small quantities of nectar production have been registered with both male and female flowers, with higher production levels in female flowers (Cárdenas, 1998; Mora, 1999). Nectar production varies greatly among flowers, even from flower to flower on the same plant (Mora, 1999).

The composition of nectar is approximately 41.5% glucose, 41.4% fructose, and 17.1% sucrose. The flowers are pollinated by short-tongued diurnal insects (Chalcoff *et al*., 2006). They hang down, and pollen is deposited on the hairy abdomen of pollinating insects and later rubs off onto the stigma of female flowers (Urban, 1934). Among the pollinizers are species of the orders Hymenoptera, Diptera, and Coleoptera. More than 90% of observed contacts with flowers during a 15-day flowering period (Valdivia area, ~39°48’00’’S; 73°14’00’’W) were made by *Policana albopilosa* Spin. and *Ruizantheda mutabilis* Spin. (native species of Chile) (Mora, 1999; Peña, 1996). In Argentina, maqui berry plant has significant participation in honey production by *Apis mellifera* during a two-month flowering in the Province of Chubut (Forcone and Kutschker, 2006). The fruit is a black shiny 5 mm in diameter, with a sweet pulp and containing two angular seeds (Urban, 1934) (Figure 1D).

The fruits are heavier and larger when the flower takes less than two days to be pollinated (Verdi, 2004) and average weight and size are significantly higher in fruit resulting from cross-pollination than those produced from self-pollination (Bonometti, 2000). Production by self-pollination results in significant losses in terms of both the quantity and quality of fruit (Vogel *et al*., 2014), indicating that the presence of male flowers is indispensable for future agricultural production.

The maturation of the fruit, which takes place in the first months of summer when the fruit has accumulated 1,100 degree days (Fredes *et al*., 2012), is characterized by the concentration of anthocyanin pigments that give the fruit its dark purple color (Rodríguez *et al*., 1983). Fruits are part of the diet of native birds, thus disappearing easily when mature.

Geographic distribution and associated vegetation

A. chilensis is a native species of sub-Antarctic forests in Chile and Argentina (Rodríguez *et al*., 1983; Forcone and Kutschker, 2006). In Chile it is found between the provinces of Limarí (30°30’S; 71°00’W) and Aysén (44°55’S; 73°35’W) at altitudes of up to 2,500 m a.s.l. It is present in different forest formations (Donoso, 2006), with a high presence in remnant Mediterranean forests (San Martín, 2003). It has also been introduced to the Juan Fernández Archipelago (Rodríguez *et al*., 1983), where it is considered an invasive, dominating open areas and forest edges and impeding the natural regeneration of species endemic to the archipelago (Arellano, 2012; Vargas *et al*., 2013). In Argentina the species is found in Andean Patagonian forests in Mendoza, Neuquén, Río Negro and Chubut Provinces (Chebez, 1999; Coode, 1985; Alonso, 2012). It is common to national parks like Lanín, Nahuel Huapi, and Los Alerces.

Its growth is favored in moist areas with high levels of organic content. Maqui berry plants are found on the slopes of hills, forest edges and on disturbed, fire-affected or exploited soils. It is considered a pioneer species owing to its capacity to rapidly invade areas devoid of vegetation, sometimes forming monospecific communities called “macales” (Rodríguez *et al*., 1983).

According to Repetto-Giavelli *et al*. (2007), maqui berry can grow under tree canopies or in open or fragmented areas with more light and less water availability. In the context of these differences, the species responds morphologically and physiologically while maintaining its photosynthetic rate. This morphological plasticity can also be seen if we compare individuals from different geographic areas (Vogel *et al*., 2014).

As with other species with seed distribution by birds (Martin-Albarracin *et al*., 2017), maqui berry is a pioneer found under the canopies of plantations of adult *Pinus radiata* and exotic species, as well as clear areas within plantations (Frank and Finckh, 1997; Ramírez *et al*., 1984). It is found in Chile in a variety of forest types, including sclerophyllous, oak-hualo, Chilean palm, mountain cypress, most Mediterranean areas, and in the south of the country, in evergreen-type forests (Donoso, 2006).

After the National Forest Inventory, in Chile there are 170,000 ha with natural maqui formations that could potentially be used for production (Salinas and Parra, 2012).

Chemical properties of maqui berry

Maqui berry has a number of chemical characteristics, making it of interest worldwide. Tables 1–3 summarize some of the reported values.

Table 1. Antioxidant capacity of maqui fruits.

Amount	Units	Observation	Source
19,850	µmol TE 100 g^{-1} fw	ORAC assays	Speisky *et al.*, 2012
359.7	mmol E Fe^{2+} kg^{-1} fw		Fredes, 2013
313.6	mmol E Fe^{2+} kg^{-1} fw		Fredes, 2013
116 ± 0.5	mmol kg^{-1} dw	FRAP	Brauch *et al.*, 2016
154.6 ± 8.8	mmol kg^{-1} dw	TEAC	Brauch *et al.*, 2016
5,569.5	mg TE 100 g^{-1} dw	Based on fresh fruits	Guerrero, 2016
42.15 ± 0.66	mmol TE 100 g^{-1} dw	DPPH	Rodríguez *et al.*, 2016
59.95 ± 1.68	mmol TE 100 g^{-1} dw	ORAC assays	Rodríguez *et al.*, 2016
18,137.6	µmol TE 100 g^{-1} dw	ORAC assays	Quispe-Fuentes *et al.*, 2017
276.92 ± 1.15	mg TE 100 mL^{-1}		Vega, 2017
250	µmol TE 100 g^{-1} dw	DPPH	Quispe-Fuentes *et al.*, 2018
800	µmol TE 100 g^{-1} dw	ORAC assays	Quispe-Fuentes *et al.*, 2018

FRAP: Feric reducing antioxidant power; TEAC: Trolox equivalent antioxidant capacity; DPPH: 2,2-diphenyl-1-picryl hydrazyl method; fw: fresh weight; dw: dry weight.

Table 2. Nutritional composition of maqui fruits (g 100 g^{-1} of dry weight).

Nutrient	Amount	Units	Source
Fatty acid	7.13 ± 0.49	g	Brauch *et al.*, 2016
Moisture	214.13 ± 3.26	g	Rodríguez *et al.*, 2016
Fat	6.28 ± 0.32	g	Rodríguez *et al.*, 2016
Water activity	0.975 ± 0.003	g	Rodríguez *et al.*, 2016
Energy	150	calories	Zúñiga, 2017
Crude protein	6.28 ± 0.17	g	Rodríguez *et al.*, 2016
Proteins	3.92 ± 0.38	g	Guerrero, 2016
	0.8	g	Zúñiga, 2017
Lipids	8.13 ± 0.33	g	Brauch *et al.*, 2016
	1.96 ± 0.11	g	Guerrero, 2016
Ash	2.61 ± 0.16	g	Rodríguez *et al.*, 2016
	3.14 ± 0.06	g	Guerrero, 2016
Carbohydrates	86.21 ± 1.83	g	Rodríguez *et al.*, 2016
	90.98	g	Guerrero, 2016
Crude fibre	33.88 ± 1.64	g	Rodríguez *et al.*, 2016
	0.8	g	Zúñiga, 2017

According to Schmidt-Hebbel *et al.* (1992), its chemical composition is of 150 g 100 g^{-1} of calories, 56.4 g 100 g^{-1} of moisture, 0.8 g 100 g^{-1} of proteins, 0.8 g 100 g^{-1} of raw fiber, 1.2 g 100 g^{-1} of ashes, and 87, 44, 30.5 and 296 mg 100 g^{-1} of calcium, phosphorus, iron and potassium, respectively.

In studies of fruit gathered in Chilean Patagonia (Aysén Commune, 45°24'S; 72°41'W), the levels of total dietary fiber are 15.37 g 100 g^{-1}, which is significantly higher than the fiber levels in other berries (Benedetti and Pavez, 2012).

Maqui berry has been the subject of much commercial interest owing mainly to its high polyphenol content and the great variety of anthocyanins and flavonoids in its fruit and leaves, which is related directly to the antioxidant capacity of the fruit (Guerrero *et al.*, 2010).

The main active compounds initially recognized in maqui berry were alkaloids (indolenine and quinoline) (Dobler and Borschberg, 1994; Echeverría and Niemeyer, 2012) and tannins, in particular in fruits (Montes and Wilkomirsky, 1987). In recent years, several studies at the national and international levels have examined the high levels of phenolic acids, proanthocyanidins, and anthocyanins, among other flavonoids, in maqui berry (Ruiz *et al.*, 2010). It has been established that maqui berry contains an extraordinarily high antioxidant capacity compared to other berries (Céspedes *et al.*, 2008, 2010a; Miranda-Rottmann *et al.*, 2002). Along with *Berberis mycrophylla* (box-leaved barberry), it presents the highest phenol content and antioxidant capacity of South American fruits (Speisky *et al.*, 2012), as well as one of the highest levels of anthocyanins (Schreckinger *et al.*, 2010a).

Phenol compounds are a group of chemical substances that are considered secondary metabolites of plants. Their presence in animal tissue is through consumption of vegetal matter (Martínez-Valverde *et al.*, 2000). Maqui berry contains more than 20 compounds, of which 8 are anthocyanins compounds, as well as phenolic acids and flavonoids (10 compounds) (Céspedes *et al.*, 2010a; Genskowsky *et al.*, 2016). The latter are found in high concentrations, similar to other berries native to Chile, like the Chilean guava (*Ugni molinae*) and box-leaved barberry (*Berberis microphylla*) (Ruiz *et al.*, 2010).

According to Guerrero *et al.* (2010), the quantity of total phenols in maqui berry gathered in February (summer in the Southern Hemisphere) was 400 mg L^{-1} of gallic acid equivalent (mg GAE L^{-1}). Fredes *et al.* (2014a) compared phenol compound content in different cultivated fruit species in Chile, and found that maqui berry had the highest total phenol content, exceeding 12 grams equivalent to gallic acid per kilo of fresh fruit (g GAE kg^{-1}), twice that of strawberry (*Fragaria* × *ananassa*), blueberry (*Vaccinium corymbosum*) and blackberry (*Rubus ulmifolius*). Even more, Genskowsky *et al.* (2016) got values of 49.74 g GAE kg^{-1} when also evaluating total phenolic content in maqui berry, much higher values than the other authors. A study by the Fundación para la Innovación Agraria (2009) found an even greater difference, with maqui berry having three times the phenol content of Chilean guava (*Ugni molinae*), which had the second highest phenol content. Comparing maqui berry with blueberry (*Vaccinium corymbosum*), a well-known commercial berry, Fundación para la Innovación Agraria (2009) found that maqui berry presents 21 g gallic acid equivalent kg^{-1} of total polyphenols, 27.6 g procianamide equivalent kg^{-1} of total tannins and 21.7 g malvidin 3-glu equivalent kg^{-1} of total anthocyanins, but blueberry presents only 3.1 g gallic acid equivalent kg^{-1}, 4.2 g procianamide equivalent kg^{-1} and 2.8 g malvidin 3-glu equivalent kg^{-1} respectively.

Polyphenol content in fruit can vary according to the genotype, environment, storage, and maturity at harvest (Fredes

TABLE 3. Main phytochemicals in maqui fruits.

Phenolic compound	Amount	Units	Source
Anthocyanin	8.82 [c]	g cyanidin-3-glucoside kg^{-1} fw	Fredes, 2013
	7.87 [d]	g cyanidin-3-glucoside kg^{-1} fw	Fredes, 2013
	36.9 ± 3.2	g kg^{-1} dw	Brauch *et al.*, 2016
	3,592.67 ± 37.03	mg cyanidin-3-glucoside 100 g^{-1} dw	Guerrero, 2016
	12.78 ± 0.55 [a]	g kg^{-1} dw	Brauch *et al.*, 2017
	14.63 ± 0.9 [b]	g kg^{-1} dw	Brauch *et al.*, 2017
	20.4 ± 0.18	mg dpd-3-glc g^{-1} dw	Quispe-Fuentes *et al.*, 2018
Phenols	1,110–1620	mg GAE 100 g^{-1} fw	Fredes *et al.*, 2014
	32 ± 2.1	g kg^{-1} dw	Brauch *et al.*, 2016
	33.65 ± 2.73	mg GAE g^{-1} dw	Quispe-Fuentes *et al.*, 2018
Delphinidins	10.5 ± 0.45 [a]	g kg^{-1} dw	Brauch *et al.*, 2017
	12.03 ± 0.82 [b]	g kg^{-1} dw	Brauch *et al.*, 2017
Cyanidins	2.28 ± 0.1 [a]	g kg^{-1} dw	Brauch *et al.*, 2017
	2.6 ± 0.09 [b]	g kg^{-1} dw	Brauch *et al.*, 2017
Diglycosides	10.55 ± 0.49 [a]	g kg^{-1} dw	Brauch *et al.*, 2017
	12.46 ± 0.74 [b]	g kg^{-1} dw	Brauch *et al.*, 2017
Monoglycosides	2.24 ± 0.06 [a]	g kg^{-1} dw	Brauch *et al.*, 2017
	2.17 ± 0.16 [b]	g kg^{-1} dw	Brauch *et al.*, 2017
Gallic acid	202 ± 1.1 [b]	mg kg^{-1} dw	Brauch *et al.*, 2017
Polyphenols	45.7 ± 1.1	mg GAE g^{-1} dw	Rubilar *et al.*, 2011
	9.95 [c]	g GAE kg^{-1} fw	Fredes, 2013
	10.14 [d]	g GAE kg^{-1} fw	Fredes, 2013
	5,415.62 ± 334.86	mg GAE 100 g^{-1} dw	Guerrero, 2016
	293.03 ± 1.5	mg EAG 100 mL^{-1}	Vega, 2017
Flavonoids	23.52 ± 0.44	mg QE g^{-1} dw	Quispe-Fuentes *et al.*, 2018

[a]: Clonal material “Morena” (University of Talca, Chile); [b]: Clonal material “Luna nueva” (University of Talca, Chile); [c]: Location Chile, Paredones, 34° S coastal range; [d]: Location Chile, Rancagua, 34° S, central valley; dw: dry weight; fw: fresh weight.

et al., 2012). Fredes *et al*. (2014b) assessed content variation in fruit from different sources and found differences of up to 10 g GAE kg^{-1}, with the highest values in fruit from the Mediterranean-climate region.

Total phenol concentrations at the first and the final stages of maturation are similar (Fredes *et al.*, 2012), which can be explained as a defense mechanism of the species to prevent herbivores from eating the fruit in early stages when the fruit does not yet contain viable seeds (Miranda-Rottmann *et al*., 2002). The increase by the end of the maturation process is largely due to anthocyanin, a pigment that gives the fruit its color. High anthocyanin content is directly related to the antioxidant capacity of the fruit (Fredes *et al*., 2012).

The maqui berry has among the highest concentrations of anthocyanins among berries in South America (Schreckinger *et al*., 2010a). Among the anthocyanins in this fruit are five pigments first identified by Pinto (1978), two of which were subsequently confirmed by Escribano-Bailón *et al.* (2006) and Céspedes *et al.* (2010b), who identified 8 anthocyanin pigments, among notably delphinidin, which regulate blood glucose levels (Rojo *et al.,* 2012).

When present even in low concentrations compared to oxidizable biomolecules like DNA proteins or lipids, antioxidants can delay or prevent oxidative damage owing to the presence of reactive oxygen species or free radicals (García *et al*., 2001). According to Speisky *et al.* (2012) maqui berry is notable among berry species owing it antioxidant capacity, measured as Oxygen Radical Absorbance Capacity (ORAC), with a value of 19,850 µmol ET 100 g^{-1} fw, which is exceeded only by that of the box-leafed barberry (*Berberis microphylla*) with a value of 25,662 µmol ET 100 g^{-1} fw. As a comparison blueberry has 5,481 µmol ET 100 g^{-1} fw (ET: Trolox equivalents; fw: fresh weight). This has earned it the reputation of the fruit with the highest antioxidant capacity in South America, comparable to fruits with high phenolic content like the açaí palm (*Euterpe oleracea*) (Gironés-Vilaplana *et al*., 2014a).

It is important to remark, that Rodríguez *et al*. (2016) determined that hot air-drying (between 40 °C and 80 °C) cause noticeable changes in the content of the bioactive components of maqui berry, and reduced their antioxidant capacity. The high temperature was not the main factor, but the thermal load, being the 40 °C processing the one with longest exposure to hot air until equilibrium moisture is reached, and therefore, the samples under this temperature and load attained the lowest antioxidant values. In the same way, Guerrero (2016) determined losses in the bioactive compounds by the effect of heat treatment during lyophilization and convection, with losses of 19 to 24% of antioxidant capacity.

Uses as an edible product

Maqui berry has been traditionally used as an edible fruit by original inhabitants in Chile, existing even evidence of its use for the production of fermented drinks in the south of Chile, between 1000 and 1300 AD (Godoy-Aguirre, 2018).

The increased demand for foods rich in antioxidants has strengthened the production of products based on berries and other fruit products with similar antioxidant characteristics. In the area of bioactive foods, maqui berry extract is recognized for its rich flavonoid and vitamin C content and its capacity to maintain its antioxidant properties and phenolic content under conditions of storage (Gironés-Vilaplana *et al.*, 2012).

Maqui berry yields a very intense dark blue dye that has been used since ancient times in the preparation and coloring of fruit juices and alcoholic beverages (Fernández, 1998), making maqui berry an excellent natural coloring agent (Escribano-Bailón *et al.*, 2006). The dye is produced by artisanal steam stripping technique that maintains antioxidant capacity (Araneda *et al.*, 2014).

Among the liquid products are maqui berry-based juices, often mixed with other fruits like açaí (*Euterpe oleracea*) and pomegranate (*Prunus granatum*), concentrates of maqui berry juice, infusions based on dehydrated maqui berry and lyophilized powders that conserve the flavor, color, smell and nutritional properties of the fruit, but as well can be preserved for long periods of time and without refrigeration. There are also food supplement and blood glucose regulators in capsule form. Liquor can be produced from maqui berry through fermentation that does not affect the antioxidant capacity of the fruit (Céspedes *et al.*, 2008, 2010b; Gironés-Vilaplana *et al.*, 2015) in a manner similar to a drink prepared by people of the Mapuche culture called tecú (Alonso, 2012). Also a fermented milk drink with antioxidant capacity based on maqui berry addition (Martínez and Tinoco, 2018), and a fermented drink based on whey coming from the cheese industry and maqui extract (Vega, 2017) have been successfully tested. Isotonic beverages based on maqui berry has demonstrated to maintain high antioxidant capacity (Gironés-Vilaplana *et al.*, 2014b).

According to Genskowsky *et al.* (2016) results, maqui berry has a great potential to be employed not only in the food industry, as potential food ingredient to development of functional food, but also as bio-preservative due to the high content in polyphenolic compounds, mainly anthocyanins, and the promising antioxidant and antibacterial properties, tested in 8 bacterial strains.

Nevertheless, some recent studies like the one of Brauch *et al.* (2016) pointed out that drying and juice production substantially affect the stability of maqui berry anthocyanins. Rodríguez *et al.* (2016) also determined that hot air-drying temperatures between 40 and 80°C caused noticeable changes in the content of the bioactive components of maqui berry and reduced antioxidant capacity. Brauch *et al.* (2015) determined that delphinidin derivatives are less stable than concomitant cyanidin derivatives when maqui berry preparations are heated, suggesting that heat exposure should be minimized during maqui berry processing. They suggested the use of maqui berry under dark and cool temperatures, being suitable for coloring beverages, fruit purees, fruit spreads and jams. Fredes *et al.* (2018) determined that the microencapsulation of maqui berry juice by spray drying using inulin improved the bioaccessibility of anthocyanins of maqui berry juice microparticles.

Medicinal uses of maqui berry compounds

Different aspects of maqui berry make it attractive to the pharmaceutical industry. The phenol compounds in maqui berry have cardioprotective activity (Céspedes *et al.*, 2008) and the flavonoid content can prevent endothelial dysfunction and cardiovascular disease (Miranda-Rottmann *et al.*, 2002; Fuentes *et al.*, 2015), as well as inhibiting lipid accumulation and adipogenesis, and acts as an anti-inflammatory (Schreckinger *et al.*, 2010b; Céspedes *et al.*, 2010b). Likewise, its characteristics as an inhibitor of cholinesterase enzymes establish maqui berry as a potential natural phytopharmaceutical against diseases like Alzheimer, senile dementia and Parkinson (Gironés-Vilaplana *et al.*, 2012).

Maqui berry extracts have been tested for the capacity to inhibit α-glucosidase and α-amylase enzymes related to metabolizing carbohydrates (Rubilar *et al.*, 2011) and as an option to reduce problems associated with obesity (Reyes-Farías *et al.*, 2014). Céspedes *et al.* (2017a) determined that the phenolics (anthocyanins, flavonoids, and organic acids) as the fractions and mixtures may provide a potential therapeutic approach for inflammation-associated disorders, and therefore might be used as antagonizing agents to ameliorate the effects of oxidative stress. Calderón *et al.* (2017) found no effect of the administration of a purified anthocyanin-rich extract of maqui berry on the experimental induced non-alcoholic fatty liver disease.

Vergara *et al.* (2015) observed that maqui berry extracts could be used to improve resistance to respiratory problems and decrease oxidative stress in patients that were smokers.

The delphinidin content of the fruit has been related to the capacity for glucose regulation *in vitro* and *in vivo*, participating in metabolic reactions at the skeletal muscular level and the liver (Jara *et al.*, 2012; Rojo *et al.*, 2012). Delphinidin also helps prevent retinal disease by reducing cell death induced by light damage (Tanaka *et al.*, 2013) and aid in recovering tearing (Nakamura *et al.*, 2014). As well, delphinidin reduces the risk of arteriosclerosis, acts as a neuroprotector and as a photoprotector against skin disease (Watson and Schönlau, 2015).

Medicinal products from the leaves

Maqui berry leaves have historically been used in folk medicine to combat throat diseases and in healing injuries and dealing with tumors, which have been attributed to the analgesic, anti-inflammatory, antimicrobial and antioxidant properties (Farías, 2009). Leaf extracts have been successfully tested as natural antioxidant and antimicrobial agent (with inhibitive effects on *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Enterobacter aerogenes*, and *Candida albicans*) for use in cosmetics (Avello *et al.*, 2009), as an antibacterial agent against *Escherichia coli*, *Staphylococcus aureus*, and *Bacillus subtilis* (Mølgaard, 2011). However, Suwalsky *et al.* (2008) point to the negative effects of flavonoids from the leaves on human erythrocytes, raising concern about the side-effects from the medicinal use of maqui berry.

Enzymes extracted from leaves have been tested as a cheese coagulant, and it has been found that coagulant capacity is lower than the standard rennet, but with higher and better stability over time and a higher level of microbial activity (Leal, 2006).

Farías (2009) determined the analgesic properties of hexane (EH, 3.5% p/v), dichloromethane (EDCM, 4.5% p/v) and methanol extracts (EM, 2.7% p/v) obtained from maqui berry leaves.

Recently, Céspedes *et al.* (2017b), testing pure compounds and extracts rich in alkaloids and phenolics from maqui berry leaves, determined their inhibition potential of acetylcholinesterase, butyrylcholinesterase and tyrosinase enzymes. Given their results, the authors suggest the potential of maqui berry leaves as a natural source of alkaloids and phenolics for phytotherapeutic treatments for cholinergic deterioration ailments, avoiding the side effects of synthetic drugs.

As a pioneer species, colonizing and growing in stressed and disturbed environments, experiments producing severe drought on nursery plants, have shown a significative increase of abscisic acid (ABA) and total anthocyanin content in forming leaves (González-Villagra, 2018).

Cosmetic products

Maqui berry has also become an ingredient in cosmetics, promoting the recovery of tissue and slowing the aging of skin cells, hair and nails. It is used in creams and shampoos produced in different parts of the world.

Scapagnini *et al*. (2016) emphasized that the richest known natural source of delphinidin is the maqui berry, and therefore its use and its delphinidin should be considered in the development of novel nutritional interventional strategies for health management and against specific age-associated diseases, having a potential positive impact on skin health. Alvim *et al*. (2018) determined a significant improvement of firmness, elasticity and an increase in dermal thickness in patients being treated with an oral nutritional supplement based on collagen peptides, vitamin C, and *Aristotelia chilensis* (Delphynol) extracts.

Innovative uses

The species has generated interest not only in the field of edible products, nutraceuticals or cosmetic products but in some other innovative fields. Although the new uses are mostly in an incipient research state, it is worthy to point them out. López de Dicastillo *et al.* (2016) tested the use of maqui berry antioxidants in films for food packaging, as protection against microorganisms and oxidation reactions. The concept is to develop antioxidant and antimicrobial packaging materials based on biodegradable polymer and natural plant extracts, with evident advantages as naturally degradable after use waste. Also, Leyrer *et al.* (2018) tested the use of maqui berry anthocyanin-enriched extract as dye-sensitizer for solar cells (Photovoltaic devices that can convert solar energy unto electrical energy) enhancing their efficiency.

Productive management

Maqui berry production is currently based on gathering fruit from natural forests located mainly in the south of the country (Valdebenito *et al*., 2003). Growing national and international demand is increasing pressure on the ecosystems where the species is found. Selection of genotypes throughout the natural distribution of maqui berry began in 2012 to assess productive aspects of wild plants and the chemical characteristics of the fruit and to propagate selected individuals from different populations to evaluate genetic and environmental variability. A plantation was established with five cloning assays, each composed on 50 clones (Fundación Chile, 2012). New studies about the cultivation of maqui berry are undergoing. The following section deals with the current state-of-the-art in the propagation and management of maqui berry.

Methods of propagation

Different methods of propagation of maqui berry have been studied, focused on seed (Doll *et al.*, 1999) or vegetative propagation (Doll *et al*., 1999; Bonometti, 2000).

There are mixed results in relation to seed propagation, ranging from 18% germination under treatments with gibberellin in doses of 2,500 and 5,000 mg L^{-1} (Molina, 2001); 30% germination with mechanical seed scarification and soaking seeds seven days in and then in gibberellic acid at a concentration of 1,000 mg L^{-1} for 24 hours (Valdebenito, s/f); to 77% germination using macerated seeds in cold water for three days (Vogel *et al*., 2005). Araneda (2006) determined that maqui germinate at moderate temperatures, reaching its maximum germination rate at 20 °C, while germination is completely inhibited at 10 °C and less or at 30 °C and over.

Rodríguez *et al*. (2017) determined that maqui berry seeds present a moderate level of primary dormancy, both exogenous and endogenous, after *in vitro* germination assays testing cold stratification and scarification. Rodríguez and Tampe (2017) accelerated germination under *in vitro* conditions, applying N^6-benzylaminopurine, gibberellic acid, and fluridone in a 100 µ concentration, reaching 74% germination in 30 days.

In terms of reproduction with cuttings, assays obtained 90% rooting with treatments of 2,000 ppm of indole butyric acid (IBA) (Oyanadel, 2002), 73.3% rooting with a concentration of 1,000 ppm of IBA and female cuttings growing in open air (Palma, 2001); 68% rooting with 3,000 mg L^{-1} of IBA, obtaining at the latter concentration longer and more abundant roots (Poblete, 1997).

Vogel *et al*. (2005) used apical segments of branches with reduced foliar area. The bases of the branches were submerged for 15 seconds in a hydroalcoholic solution with IBA at 0.1%. According to the results of this assay, 100% rooting can be obtained with this method.

In vitro culture is under development, with propagation yield of 68% of the plants, when moving the *in vitro* material to the *ex vitro* phase (Fundación para la Innovación Agraria, 2018).

Cultivation and breeding

Vogel *et al*. (2005) indicated that the best season for planting maqui berry is autumn-winter, during the vegetative recess, which allows the development of the root system, prior to growth in the spring. The planting distance proposed by the authors is 0.5 m above the row and 1.5 m between rows.

The distance between plants affects the antioxidant capacity of the fruit. Hasanuzzaman *et al*. (2013) found that antioxidant concentrations increase in the context of water stress and higher temperatures and levels of light exposure, a finding supported by Jeong *et al.* (2004), who obtained lower anthocyanin concentrations in grapes grown under shade, a response that can be expected in berries as well. In the case of maqui berry, González-Villagra *et al*. (2018a) determined that abscisic acid (ABA, that regulates physiological and biochemical mechanisms required to tolerate drought stress), is involved in phenolic compounds biosynthesis (mainly anthocyanins) in leaves of *Aristotelia chilensis*. It poses the question about the concentrations of antioxidants that maqui berry will present, if produced under irrigation systems.

Other important factors to consider are the architecture of the crown and the space for management and harvesting activities.

According to Doll *et al*. (2017), heading procedures during spring produces higher fruit yield in the next seasons and suggest constantly renewing the plant heading apical sprouts in vigorous plants, to maintain a small plant size.

Currently, many commercial nurseries have begun propagating maqui berry, and through direct communication, owners indicate that demand for plants from agricultural producers is growing.

At the moment, high yielding plants with good fruit quality have been selected from eight wild populations between latitude 34° and 41° S, and accessions have been cultivated under different environmental conditions to select the most suitable genotypes (those with the highest monomeric anthocyanin contents) for the establishment of commercial orchards (Vogel *et al.*, 2016; Brauch *et al.*, 2017). Salgado *et al.* (2017) determined that only 5% of the variability of this selected material could be attributed to the provenance, whereas 95% was found between individuals of the same population. Some of the most promising clones, from a population of 68 selected clones, are under deeper analysis to reveal their commercial potential (Brauch *et al.*, 2017).

Harvest

In managed sites, plants should be pruned to keep them at a height convenient for harvesting. Harvesting should be conducted in a manner that does not affect the future productivity of the plants, progressing toward less invasive mechanisms that remove fruit without affecting the rest of the plant (Vogel *et al.*, 2014). About this, Damascos *et al.* (2005) found that removing a cohort of leaves in the fall or at the end of winter reduces yields and the distance between branch knobs the following season. At present, harvesting from natural plant formations is done by cutting fruit-bearing branches, which generates significant losses of foliar biomass and progressive deterioration of the productivity of natural populations.

González *et al.* (2015) determined that fruit at different stages of maturity can be found on the same plant at the same time. The concentration of polyphenols did not vary throughout the maturation of the fruit, while anthocyanin concentrations increased as the fruit matured (Fredes *et al.*, 2012; González *et al.*, 2015). According to Fredes *et al.* (2012) this occurs when the fruit has matured, having accumulated 1,100 growing degree days. Consequently, it is necessary to develop techniques to distinguish between mature and maturing fruit to optimize the quality of harvests.

When harvesting, it is suggested to leave at least 30% of the branches with fruits to ensure the sustainable propagation of wild populations, to apply thinning to highly dense wild populations, in order to increase the light on the buds and to maintain male individuals as pollinators of female individuals (Tacón, 2017).

Maqui berry stored at -20 °C for six months after harvest maintained the initial levels of anthocyanin concentrations, while polyphenol content increased. Drying the fruit is recommended for producers in remote areas that cannot maintain an adequate cold storage chain (González *et al.*, 2015).

The harvesting of wild population is done by local families, with a yield of 80 kg d^{-1} (Fundación para la Innovación Agraria, 2018), but unfortunately the harvesting process is sometimes detrimental for the structure and survival of native populations, due to bad practices as over-harvesting of stems by cutting them without silvicultural principles (Silva *et al.*, 2017).

The market

All the fruit currently being marketed is collected from natural populations, mainly located in Chile. The fruit is mostly sold to intermediaries or directly to export companies and end up in processing plants both within Chile and abroad. It is mainly sold in bulk, dehydrated as powder, or as fruit juice concentrates (Salinas *et al.*, 2012; Valdebenito *et al.*, 2003). There is a growing local industry processing maqui berry for juice, powder, and other formats.

The first record of exports of maqui berry was in 1996, with a total of 10 tons, with sustained increases in export in successive years (Salinas *et al.*, 2012; Soto *et al.*, 2014; Valdebenito *et al.*, 2003). During the first nine months of 2015, Chile exported 189 tons, with a 168% of exports increment in relation with the previous year. The main countries are Japan, South Korea, Italy, the United States, Germany, Australia, Denmark, France, Brazil, Argentina, Switzerland, among others (ODEPA, 2015; Romo, 2016). New maqui berry-based commodities are consistently appearing in the international market, correlating with an increase in Chilean exports of maqui berry (ODEPA, 2017).

Benatrehina *et al.* (2018) analyses the continuous growth of the botanical dietary supplement industry and the increased popularity of lesser known or exotic botanicals, including acaí, noni, mangosteen, black chockberry, and maqui berry. Reviewing safety studies and chemical descriptions of maqui, they conclude that the species can be considered safe for human consumption. The growing United States demand for this kind of products is an important signal for maqui berry producers.

Future challenges for maqui berry production and exports are the development of sustainable management practices in natural formations, and the stabilization of offer under a growing international demand, probably based on agricultural production (Romo, 2016).

Conclusions

Recent national and international demand for maqui berry makes it necessary to improve propagation, management, harvest and fruit storage techniques. This review indicates that maqui berry production will soon go from harvesting natural populations to agricultural production involving current techniques like selection, cloning by *in vitro* culture, and intensive cultural management (irrigation, fertilization and pruning techniques). The wide geographic distribution of the species and the variety of ecotypes offer the promising possibility of finding genotypes adapted to a wide range of climatic conditions.

The most critical areas for future research are the phenology and physiology of the species, the architecture of its crown and the relationship of these factors to productivity. These studies can complement agricultural research into techniques for planting, pruning, fertilizing and their effects on fruit quality and quantity. Particularly, the chemical changes of cultivated specimens due to irrigation is a matter of concern.

Finally, it is important to protect natural formations of the species so that their use for fruit production does not deteriorate, given that these formations are the primary sources of new genotypes. The preservation of those natural formations is important as part of Chilean ecosystems.

Regarding new properties, products and uses, the growing research probably will continue developing new interesting possibilities for the species. Researchers from Chile, Germany, Denmark, Spain, Japan, Saudi Arabia, USA, Canada, Brazil, Ecuador, Argentina, among others, demonstrate that the species, although its Chilean origin, has generated large international interest.

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