Indigenous Andean Root and Tuber Crops: New Foods for the New Millennium

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Thousands of years before the arrival of European explorers, Andean farmers had domesticated at least 180 plant species; out of these, at least 20 are roots and tubers. Multiple landraces of species like potato were selected and maintained by farmers over thousands of years. Recent studies confirm the potential value of such intra-specific diversity for securing food availability and reveal sources of bioactive products for human nutrition and health.

ANDEAN ROOT AND TUBER CROPS (ARTCs)

The best known ARTCs include arracacha, achira, yacon, mauka, and ahipa from the inter-Andean valleys; and ulluco, oca, mashua, maca, and 8 potato species from the highlands. These crops are grown from southern Venezuela to northwestern Argentina with the highest varietal diversity and uses in the region between central Peru to central Bolivia. Table 1 presents basic botanical information and current uses of these ARTCs.

Oca

The name *oca* is derived from the Quechua word *Ok'a, occa, uqa*. Oca is a perennial herb whose top part senesces, with the tubers per-

Figure 1. A plant of the oca cultivar *yuraq oqa* from farmers of the community of Qasanqay, Ayacucho, Peru, 3600 masl (a). Heterostyly of the flower facilitates cross-pollination (b). Leaves resemble clover in shape, and mature tubers are mainly of claviform and cylinder shape, their color ranges from white to deep grayish purple (c), and are used to plant oca in the Andes. Harvest occurs 7 months after planting.

Table 1. Main features of Andean roots and tubers.

Common name	Botanic name	Family	Altitude (m)	Edible part	Main current uses: Fresh	Main current uses: Traditional processing
Achira	*Canna edulis*	Cannaceae	1000-2900	Rhizome	Baked, boiled, industrial starch	Starch
Ahipa	*Pachyrhizus ahipa*	Fabaceae	1500-3000	Root	Snacks, salads	
Arracacha	*Arracacia xanthorriza*	Umbelliferae	1500-3000	Root	Boiled, baked, soups, stews, fried, baby food, puddings	Kawi
Maca	*Lepidium meyenii*	Brassicaceae	3500-4500	Hypocotyl	-	Juices, bakery, biscuits, drink
Mashua	*Tropaeolum tuberosum*	Tropaeolaceae	2800-4000	Tuber	Boiled, baked	Tayacha
Mauka	*Mirabilis expansa*	Nyctaginaceae	3000	Root	Boiled, baked, soups, puddings	Boiled, baked, soups, puddings
Oca	*Oxalis tuberosa*	Oxalidaceae	2800-3800	Tuber	Boiled, baked	Kaya
Olluco	*Ullucus tuberosus*	Basellaceae	2800-3800	Tuber	Soups, stews	Lingle, chullqi, tuntilla
Native potato	*Solanum andigena, S. phureja, S. chaucha, S. goniocalyx, S. curtilobum, S. ajanhuiri, S. juzepczukii, S. stenotomum*	Solanaceae	3000-4300	Tuber	Boiled	Chuño, tunta, moraya
Yacon	*Smallanthus sonchifolius*	Asteraceae	1800-3000	Root	Snacks, syrup	Sugar

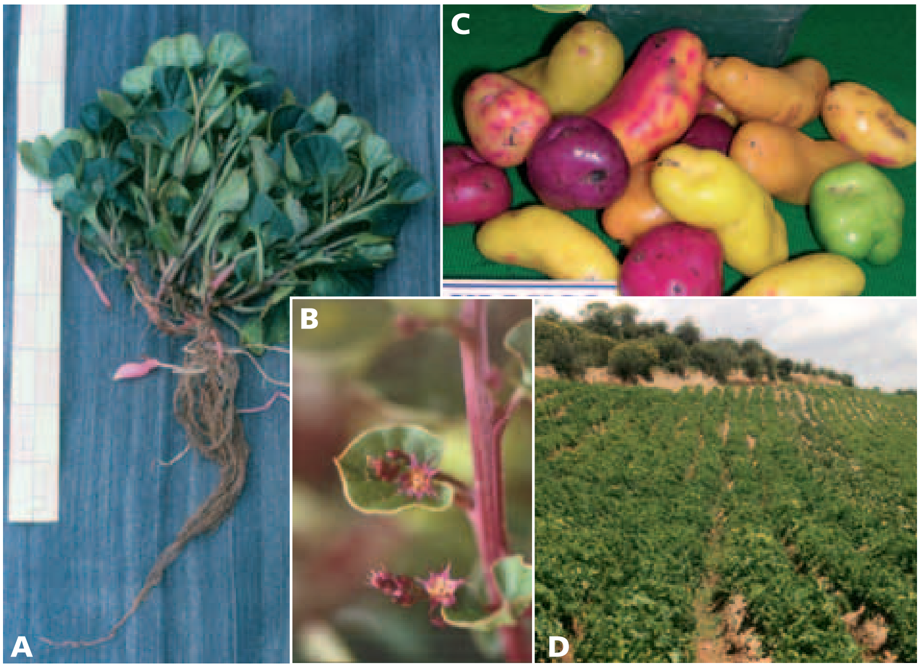


Figure 2. Growing plant of cultivar *puka ulluco* from farmers of Qasanqay community, Ayacucho, Peru, 3600 masl (a). Ulluco stems are glabrous and ridged with colors ranging from green to grayish red. Leaves are alternate and have ovate, cordate, deltoid and semi-reniform shape. Bisexual flowers rarely set seeds (b). Tubers are mainly round, cylinder and semifalcate shaped with colors ranging from white and yellow to purplish red, including variegation (c). The crop is harvested 7 months after planting (d).

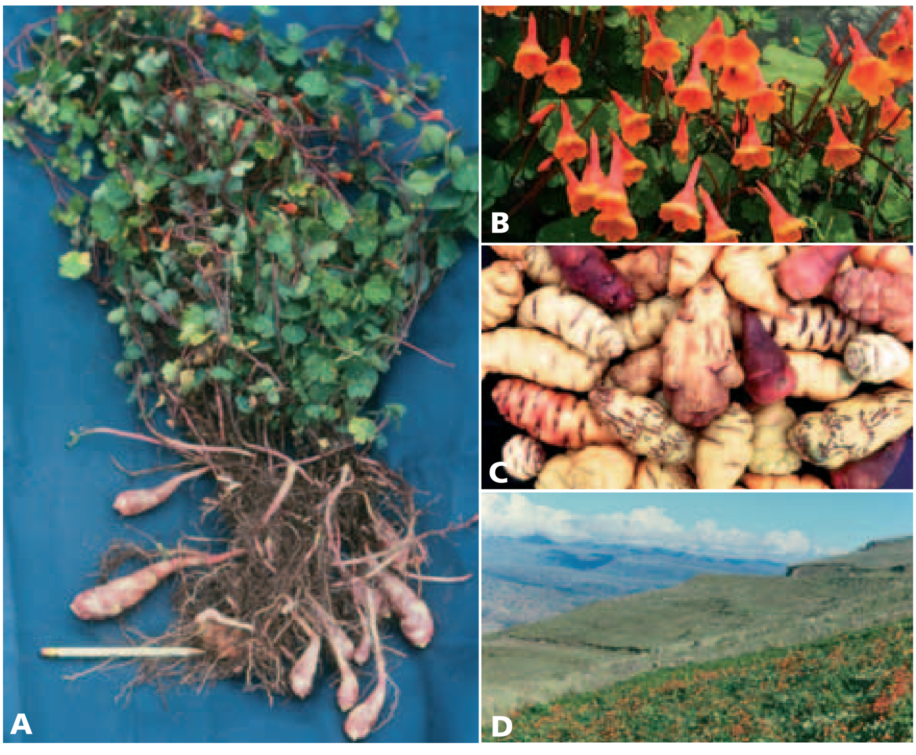


Figure 3. A plant of the mashua cultivar *Cristopa yawarnin* (Christ's blood) from the community farmers of Qasanqay, Ayacucho, Peru, 3600 masl (a). Mashua is a perennial tuberous herb resembling nasturtium whose upper part dies at the end of the growing season in the Andes. The plant is glabrous in all parts, with green yellowish to dark green stems; leaves are alternate and peltate with twining petioles. The flowers are orange color with long peduncles, and sepals fused at the base forming a spurred calyx, zygomorphic, and single ones (b). Mashua sets many seeds of orthodox behavior. Tuber color ranges from white to deep grayish purple (c). They are harvested 7 months after planting (d).

sisting to reinitiate growth in the next season (Fig. 1). The basic chromosome number of oca is *x*=8, whereas the ploidy of the wild *Oxalis* species ranges from diploid to hexaploid, and cultivated oca is an octoploid. Oca is cultivated in sandy soils; in Peru, oca is grown on approximately 22 000 ha, yielding up to 20-40 tonnes (t) per hectare. Besides the Andes, oca is also grown in Mexico and New Zealand (King, 1988).

Ulluco

The name *ulluco* is derived from a Quechua word, *ulluku*. Ulluco includes two subspecies: *tuberosus*, comprising all the cultivated ullucos and *aborigineus*, all the wild forms. The latter species may be the ancestor of *tuberosus*. The basic chromosome number is *x*=12; wild ullucos are triploids and the cultivated ranges from diploids to tetraploids. The plant (Fig. 2) prefers soils rich in organic matter, and the period between planting and harvest ranges from 140 to 200 days, depending on the variety, latitude and altitude (NRC, 1989). Yield is 20-30 t/ha; the total area of cultivation in Peru is 20 000 ha.

At times of overproduction, like oca, ulluco is dehydrated into a product that can be stored for years. Ulluco is sold in rural and urban markets of the Andes, usually at higher prices than potatoes, and appears to contain enough diversity to attempt its cultivation outside the Andes, such as the temperate zones of the World.

Mashua

The name is derived from the Quechua word *maswa* or *mashwa*. Mashua includes two subspecies: *tuberosum* and *silvestre*, but only the former sets tubers. Although the two species appear to be sympatric in the Andes (Sparre and Anderson, 1991), the wild ancestor of mashua is still unknown. The plant (Fig. 3) prefers soils rich in organic matter and its yield can reach 70 t per hectare. It is widespread in Colombia (NRC, 1989), and in Peru 8000 ha are cultivated. Traditionally, mashua tubers are exposed to the sun to increase their sweetness and reduce odor due to cyanide content.

Arracacha

The name *arracacha* is derived from a Quechua word, *rakacha*. The wild species *Arracacha incise*, which is sympatric with the cultivated arracacha, is its closest relative (Blas, 2005). Arracacha is a tetraploid of 2*n*=4*x*=44 and is restricted to relatively cool, but frost-free, montane environments, and frequently grown with maize, beans, or underneath coffee plants (NRC, 1989).

Arracacha (Fig. 4) was introduced from the Andes into Central America, apparently at the end of Colonial times. The plant was also moved to Jamaica by the British, who further introduced it into their colonies, with some success in India and Sri Lanka at the end of the

Figure 4. Arracacha plants close to maturity (a) (Photo: F. dos Santos). The upper part of the plant resembles celery. The compound leaves vary from pale green to purplish grey. The flowers are small, of yellow or purple color, arranged in umbel inflorescence (b). Although the plant sets seeds occasionally in the Andes, it is however propagated by cormels. Arracacha can be harvested 8-12 months after planting (c) (Photo: F. dos Santos). Diversity of the crop appears to be evenly distributed in the warm Andean valleys of Colombia, Ecuador, Peru, and Bolivia and three main cultivars, 'Amarillo' (yellow), 'Blanco' (white) and 'Morado' (purple) can be found (d). The rate of cross-pollination in arracacha is high and used for breeding purposes in Brazil (dos Santos, pers. commun.).

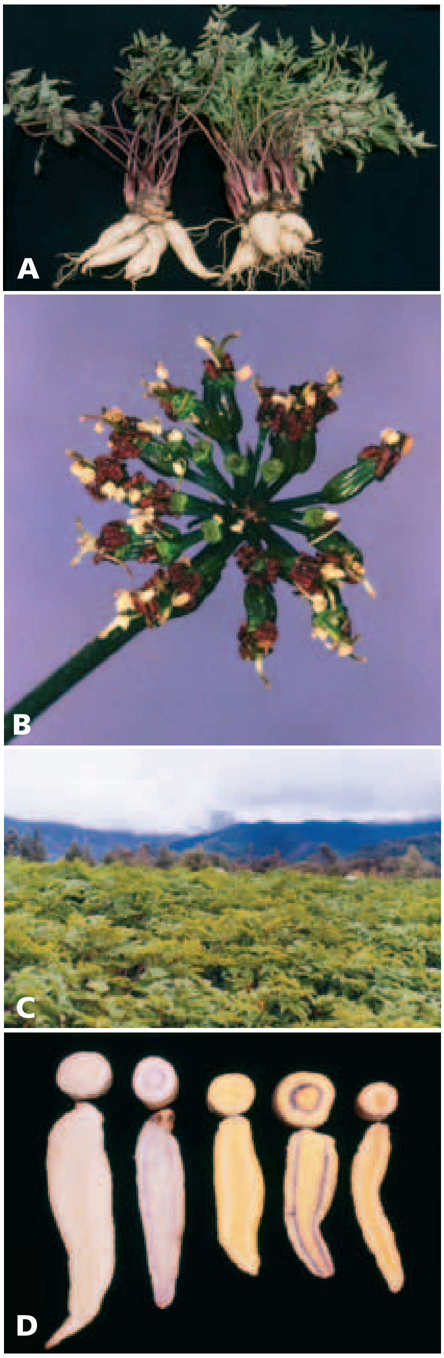
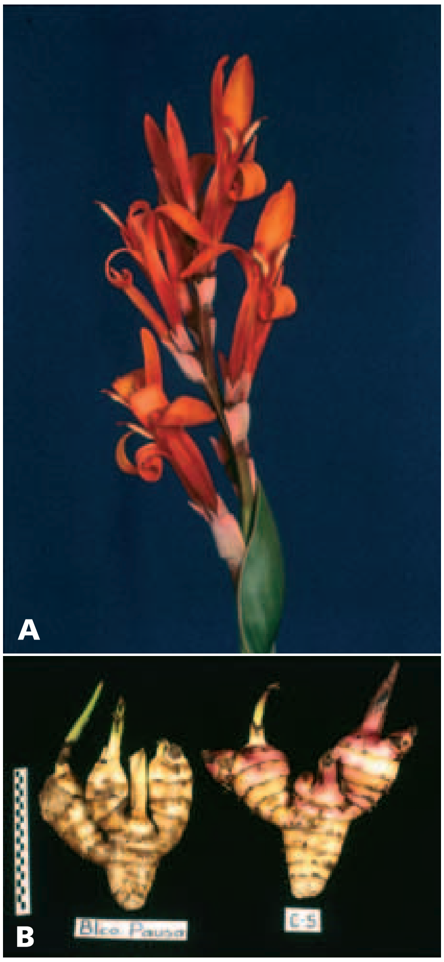


Figure 5. Achira is a perennial, with alternate leaves of ovate elliptic to ovate oblong shape. The inflorescence has flowers from red to yellowish orange color (a). The fruit is a capsule and the seeds need scarification to germinate (Maas and Maas, 1988). The rhizomes are fully expanded for harvesting 8-10 months after planting (b). The plant appears to be daylength neutral (NRC, 1989).



19th century (Hodge, 1954). Arracacha is an important food in the Andes, but it is outside the Andes where arracacha appears to have a brighter future. Approximately 30 000 ha are grown in southern Brazil for fresh consumption and for the industry of baby food and instant soups.

Achira

The name derives from the Quechua word *achira*. There are 30 to 60 species of achira in America and Asia (Maas and Maas, 1988); most of them produce fleshy starchy rhizomes with different degrees of success (Fig. 5). *C. paniculata*, and *C. iridiflora* are sympatric with the edible *Canna* in the Andes, and might be their ancestors. Achira's basic chromosome number is x=9. Diploid and triploid achiras are grown for their starchy rhizomes. The diploid achiras are inbreeders and set viable seed easily. The edible achira has not changed much, but the ornamental ones are basically the result of improvement programs for better quality blooms (Motial, 1982). Baked achiras can last several weeks under ordinary storage conditions. Achira starch is an important income generator in several Andean rural villages. In Vietnam, around 30 000 ha are grown to make prized noodles (Ho and Hao, 1995).

Figure 6. Yacon is a perennial compact herb with pilose stem up to 2-3 m height (a), with opposite triangular or rather hastate leaves. It is close to sunflower (b). Storage roots are expanded and ready for harvesting 7-8 months after planting (c). Reaction of the plant to daylength is neutral (NRC, 1989).

Yacon

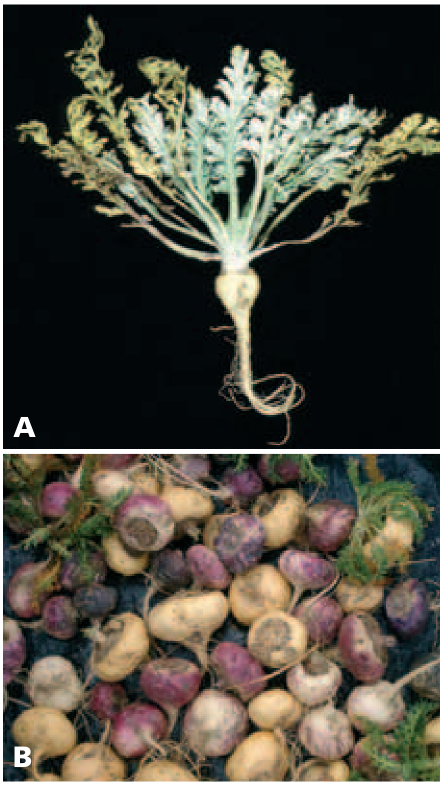
The name is derived from the Quechua word *yaku*, alluding to the high water content of its storage roots. Yacon has $2n$=58 chromosomes. There are at least 21 species of *Smallanthus*, all from the Americas. The richest diversity is found on the eastern Andean slopes between Peru and Bolivia, which seems to be the center of origin of the species (Grau and Rea, 1997).

Harvested yacon root (Fig. 6) productivity ranges from 30 to 40 t per hectare, although yields of up to 100 tonnes have been reported in Brazil and Peru. In the past two decades, yacon was introduced from the Andes to New Zealand and then to Japan. From Japan it was distributed to Korea and Brazil. Yacon is currently cultivated in USA, Philippines, Czech Republic and lately in China. Yacon is eaten raw as a fruit and could also be processed.

Maca

The name maca is derived from the Quechua word *maca*. Maca is an inbreeder with 64 chromosomes. Maca cultivation is mostly restricted to the highlands of the central Peruvian Andes, with populations morphologically very uniform. Maca's domestication probably occurred in the Bombon plateau, Peru. The plant (Fig. 7) prefers very cold climates, with adequate moisture, and the estimated yield of fresh hypocotyls is 15-20 t per hectare. Total cultivation area in Peru is approximately 2000 ha. Maca is becoming a popular medicine and has the reputation to enhance human and animal fertility.

Figure 7. Maca is an annual herb (a), but managed as a biennial crop. The first year maca grows vegetatively forming edible hypocotyls 6-8 months after planting (b). The second year maca grows reproductively to set flowers and seeds. Leaves are produced at the centre of the rosette and are highly resistant to frost.



Mauka

The name is derived from the Aymara word *mauka*. The species *Mirabilis expansa* is apparently the only one setting tuberous roots within the family. Although the species has been described since 1794, it remained in obscurity until 1965 when Rea and Leon (1965) re-discovered it in the rural community of Yokarguaya, Camacho, Bolivia at 2900 m. The plant (Fig. 8) is a good substitute for cassava, arracacha or sweetpotato. The roots are exposed to sunlight before consumption to remove their unpleasant bitter taste. The foliage can be used as a livestock feed.

Figure 8. Mauka (a) is compact perennial herb with branching basal shoots from which opposite ovoid and rather coriaceous leaves emerge. The small flowers range from white to purple color. The plant sets many viable seeds, but the usual way to propagate the plant is by cuttings. Its storage roots resemble cassava (b).

Ahipa

The name ahipa is derived from the Quechua word *aqipa* or *ashipa*. The species *Pachyrhizus ahipa* is an inbreeder of 22 chromosomes; orthodox seeds are used to propagate the crop (Sorensen, 1996). Greatest diversity and uses occur in Bolivia. Other cultivated species are: *P. tuberosus*, and *P. erosus*. The plant (Fig. 9) is usually cultivated in family orchards. There are no records of known wild ancestral material (NRC, 1989).

Figure 9. A full grown plant of *ahipa* (*P. tuberosus*) from San Ramon CIP's Experimental Station, Junin, Peru, 800 masl. The species is a herbaceous vine grown in the highland rain forest of Peru and Ecuador from sea level to 1500 m. *P. ahipa*, on the other hand, is an erect to semi-erect herbaceous tuberous plant that sets only one swollen root, which is thickened at the top end tapering toward the tips "radish-like" (Sorensen, 1996).

Native Potato

The name *papa* is derived from the Quechua word *papa*. Potato landraces were domestica-

Figure 10. Variation in shape and color of native potato tubers from the Andes.This is a sample of the collection maintained in CIP genebank, Lima, Peru. Each tuber represents a distinct cultivar of the 7 species (a): *S. stenotomum* subsp. *stenotomum* (1-7); *S. stenotomum* subsp. *goniocalyx* (8-12); *S. phureja* (14-15); *S.* x *ajanhuiri* (13); *S.* x *juzepczukii* (16-19); *S.* x *chaucha* (20-23); *S. tuberosum* subsp. *andigenum* (24-42); *S.* x *curtilobum* (43-44). Variability also is high in tuber flesh color and texture as it is expressed after boiling harvested tubers (b). Likewise, chips produced from thin tuber slices show pigmentation patterns proper to each cultivar (c). The International Potato Center (CIP) has assembled the world's largest and most complete collection of native potatoes, comprising 4,383 morphologically unique accessions.

ted in the Andes. Native potatoes are very well adapted to the extremely hostile conditions in the high Andes. Their morphological diversity is related to the genetic diversity, with ploidies of $2n=2x=24$ for *S. stenotomum* subsp. *stenotomum*, *S. stenotomum* subsp. *goniocalyx*, *S. phureja* and *S. xajanhuiri*; $2n=3x=36$ for *S. xchaucha* and *S. xjuzepczukii*; $2n=4x=48$ for *S. tuberosum* subsp. *andigenum*; and $2n=5x=60$ for *S. xcurtilobum*. Native potatoes were discovered by the Spanish when they arrived in Peru in 1532-34; they were transported to the Canary Islands in 1560-65 and to Spain in 1570.

Due to their glycolakaloid content, two groups can be distinguished within the native potatoes: bitter and non-bitter. The bitter group includes the species *S. xjuzepczukii*, *S. xcurtilobum* and a form of *S. xajanhuiri*; bitter tubers are traditionally processed (frozen, washed and dehydrated) into white chuño, moraya or tunta to make the tubers edible and storable for a long time. The non-bitter group contains many more varieties and is mainly used as a fresh product, and for processing and industrialization (Fig. 10). In the highlands, potatoes are grown by farmers in small parcels of less than 0.3 ha. At those harsh conditions, yield ranges from 5 to 18 t per ha.

POTENTIAL OF ARTCS FOR NUTRITION AND HEALTH

ARTCs constitute a major source of carbohydrates (59-96% DM) and calories (NRC, 1989). However, it is not well known that these crops are also important sources of chemical components that can greatly promote health and enhance nutrition.

Starch is the most important nutritional constituent of ARTCs (Table 2); its physicochemical and nutritional properties vary significantly, both within and between species (King and Gershoff, 1987). Therefore, the uses and applications in food and industry are also variable. For example, arracacha and achira starch grains are very small (~10 µm), with high levels of amylopectin, above 85%, and excellent digestibility. These starches are ideal sources for children and dieting people. Native potatoes, with high dry matter content (24-32%), have excellent culinary quality. They can be consumed fresh and processed as French fries, chips, mashed potatoes, chuño (tunta and moraya), among other uses (Table 1).

Yacon is the only ARTC that stores fructooligosaccharides (FOS) rather than starch (Table 2). FOS are particular fructose-containing carbohydrates that the human body cannot metabolize, but they are fermented by beneficial bacteria of the colon. FOS have been reported to help reduce cholesterol and triglyceride levels, enhance calcium assimilation, strengthen the immune system and prevent colon cancer. Yacon is probably the only vegetable source with high FOS content (40-60% DM).

Protein content of ARTCs is generally low, but can be particularly high in selected olluco, maca, mashua, and ahipa cultivars (10.0, 10.2, 15.7 and 17.5% DM, respectively). There are mashuas, ocas and ollucos with lysine contents higher than milk, beef and fish (Table 2), while other essential amino acids like isoleucine, leucine, lysine, phenylalanine, triptophan, threonine and valine have been occasionally reported to occur at higher levels than the doses recommended by FAO/WHO (King and Gershoff, 1987). The lipid content of ARTCs is very low (less than 1% DM), except maca (2.2% DM). Maca lipids are usually found in the form of unsaturated fatty acids like linoleic, oleic and palmitic acids, and sterols like campesterol and sitosterol (Table 2).

ARTCs are also a very important source of biologically active compounds with antioxidant, anticarcinogenic or antimicrobial attributes, for example. Glucosinolate, benzylglucosinolate and *p*-methoxybenzylglucosinolate, and the products derived from their hydrolysis, i.e. isothiocyanates, are abundant in maca (Piacente et al., 2002) and mashua. These compounds have been reported to have anticancer-related properties (Noratto et al., 2004). Moreover, maca also contains unique compounds like the amides of fatty polyunsaturated acids, known as macaenes and macamides (Muhammad et al., 2002). These have been related to fertility enhancement in humans and animals. Human subjects consuming powdered maca for 4 months showed significant increase in sperm number and motility, while sperm morphology remained normal (Gonzales et al., 2001). On the other hand, male rats fed with mashua showed a 45% drop of testosterone/dihydrosterone in their blood levels (Johns et al., 1982).

Table 2. Major chemical constituents found in Andean root and tuber crops.

Common name	Major chemical constituents	References
Achira	Starch, Fe, K	Hermann (1994), NRC (1989)
Ahipa	Starch, amylopectin, protein, K, vitamin C, rotenone	Forsyth and Shewry (2002), Sorensen (1996)
Arracacha	Amylopectin, ß-carotene, ascorbic acid, niacin calcium, Fe	NRC (1989)
Maca	Starch, unsaturated fatty acids, sterols, glucosynolates, isothiocyanates, flavonoids macaenes, macamides, lysine, alkaloids, Fe, Ca	Dini et al. (1994), Valentova and Ulrichova (2003)
Mashua	Starch, protein, carbohydrates, phenols, glucosynolates, isothiocyanates, anthocyanin carotenoid, vitamin A and C	Campos et al. (2006), King and Gershoff (1987)
Mauka	Starch, protein, Ca, P and K	NRC (1989)
Oca	Starch, vitamin C, anthocyanins, carotenoids, oxalates	Campos et al. (2006), King and Gershoff (1987)
Olluco	Starch, protein, betalains, betaxanthins, mucilage, Ca	Campos et al. (2006), King and Gershoff (1987)
Native potato	Starch, protein, vitamin C, phenols, anthocyanins, carotenoids, pigments, Ca	Campos et al. (2006), King and Gershoff (1987)
Yacon	Fructooligosaccharides, phenols, sesquiterpenic lactones, tryptophan, chlorogenic and caffeic acids, K	Grau and Rea (1997), Valentova and Ulrichova (2003)

Figure 11. Display of maca derived products commercialized in Andean countries. The most important in terms of commercial value are: flour and gelatinized flour, snacks, pills, liquors, and energized food and drinks. Total maca flour volume exported from Peru in 2006 was 271.6 TM.

Figure 12. Artisanal yacon processing plant installed in Oxapampa, Peru. Most common yacon processed products include: syrup, ships, tea and flour.

Native potatoes are rich in vitamin C (Andre et al., 2006). It is estimated that the daily consumption of a medium-size tuber might be sufficient to satisfy half of the vitamin C requirements of an adult person. Oca, mashua and native potato exhibit strong antioxidant activity due to their high phenolic, carotenoid and anthocyanin contents (Table 3). Some mashua cultivars show antioxidant values (9800 µg TE/g) higher than blueberry cv. Premier (9572 µg TE/g), a well-known source of antioxidants with hydrophilic capacity (Campos et al., 2006).

The leaves of yacon have been reported to have hypoglycemic properties (Aybar et al., 2001). These are rich in sesquiterpene, lactone and phenolic compounds with high antioxidant activity, such as chlorogenic acid and some derivatives of caffeic acid. However, the nature of the hypoglycemic principle is still unknown. Dehydrated leaves of yacon are marketed for diabetes treatment in Japan, Brazil and Peru. Commercialization of processed yacon and maca products has drastically increased in the Andean countries in recent years (Figs. 11 and 12).

ARTCs offer a great potential to become new and important nutraceutical sources to favor human health. Besides, they can also be of interest to other industries, for example seeds of ahipa contain rotenone, a powerful insecticide in organic agriculture; mashua, maca and yacon contain chemical compounds with nematicide, insecticide, fungicide and bactericide properties (Valentova and Ulrichova, 2003; Guimaraes, 2001). Moreover, papa, oca, ulluco and mashua tubers contain strong and stable color pigments (Rodriguez-Saona et al., 1998) demanded by the food and cosmetic industry.

Table 3. Secondary metabolites and hydrophilic antioxidant capacity (AAC) of four indigenous Andean tuber crops.

Metabolites and AAC	Native potato (n=15)	Mashua (n=11)	Oca (n=14)	Olluco (n=15)	Other
Phenolic compounds (mg chlorogenic acid equiv./g)	0.6-2.3	0.9-3.4	0.7-1.3	0.4-0.8	3.3 (strawberry)
Anthocyanins (mg cyanidin 3-glucoside equiv./g)	0.1-0.8	0.5-2.1	0.1-1.3	0	1.4-3.9 (blueberry)
Carotenoids (µg ß-carotene equiv./g)	2-5	1-25	2-25	0	90 (carrot)
Hydrophilic antioxidant capacity (µg trolox equiv./g)	860-3780	955-9800	1637-4771	483-1524	6900-9572 (blueberry)
Dry matter (%)	25.1-31.9	8.8-11.2	15.1-18.9	11.6-15.0	-

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