5

Potato Antioxidant Compounds: Impact of Cultivation Methods and Relevance for Diet and Health

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1. Introduction

Potato is currently the fourth most important food crop in the world after maize, wheat and rice, with a production of 329 millions tons (FAO, 2009). As for the harvested area, potato ranks 7th after wheat, rice, maize, barley, sorghum and rapeseed worldwide. In terms of consumption, potato ranks third after rice and wheat. Interestingly, the importance of potato in the diet is higher in developed as compared to developing countries, accounting for 130 kcal per person per day for the developed world and for 41 kcal per person per day in the developing world (Burlingame et al., 2009). In Europe, the per capita consumption reaches almost 90 kg $year^{-1}$, whereas in developing countries, its per capita consumption is smaller, reaching around 20 kg $year^{-1}$ (André et al., 2007a, FAO, 2009)).

Potato is mainly known to supply dietary fibre, carbohydrates, high-quality proteins, vitamins and minerals. According to the USDA National Nutrient Database, contents would be 2.4 g for dietary fiber, 15.7 g for carbohydrates, 1.7 g for protein content, 19.7 g for vitamin C, each per 100 g of white, raw potato (flesh and skin) (Singh & Kaur, 2009). As for the minerals, iron and zinc contents are around 0.52 mg and 0.29 mg per 100 g (Singh & Kaur, 2009). Potatoes are also known as sources of antioxidant compounds, including polyphenols, carotenoids and vitamins, pointing to their relevance not only as a starchy food, but also as a vegetable.

Data on the antioxidant content of potatoes can be found in several national food composition tables. Table 1 summarizes some of the data available on contents of ascorbic acid, β-carotene, α-tocopherol, lutein and zeaxanthin. Phenolic compounds were not specified in these databases.

Potato's genetic diversity is huge; more than 4000 different wild varieties have been collected at the International Potato Center in Lima (Peru). They are diverse regarding tuber shape, flesh and skin colour, flavour, storage quality and cooking quality (André et al., 2007a).

The classification of cultivated potatoes has been reviewed several times and still is a matter of debate. Huaman and Spooner (2002) classified all landrace populations of cultivated

Compound	DK	F	D	CH	USA white	USA red
Ascorbic acid (mg/100 g)	26.4	11.1	18.8	17.0	19.7	8.6
β-Carotene (µg/100 g)	10	2	5	5	5	4
Lutein + Zeaxanthin (µg/100 g)	n.a.	n.a.	n.a.	n.a.	13	21
α-Tocopherol (mg/100 g)	0.10	0.05*	0.05	0.06*	0.01	0.01

Table 1. Antioxidant contents of potatoes. Data were obtained from national food composition tables. DK = potato, raw, Denmark (National Food Institute - Technical University of Denmark, 2009), F = potato, boiled, France (French Information Center on Food Quality, 2008); D = potato, peeled, raw, Germany (Max-Rubner-Institut - Karlsruhe, 2010); CH = potato, peeled, raw, Switzerland (ETH Zürich, 2009); USA white = potato, white, raw, U.S.A. (Nutrient Data Laboratory, 2010); USA red = potato, red, raw, U.S.A. (Nutrient Data Laboratory, 2010); n.a. = not analyzed; * = α-tocopherol equivalents.

potatoes in a single species *Solanum tuberosum* with 8 cultivar groups: Ajanhuiri Group (2x), Andigenum Group (4x), Caucha Group (3x), Chilotanum Group (4x), Curtilobum Group (5x), Juzepczukii Group (3x), Phureja Group (2x) and Stenotonum Group (2x). Modern cultivars were classified into a ninth cultivar group, the Tuberosum Group. However, it is worth mentioning that Spooner et al. (2007) reviewed the classification combining morphological data with molecular fingerprinting data.

In South America, the center of potato origin and diversity, potato constitutes the main staple crop and farmers cultivate up to 50 varieties in a field (FAO, 2008). This not only enables them to be protected from a complete loss in the case of a disease or an abiotic stress, it also allows them to get a more diversified diet. Indeed, the composition of the tubers varies according to the cultivar, agricultural practices, climate and soil (Rodriguez et al., 2010); moreover cooking and processing may have an effect on tuber composition (Xu et al., 2009).

Biofortification programs aiming at enriching nutrient contents of edible plants for health improvement and disease prevention are ongoing. They include biofortification through fertilization, breeding or biotechnology (White & Broadley, 2005). Nutrient biofortification of food crops may not only include elevated mineral and amino acid levels, but also enhanced antioxidant levels (Diretto et al., 2007, Rommens et al., 2008). Traditional agricultural approaches, such as breeding, can improve the nutritional value to some extent (Hirschi, 2009); especially if the corresponding trait is strongly dependent on the genotype, the selection of adequate progenitors allows to expect good progress in breeding (Burgos et al., 2009a).

The present chapter gives an overview on the potato antioxidants and on parameters impacting their contents in the tuber. Moreover, it will give an insight into potential health-promoting effects and bioavailability of antioxidants.

2. Antioxidants in potato

The concept of potato as a source of antioxidants is not widely spread. However, recent studies have placed potato into the perspective of an antioxidant-rich crop. More precisely, potatoes contain phenolic compounds including hydroxycinnamic acids, the predominant being chlorogenic acid (André et al., 2007b, Brown, 2005) and flavonoids, for example

catechin, epicatechin and anthocyanins. Potato contains low amounts of carotenoids, such as β-carotene (Brown, 2005), indicating that potato is not a good source of pro-vitamin A carotenes; more important are the oxygenated carotenoids, the xantophylls, such as neoxanthin, violaxanthin, antheraxanthin, lutein and zeaxanthin (Griffiths et al., 2007). As for the vitamins, potato contains on average 20 mg per 100 g FW of vitamin C (Brown, 2005) and concerning vitamin E, mainly α-tocopherol is present at concentrations between 55 and 416 µg per 100 g FW (André et al., 2007b). Hereafter, the types and contents of potato antioxidants will be discussed in more detail.

2.1 Polyphenols

Polyphenols are secondary plant metabolites. In potatoes, mainly hydroxycinnamic acid derivatives and flavonoids occur. As examples, the chemical structures of chlorogenic acid, a hydroxycinnamic acid ester with quinic acid, and kaempferol 3-*O*-rutinoside, a flavonol glycoside, are shown in Figure 1.

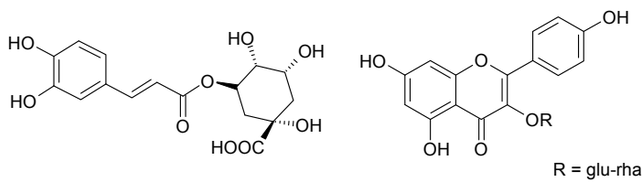

Fig. 1. Chemical structures of chlorogenic acid (left) and kaempferol 3-*O*-rutinoside (right).

Plant material	Total phenolic content (mg/g DW)	Sample preparation	Reference
S. tuberosum	2.5 – 4.8	crude, freeze-dried	(Lachman et al., 2008)
unspecified	4.5 – 6.8	crude, freeze-dried	(Stratil et al., 2006)
Solanum sp.	1.8 – 11	crude, freeze-dried	(Navarre et al., 2011)
unspecified	0.9 – 3.0	crude, freeze-dried	(Xu et al., 2009)
S. tuberosum	1.1 – 27.4[a]	crude, freeze-dried	(André et al., 2007a, André et al., 2009a)
unspecified	0.32[b]	crude	(Chiou et al., 2007)
S. tuberosum	0.3 – 0.5	crude, freeze-dried	(Rumbaoa et al., 2009)
S. tuberosum	15.1	crude	(Natella et al., 2010)
unspecified	0.6 – 2.3[a]	crude	(Blessington et al., 2010)
Solanum sp.	3 – 16 [a]	crude	(Campos et al., 2006)
S. tuberosum	1.5 – 3.2	cooked, peeled, mashed	(Kaspar et al., 2011)
S. tuberosum	2.1 – 7.8 [a]	crude	(Reddivari et al., 2007)
S. tuberosum	1.0 – 2.9	crude, freeze-dried	(Leo et al., 2008)
S. tuberosum	1.3 – 13.4	crude	(Madiwale et al., 2011)
S. tuberosum	1.8	crude, freeze-dried	(Mäder et al., 2009)
S. tuberosum	8 - 78	crude, freeze-dried	(Stushnoff et al., 2010)

Table 2. Total phenolic content of potatoes determined with the Folin-Ciocalteau assay. As far as not otherwise indicated, the results are expressed as gallic acid equivalents. [a] As chlorogenic acid equivalents, [b] as caffeic acid equivalents. Contents reported in another unit than mg/g dry weight (DW) were recalculated utilizing an average moisture content of 80%.

Here, we present an overview on current available literature on total phenolic contents (Table 2), anthocyanins (Table 3) and individual polyphenols (Table 4). Total phenolic contents have been determined by using a spectrophotometric assay, the Folin-Ciocalteau assay. This assay estimates the phenolic content in plants, but other plant compounds (for example thiol derivatives, vitamins, and amino acids) may also be detected (Everette et al., 2010). Total anthocyanins, which impart for colour in red and purple potatoes, have been determined using the pH differential method (Giusti & Wrolstad, 2001). This method gives the sum of all anthocyanins present in the sample. Individual polyphenols have been quantified by HPLC with UV-detection.

Plant material	Total anthocyanin content (mg/g DW)	Sample preparation	Reference
S. tuberosum	0 – 21.4 [a]	crude, freeze-dried	(André et al., 2009a, André et al., 2009b)
S. tuberosum	0.3 – 1.8 [b]	crude, freeze-dried	(Brown, 2008)
Solanum sp.	0 – 4 [b]	crude	(Campos et al., 2006)
S. tuberosum	0 – 6.2	cooked, peeled, mashed	(Kaspar et al., 2011)
Solanum sp.	0 – 1.2 [b]	crude	(Brown et al., 2007)
S. tuberosum	1.0 –5.5	crude	(Madiwale et al., 2011)
S. tuberosum	2 - 45	crude, freeze-dried	(Stushnoff et al., 2010)

Table 3. Total anthocyanin content of potatoes determined with the pH differential method. The results are expressed as [a]petanin or [b]cyanidin 3-O-glucoside. In some references the standard compound was not stated. Contents reported in another unit than mg/g dry weight (DW) were recalculated utilizing an average moisture content of 80%.

Plant material	Phenolic content (µg/g DW)	Sample preparation	Reference
Chlorogenic acid			
S. tuberosum cvs. Siikli and Timo	455 – 600	cooked, freeze-dried	(Mattila & Hellström, 2007)
S. tuberosum cv. Désirée	1500	crude, freeze-dried	(Lukaszewicz et al., 2004)
S. tuberosum cv. Sava	361 – 520	crude, peeled, freeze-dried	(Soltoft et al., 2010)
S. tuberosum	421 -2185	crude, freeze-dried	(Zhu et al., 2010)
Solanum sp.	220 -4730	crude, freeze-dried	(Navarre et al., 2011)
Solanum sp.	55 - 1340	crude	(del Mar Verde Mendez et al., 2004)
unspecified	420.5 – 3183.4	crude, freeze-dried	(Xu et al., 2009)
S. tuberosum	216 – 12746	crude, freeze-dried	(André et al., 2007b, André et al., 2009a, André et al., 2009b)
unspecified	6. 5	crude	(Chiou et al., 2007)
unspecified	33 - 6370	crude, freeze-dried	(Im et al., 2008)
S. tuberosum	600 - 2100	crude, freeze-dried	(Navarre et al., 2010)

Plant material	Phenolic content (µg/g DW)	Sample preparation	Reference
S. tuberosum cv. Norkotah and Ranger	2200 and 1000	crude, freeze-dried	(Shakya & Navarre, 2006)
S. tuberosum	343 - 1249	crude	(Hajslova et al., 2005)
unspecified	39.5 - 65	crude	(Blessington et al., 2010)
S. tuberosum	470 - 920	crude, freeze-dried	(Leo et al., 2008)
S. tuberosum	718	crude, freeze-dried	(Mäder et al., 2009)
Caffeic acid			
S. tuberosum cv. Désirée	800	crude, freeze-dried	(Lukaszewicz et al., 2004)
Solanum	5 - 476	crude, freeze-dried	(Navarre et al., 2011)
Solanum sp.	5 - 135	crude	(del Mar Verde Mendez et al., 2004)
unspecified	0 – 93.8	crude, freeze-dried	(Xu et al., 2009)
S. tuberosum	7 – 143	crude, freeze-dried	(André et al., 2007b, André et al., 2009a, André et al., 2009b)
unspecified	5 - 293	crude, freeze-dried	(Im et al., 2008)
S. tuberosum cv. Norkotah and Ranger	100 and 200	crude, freeze-dried	(Shakya & Navarre, 2006)
S. tuberosum	50 - 120	crude, freeze-dried	(Leo et al., 2008)
S. tuberosum	203	crude, freeze-dried	(Mäder et al., 2009)
Quercetin 3-*O*-rutinoside (= Rutin)			
S. tuberosum cv. Monalisa	180	crude	(Tudela et al., 2002)
Solanum sp.	0 - 141	crude, freeze-dried	(Navarre et al., 2011)
S. tuberosum	0 – 256	crude, freeze-dried	(André et al., 2007b, André et al., 2009a, André et al., 2009b)
S. tuberosum	6.6 – 7.4	crude, freeze-dried	(Navarre et al., 2010)
unspecified	26.5 - 49	crude	(Blessington et al., 2010)
Kaempferol 3-*O*-rutinoside			
Solanum sp.	0 - 433	crude, freeze-dried	(Navarre et al., 2011)
S. tuberosum	0 – 227	crude, freeze-dried	(André et al., 2007b, André et al., 2009a, André et al., 2009b)
S. tuberosum	5.5 – 7.0	crude, freeze-dried	(Navarre et al., 2010)
(+)-Catechin			
Solanum sp.	90 - 1305	crude	(del Mar Verde Mendez et al., 2004)
S. tuberosum	430 - 1570	crude, freeze-dried	(Leo et al., 2008)
S. tuberosum	13	crude, freeze-dried	(Mäder et al., 2009)

Table 4. Content of individual polyphenols in potatoes determined by HPLC-UV. Contents reported in another unit than µg/g dry weight (DW) were recalculated utilizing an average moisture content of 80%.

As can be seen in tables 2, 3 and 4, potatoes contain between 0.3 and 78 mg/g DW of phenolic compounds, whereas the total anthocyanin content was shown to be 0 in white or yellow fleshed potatoes and up to 45 mg/g DW in some red and purple fleshed cultivars. Regarding the individual polyphenols, chlorogenic acid is the predominant compound in potatoes with contents ranging from 6.5 to 12746 µg/g DW. The contents of caffeic acid, quercetin 3-*O*-rutinoside, kaempferol 3-*O*-rutinoside and (+)-catechin ranged from 0 to 800 µg/g DW, 0 to 256 µg/g DW, 0 to 433 µg/g DW, and 13 to 1570 µg/g DW, respectively. Generally, purple and red fleshed cultivars contained higher amounts of polyphenols than cultivars with a cream or white flesh.

Additionally to the phenolic compounds listed in Table 4, other compounds have been described, namely neochlorogenic acid, cryptochlorogenic acid, caffeoyl putrescine, *p*-coumaric acid, ferulic acid, cinnamic acid, syringic acid, sinapic acid, gallic acid, vanillin, vanillic acid, *p*-hydroxybenzoic acid, *p*-hydroxyphenylacetic acid, myricetin, (-)-epicatechin, p-coumaroylhydroxyagmatine, and petanin *(*André et al., 2007b, André et al., 2009b, Blessington et al., 2010, Chiou et al., 2007, del Mar Verde Mendez et al., 2004, Mäder et al., 2009, Navarre et al., 2011*)*.

2.2 Carotenoids

The carotenoid levels in potatoes determine whether the tuber flesh is white (low carotenoid content), yellow (moderate content), or orange (high content). Carotenoids in potatoes belong to the groups of the bicyclic carotenes and the xanthophylls. Carotenes (e.g. β-carotene) are pure polyen hydrocarbons whereas xanthophylls (e.g. lutein) contain oxygen groups (hydroxyl-, epoxy-, or carbonyl-groups). The chemical structures of two carotenoids from potatoes are shown in Figure 2.

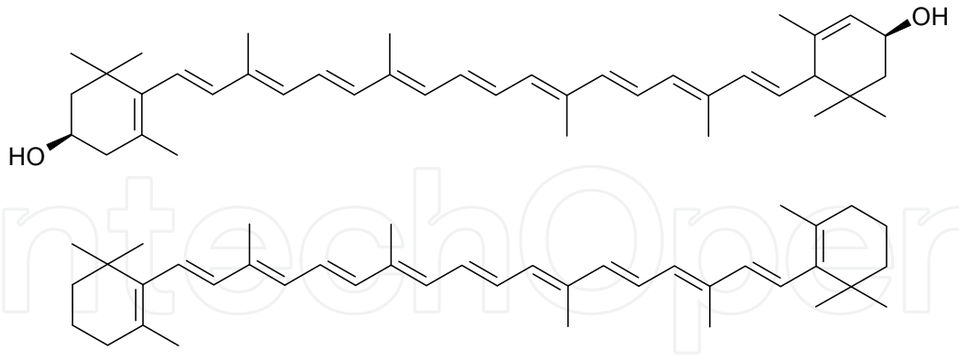

Fig. 2. Chemical structures of the carotenoids lutein (above) and β-carotene (below).

The total carotenoid contents and concentrations of individual carotenoids reported in literature are summarized in Table 5 and Table 6. To achieve a better comparability, values that were not expressed in µg/g DW were recalculated to this basis. The major carotenoids in potatoes are violaxanthin, lutein, zeaxanthin, neoxanthin, and antheraxanthin, but according to the publications cited in Table 6 their contribution varies among the cultivars. The composition of carotenoids in the skin and the flesh of the potato tubers is similar *(*Burmeister et al., 2011*)*.

The determination of the total carotenoid content was mostly conducted in saponificated carotenoid extracts using a spectrophotometric assay, whereas individual carotenoids were identified and quantified by HPLC-UV analysis. Near-infrared reflectance spectroscopy (NIRS) – an analytical method that is less expensive and more rapid than HPLC - was also applied for the determination of individual carotenoids (Bonierbale et al., 2009).

Plant material	Carotenoid content (µg/g DW)	Sample preparation	Reference
S. tuberosum	2.5 – 17.5	crude	(Brown, 2008)
S. tuberosum	3.9 – 7	crude	(Blessington et al., 2010)
S. tuberosum	10 – 25	crude	(Campos et al., 2006)
S. tuberosum cv. Pentland Javelin	1.6	crude, freeze-dried, white fleshed	(Morris et al., 2004)
S. tuberosum cv. Desiree	4.9	crude, freeze-dried, cream/yellow-fleshed	(Morris et al., 2004)
S. phureja cv. DB375\1	36.3	crude, freeze-dried	(Morris et al., 2004)
S. tuberosum	1.9 – 43.9	crude	(Nesterenko & Sink, 2003)
S. tuberosum cv. Yukon Gold and Superior	3.2 and 5.6	crude, without skin	(Lu & Haynes, 2001)
Hybrid from S. phureja and S. stenotomum	6.8 and 71.8	crude, without skin	(Lu & Haynes, 2001)
S. tuberosum	7.5 – 233	crude	(Kotikova et al., 2007)
Cross between S. tuberosum and S. phureja	17.7 – 34.9		(Kobayashi et al., 2008)
S. phureja	0.6 – 42.7	crude, freeze-dried	(Griffiths et al., 2007)
S. tuberosum	1.3 – 58	cooked, without skin, mashed	(Kaspar et al., 2011)
Solanum sp.	1.7 – 84.2	crude	(Brown et al., 2007)
S. tuberosum	2.6 – 14.8	crude, freeze-dried	(Burmeister et al., 2011)
S. phureja	8.9 – 9.9	crude, freeze-dried	(Burmeister et al., 2011)
S. phureja	4.9 – 92	crude	(Burgos et al., 2009b)
S. tuberosum	4.8 – 46.5	crude	(Reddivari et al., 2007)
S. phureja	1.0 – 21.4	crude, freeze-dried	(Bonierbale et al., 2009)
S. tuberosum	1 – 3	crude, freeze-dried	(Leo et al., 2008)
S. tuberosum	2.8 – 36.2	crude, freeze-dried	(André et al., 2007a)

Table 5. Total carotenoid content in potatoes reported in literature. Contents reported in another unit than µg/g dry weight (DW) were recalculated utilizing an average moisture content of 80%.

Plant material	Carotenoid content (µg/g DW)	Sample preparation	Reference
Lutein			
S. tuberosum	0.5	crude	(Blessington et al., 2010)
S. tuberosum	1.0 – 6.0	crude	(Nesterenko & Sink, 2003)
S. tuberosum cv. Yukon Gold and Superior	1.2 and 0.8	crude, without skin	(Lu & Haynes, 2001)
Hybrid from S. phureja and S. stenotomum	2.8 – 26.6	crude, without skin	(Lu & Haynes, 2001)
Cross between S. tuberosum and S. phureja	0.8 – 11.6		(Kobayashi et al., 2008)
S. tuberosum	n.d. – 0.03	crude	(Zhou et al., 2011)
S. tuberosum cv. Baltica	3.3	cooked and mashed	(Bub et al., 2008)
S. tuberosum cv. Red Laura and Shetland Black	3.2 and 0.5	crude, freeze-dried	(Burmeister et al., 2011)
S. phureja cv. Mayan Twilight and Mayan Gold	2.1 and 2.7	crude, freeze-dried	(Burmeister et al., 2011)
S. phureja	2.8 – 10.6	crude	(Burgos et al., 2009b)
S. tuberosum cv. Désirée	0.7	crude, freeze-dried	(Ducreux et al., 2005)
S. tuberosum	1.1 – 17.7	crude, freeze-dried	(André et al., 2007b)
S. phureja	0.6 – 1.9	crude, freeze-dried	(Bonierbale et al., 2009)
S. tuberosum	5.0 – 11.4	crude, freeze-dried	(André et al., 2009b)
Violaxanthin			
S. tuberosum	0.2 – 6.2	crude	(Nesterenko & Sink, 2003)
S. tuberosum cv. Yukon Gold and Superior	2.6 and 1.0	crude, without skin	(Lu & Haynes, 2001)
Hybrid from S. phureja and S. stenotomum	1.2 – 22.0	crude, without skin	(Lu & Haynes, 2001)
S. tuberosum	0.2 – 3.3	crude, without skin	(Breithaupt & Bamedi, 2002)
S. tuberosum	n.d. – 0.03	crude	(Zhou et al., 2011)
S. tuberosum cv. Red Laura and Shetland	6.1 and 1.3 (9-cis)	crude, freeze-dried	(Burmeister et al., 2011)

Plant material	Carotenoid content (µg/g DW)	Sample preparation	Reference
Black			
S. phureja cv. Mayan Twilight and Mayan Gold	2.9 and 3.1 (9-cis)	crude, freeze-dried	(Burmeister et al., 2011)
S. phureja	traces – 20.5	crude	(Burgos et al., 2009b)
S. tuberosum cv. Désirée	2.2	crude, freeze-dried	(Ducreux et al., 2005)
S. phureja cv. Mayan Gold	11.7	crude, freeze-dried	(Ducreux et al., 2005)
Zeaxanthin			
Cross between S. tuberosum and S. phureja	7.7 – 24.6		(Kobayashi et al., 2008)
S. tuberosum	n.d. – 0.5	crude	(Zhou et al., 2011)
S. tuberosum cv. Baltica	0.6	cooked and mashed	(Bub et al., 2008)
S. phureja	traces – 64.5	crude	(Burgos et al., 2009b)
S. tuberosum	0 – 17.7	crude, freeze-dried	(André et al., 2007b)
S. tuberosum	2.7 – 4.3	crude, freeze-dried	(André et al., 2009b)
Antheraxanthin			
S. tuberosum	0.4 – 2.4	crude, without skin	(Breithaupt & Bamedi, 2002)
S. phureja	0.3 – 18.8	crude	(Burgos et al., 2009b)
S. phureja cv. Mayan Gold	4.2	crude, freeze-dried	(Ducreux et al., 2005)
S. phureja	0.03 – 3.54	crude, freeze-dried	(Bonierbale et al., 2009)
Lutein-5,6-epoxide (Taraxanthin)			
S. tuberosum cv. Yukon Gold and Superior	0.9 and 0.5	crude, without skin	(Lu & Haynes, 2001)
Hybrid from S. phureja and S. stenotomum	1.1 – 27.4	crude, without skin	(Lu & Haynes, 2001)
β-Carotene			
S. tuberosum cv. Baltica	0.7	cooked and mashed	(Bub et al., 2008)
S. phureja	0 – 1.4	crude	(Burgos et al., 2009b)
S. tuberosum	0 – 2.2	crude, freeze-dried	(André et al., 2007b)

Table 6. Individual carotenoid content of potatoes reported in literature. Contents reported in another unit than µg/g dry weight (DW) were recalculated utilizing an average moisture content of 80%.

Total carotenoid contents in potatoes were reported to be between 0.6 and 233 µg/g DW. None of the carotenoids were quantifiable in all potatoes under study and a huge range of the contents of the individual compounds was observed. In potatoes where lutein was quantifiable, the contents ranged between 0.5 and 26.6 µg/g DW. The contents of violaxanthin, zeaxanthin, antheraxanthin, lutein-5,6-epoxide, and β-carotene ranged between 0.2 and 22.0 µg/g DW, 0.6 and 64.5 µg/g DW, 0.03 and 18.8 µg/g DW, 0.5 and 27.4 µg/g DW, and 0.7 and 2.2 µg/g DW, respectively.

2.3 Ascorbic acid

Regarding the content of ascorbic acid (vitamin C, chemical structure is shown in Figure 3) in potatoes, a huge number of publications are available. Quantification was done either by HPLC-UV, a spectrophotometric assay (after addition of 2,6-dichloroindophenol or 2,4-dinitrophenylhydrazine) or by fluorescence measurement (after addition of sodium acetate and O-phenylene diamine, for references see Table 7). In most cases, the total ascorbic acid content including dihydroascorbic acid was determined. Table 7 shows the contents of ascorbic acid that have been described in literature. The amounts ranged from 0.2 to 5.6 mg/g DW.

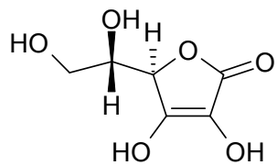

Fig. 3. Chemical structure of ascorbic acid (vitamin C).

2.4 Vitamin E

In addition to the antioxidants described above, potatoes also contain vitamin E. Vitamin E includes four tocopherols (α, β, γ, and δ) and four tocotrienols (α, β, γ, and δ), among which α -tocopherol has the highest biological activity in humans. In potatoes, α-tocopherol is the predominant vitamin E representative. γ-Tocopherol and α-tocotrienol were detectable in minor amounts *(*André et al., 2007b, Chun et al., 2006, Crowell et al., 2008*)*. The amounts of α-tocopherol found in potatoes are summarized in Table 8. When recalculated to the DW of potatoes, the amounts ranged between 0.8 and 34.8 µg/g DW.

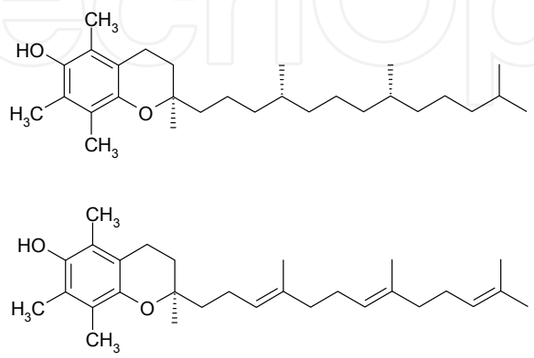

Fig. 4. Chemical structures of the vitamin E representatives α-tocopherol (above) and α-tocotrienol (below).

Plant material	Ascorbic acid content (mg/g DW)	Sample preparation	Reference
S. tuberosum	1.4	Skin, crude	(Singh et al., 2011)
S. tuberosum	0.5 – 1.7	crude, freeze-dried	(Dale et al., 2003)
S. tuberosum L. cv. Favorite	4.2	crude	(Qin et al., 2011)
S. tuberosum cvs. Bintje, Piccolo and Purple Majesty	0.4 – 0.6	crude, freeze-dried	(Navarre et al., 2010)
S. tuberosum ssp. Andigenum	0.4 – 0.7	crude	(Jimenez et al., 2009)
S. tuberosum cv. Spunta	1.4	crude	(Jimenez et al., 2009)
S. tuberosum	0.6 – 1.5	crude, freeze-dried	(Love & Salaiz, 2004)
S. tuberosum cvs. Russet Burbank and Shepody	0.5 – 1.2	crude, freeze-dried	(Rogan et al., 2000)
S. tuberosum cv. Norkotah and Ranger	0.4 and 0.8	crude, freeze-dried	(Shakya & Navarre, 2006)
S. tuberosum	0.3 – 0.7	crude	(Hajslova et al., 2005)
S. tuberosum and S. x chaucha	2.0 – 5.6	crude	(Rodriguez et al., 2010)
S. tuberosum	0.5 – 1.0	crude, freeze-dried	(Leo et al., 2008)
S. tuberosum	0.8 – 2.1	crude	(Han et al., 2004)
S. tuberosum	1.9	crude	(Natella et al., 2010)
S. tuberosum	0.2 – 1.2	crude	(Burgos et al., 2009a)
S. tuberosum	0.2 – 1.8	crude, freeze-dried	(André et al., 2007a, André et al., 2009b)

Table 7. Ascorbic acid content in potatoes reported in literature. Contents reported in another unit than mg/g dry weight (DW) were recalculated utilizing an average moisture content of 80%.

Plant material	α-Tocopherol content (µg/g DW)	Sample preparation	Reference
S. tuberosum cv. Spunta	2.1	crude	(Crowell et al., 2008)
S. tuberosum cv. Spunta	1.4	crude	(Crowell et al., 2008)
S. tuberosum	2.7 –34.8	Andean cultivars, crude, freeze-dried	(André et al., 2007b, André et al., 2009b)
S. tuberosum cv. Nicola	0.8	crude, freeze-dried	(André et al., 2007b)
S. tuberosum cv. Vitelotte	2.3	crude, freeze-dried	(André et al., 2007b)
S. tuberosum	3.5	crude	(Chun et al., 2006)
S. tuberosum	3.0	boiled	(Chun et al., 2006)
S. tuberosum	0.7 – 1.4	stored, crude	(Spychalla & Desborough, 1990)
S. tuberosum cv. Désirée	22.5	crude, freeze-dried	(Ducreux et al., 2005)

Table 8. Vitamin E (α-tocopherol) content in potatoes reported in literature. Contents reported in another unit than µg/g dry weight (DW) were recalculated utilizing an average moisture content of 80%.

3. Impact of cultivation, storage and processing on antioxidant compounds in potato

3.1 Impact of cultivation conditions

Environmental or abiotic stresses may have an impact on antioxidant contents, as these can generate reactive oxygen species in plants, thereby causing oxidative stress and impacting the antioxidant responses. Many plant secondary metabolites are determinants of both plant stress tolerance and nutritional quality (Jansen et al., 2008). In a study on potato exposed to drought stress (André et al., 2009c), highly cultivar-specific responses were observed. Thus, in yellow tubers, changes in the contents of antioxidants were weak, whereas in pigmented (red- and purple fleshed) tubers, variations (reduction or increase) were high. Hamouz et al. (2010) reported higher total polyphenol contents in potatoes grown under drought in a warm lowland location and under low temperatures during the vegetation period, both reflecting extreme climatic conditions. Carotenoid contents increased in most of the cases, whereas vitamin C was not affected by drought, except in one of the investigated cultivars. In a review on plant stress and human health (Jansen et al., 2008), polyphenol and vitamin C changes upon exposure of a range of plants to UV-B radiation were variable and dependent on the experimental system under investigation. It can be said that the effect of a stress on the nutritional composition of plants is still poorly understood and needs further investigations.

Higher anthocyanins and total phenolics were observed at locations with longer days and cooler temperatures (Reyes et al., 2004); according to the authors, light and day length may have an influence on the phenylpropanoid metabolism thereby affecting/favouring the synthesis of some compounds. Lachman et al. (2008) compared total phenolic contents from potato tubers grown in 4 different localities and attributed higher total phenolic contents (a difference of approximately 12% between highest and lowest contents) at harvest mainly to lower temperatures in the end of the vegetation period.

Concerning cultivation methods (conventional versus organic), the nutrient composition of plants is affected by the differences in organic and conventional farming, mainly due to fertilization management (Soltoft et al., 2010). However, it cannot clearly be said that significant differences in health-promoting compounds exist between the two farming systems. Potatoes produced in organic cultivation when compared to conventional cultivation contain higher levels of chlorogenic acid (Hajslova et al., 2005, Soltoft et al., 2010). Vitamin C content in the tubers from organically grown potatoes were not significantly higher than those from conventional farming (Hajslova et al., 2005, Rembialkowska, 1998). More generally, Faller and Fialho (2010) found that polyphenol content and antioxidant capacity in plant foods (several vegetables and fruits) were mostly similar or slightly higher in organic agriculture. Further studies are however necessary to clarify the impact of organic versus conventional agriculture on the contents of antioxidants in potato.

3.2 Post-harvest storage

Potatoes are mainly grown as single crop, with subsequent storage for three to ten months, a period in which they may undergo high metabolic activities (Pinhero et al., 2009).

It is known that ascorbic acid in fresh foods, including potato, is not stable postharvest (Pinhero et al., 2009) with levels decreasing to 40 to 60% of the initial value (Woolfe, 1987) or even to about 25% of the original one (Dale et al., 2003). Similarly, according to Burgos et al. (2009a), ascorbic acid concentrations decreased as the storage time increased.

As for carotenoids, Griffiths et al. (2007) found that postharvest storage reduces carotenoid contents, whereas Morris et al. (2004) describe only slight or no total carotenoid content changes at all during storage at cold temperatures. However, according to Morris et al. (2004), individual carotenoid levels do change during storage. Blessington et al. (2010) describe higher carotenoid contents (contents increase between 1 and 100%) in stored (4°C and 20°C) potatoes as compared to non-stored potatoes.

Storage at 4°C and 20°C also increased the total phenolic contents compared to non-stored potatoes (Blessington et al., 2010).

According to Dale et al. (2003), storage would be the major effect impacting contents of antioxidants, whereas location, year and genotype also would play a role. Interestingly for vitamin C, there is a high level of consistency in the ranking of genotypes across years, indicating heritability, a trait to be exploited during breeding. Burgos et al. (2009a) corroborate this information and found that the genotype effect is higher than the environment and than the genotype x environment interaction.

3.3 Cooking

Vitamin C changes during cooking have been evaluated by Burgos et al. (2009a) by boiling, microwaving and baking tubers. Losses of vitamin C were most important in baked and microwaved tubers as compared to boiled tubers. The percentage of retention ranged from 53 to 97%, from 6 to 66% and from 6 to 39% in boiled, baked and microwaved potatoes. In new potatoes, harvested at a young developmental stage, contents of total phenolics and vitamin C did not decrease after cooking by any method, presumably because of the small size of these tubers and the short cooking time required (Navarre et al., 2010).

Similarly, according to Xu et al. (2009), antioxidant capacity, mainly determined by the potato variety, was slightly influenced by cooking conditions depending on the cultivar. According to Blessington et al. (2010), when comparing different cooking methods of potatoes prepared with skin (baking, boiling, frying, microwaving), boiled samples were lower in total carotenoid contents, whereas for total phenolics, increased contents were observed after baking, frying and microwaving as compared to uncooked samples. Mulinacci et al. (2008) describe unaltered phenolic acid contents after cooking and microwaving unpeeled potatoes; however, in coloured potatoes, a decrease in the total anthocyanin content was observed (decrease in the range 16-29%). It has been shown by Dao and Friedman (1992) that peeling influences the contents of health-promoting compounds; they showed that potato peels contain high levels of phenolics, making them a promising material for the generation of functional foods. Mattila and Hellström (2007) observed a decrease in phenolics when comparing a peeled and cooked potato with an uncooked potato. It was also suggested that during the cooking process (cooking with skin), phenolics might migrate from the peel into the cortex and the internal tissues suggesting an improved extractability from cooked samples.

A more specific processing is the so-called chuno production. Chuno corresponds to a traditional Andean freeze and sun-dried potato, in which water is completely removed by mechanical pressing facilitated through freeze and thaw cycles implicating destruction of cellular structure (Penarrieta et al., 2011). During this process, a loss of antioxidants and phenolic compounds was shown, though some compounds seemed to be transferred from the peel to the flesh during the process, as also reflected by the dark to black colour of the chuno.

4. Nutritional relevance and health-beneficial properties of potato antioxidants

Oxidative stress is a disturbance of the equilibrium between pro-oxidants and antioxidants, in favour of the former (Kaspar et al., 2011). This imbalance may lead to cellular damage, as oxidation of cellular lipids, proteins and DNA imparts cellular function and increases susceptibility to a number of chronic diseases. Antioxidant molecules may scavenge reactive oxygen species, thereby limiting oxidative stress (Robert et al., 2006).

4.1 Vitamins

Potato is known to be a good source of vitamin C in the human diet. In the human body, ascorbate plays a role as a water-soluble antioxidant and as cofactor in reactions catalyzed by a number of metal-dependent oxygenases (André et al., 2010). Besides its positive effect on human health, it is also important to mention that vitamin C plays an important role as enhancer of iron bioavailability from potato (Yun et al., 2004).

As for vitamin E, its major biological role is to prevent lipid peroxidation and to protect poly unsaturated fatty acids and low density lipoproteins from oxidation by free radicals (André et al., 2010).

4.2 Carotenoids and polyphenols

As previously said, potatoes are good sources of antioxidants, such as the hydrophilic polyphenols and only moderate sources of the lipophilic carotenoids. Dietary carotenoids are associated with health benefits. On one hand, the provitamin A activity of carotenoids, such as beta-carotene, alpha-carotene and beta-cryptoxanthin is well-known; on the other hand, non pro-vitamin A carotenoids, such as lutein and zeaxanthin for example, have important antioxidant activity and are known to provide protection against age-related macular degeneration (Griffiths et al., 2007).

A correlation between polyphenol intake and reduced incidence of cancers, cardiovascular and neurodegenerative diseases was shown by Arts and Hollman (2005); however these positive effects could not only be attributed to their antioxidant properties. Polyphenols also exert their health beneficial effects through modulation of cellular signalling processes: as inflammation modulatory agents, as regulators of cell proliferation and differentiation, angiogenesis and apoptosis and as modulators of signalling cascades and apoptotic processes (reviewed in (Stevenson & Hurst, 2007)).

Few studies are available in the literature on health-promoting effects of potato antioxidants and will be presented hereafter. The impact of the consumption of pigmented potatoes on

oxidative stress and inflammatory damage in man has been studied by Kaspar et al. (2011). Men consumed either white, yellow (high concentrations in phenolic acis and carotenoids) or purple fleshed (high concentrations of phenolic acids and anthocyanins) potato once per day in a randomized 6-week study with good compliance. The consumption of pigmented potato resulted in elevated antioxidant status and reduced inflammation and DNA damage, as reflected by e.g. decreased inflammatory cytokine and C-reactive protein concentrations. Another study on the lipid-lowering effect of potato in rats showed that feeding rats a potato-enriched diet led to a decrease in cholesterol and triglyceride levels in plasma, decreased cholesterol level in the liver and improved antioxidant status (Robert et al., 2006, Robert et al., 2008). These results suggest that potato consumption may enhance antioxidant defense and improve the lipid metabolism. Similarly in a study performed by Han et al. (2006) on rats fed with anthocyanin-rich purple potato flake extracts, it was shown that these extracts have antioxidant capacity with regard to radical scavenging activity and inhibition of linoleic acid oxidation; moreover, they would enhance hepatic Mn-SOD, Cu/Zn-SOD and GSH-Px mRNA expression suggesting a reduced hepatic lipid peroxidation and an improved antioxidant potential in the rats.

In a study performed by Thompson et al. (2009) on induced breast cancer in rats, a greater inhibition of carcinogenesis was shown when the rats were fed with a red pigmented cultivar as compared to a White Russet Burbank. The red cultivar had high levels of anthocyanin and chlorogenic acid derivatives, previously reported to inhibit the growth of human breast cancer cells grown in monolayer culture (Hakimuddin et al., 2004).

5. Bioavailability

Studies on the bioavailability of antioxidants and/or clinical outcomes following the administration of antioxidants from potato are scarce. Concerning nutrition, the term bioavailability describes the quantity of an ingested nutrient that is used by the body in its original or metabolized form. Many problems are to be faced, such as those related to cultivar variability, sample preparation and metabolism in the organism as well as interaction with gut microflora.

A few studies on the bioavailability of β-carotene from sweet potato are available (Bengtsson et al., 2009, Failla et al., 2009). It is worth mentioning that the bioavailability of carotenoids is dependent on a number of parameters including the physicochemical state, cooking style, other components of the meal (e.g. fat content), to name only a few. Failla et al. (2009) pointed to a relatively poor bioaccessibility (i.e. the release from the food matrix and the solubility in the gastro-intestinal fluids) of β-carotene from sweet potato together with a poor micellarization; this latter process corresponds to the transfer of the carotenoids from the food matrix into mixed bile salt micelles, during the small intestinal phase of digestion, a process that was however improved by the addition of oil. In a study performed by Bub et al. (2008) on genetically modified, zeaxanthin-enriched potato (270 μg/100g), the concentration of zeaxanthin was significantly increased in chylomicrons, a group of lipoproteins reflecting newly absorbed carotenoids, after the consumption of genetically modified potatoes (by three men, randomized, controlled double-blinded) as compared to no increase after consumption of control potatoes (12.9 μg/100g).

There are a number of studies on the bioavailability of polyphenols, such as e.g. D'Archivio et al. (2010), Manach et al. (2004), Scalbert and Williamson (2000), and Williamson and Manach (2005), though none specifically on potatoes. Within polyphenols, the bioavailability greatly differs and decreases from isoflavones, to flavonols, to flavan—3-ols, to anthocyanins and proanthocyanidins. The difficulty in realizing polyphenol biovailability studies lies in the fact that they may undergo substantial modifications following ingestion. Some compounds may be absorbed in the small intestine. Others reach the colon where they undergo modifications such as hydrolization of glycosides into aglycones by the colonic microflora. Prior to the passage into the blood stream, other modifications might occur including methylation, sulfation, glucuronidation (D'Archivio et al., 2010). Since chlorogenic acid is the major phenolic acid present in potato, it is worth mentioning a study on the bioavailability of chlorogenic acid from coffee (Stalmach et al., 2010). This study implicating human ileostomy volunteers indicates a potential absorption of 29% of the intake by the small intestine; thus approximately one third of ingested chlorogenic acid in foods would be absorbed and enter the bloodstream; in healthy subjects with a functioning colon, the remaining part would reach the large intestine. A recent publication on the bioavailability of quercetin 3-*O*-rutinoside included healthy volunteers and those with an ileostomy. After consumption of tomato juice fortified with quercetin 3-*O*-rutinoside, no metabolites were detected in the plasma and urine of the ileostomists and 86% of the ingested quercetin 3-*O*-rutinoside was detected in the ileostomy bag. In healthy subjects, this amount reaches the colon. In the colon, the quercetin 3-*O*-rutinoside is converted to phenolic acids by the microflora. Amounts of these phenolic acids corresponding to 22% of the quercetin 3-*O*-rutinoside intake have been detected in the urine of the healthy volunteers (Jaganath et al., 2006).

Informations on the bioavailability of α-tocopherol are scarce. An *in vitro* study with broccoli showed that 20% of the applied α-tocopherol has been incorporated into the aquaeous phase by micellarization in a digestion model (Granado et al., 2006). The bioavailability of α-tocopherol in humans was assessed after the consumption of d_6- α-tocopherol spiked apples. When the apples were consumed together with a breakfast containing no fat, 10% of the 22 mg d_6- α-tocopherol were detected in the plasma of the probands. Increasing the breakfast fat content to 6% and 21%, 20% and 33% of the d_6- α-tocopherol has been detected, respectively (Bruno et al., 2006).

The determination of the bioavailability of ascorbic acid in doses present in food is difficult. The plasma levels of healthy persons after oral ingestion of vitamin C are saturated at 70 to 80 μM (Duconge et al., 2008) and the ingestion of additional ascorbic acid does not lead to a simple increase of the plasma levels. A study with seven healthy vitamin C depleted volunteers showed that the bioavailability was 100% at doses of 200 mg. When using higher doses, the bioavailability was lower than 50% (Levine et al., 1996). When stable, isotopically labelled ascorbic acid was administered to four healthy probands, the unspecific measurement of ascorbic acid in their plasma revealed a 12% increase of the plasma level. When the samples were analysed for their isotope content, an increase of 3 to 6% was observed. The authors of the study stated that the ingested vitamin C dose enters an existing pool in the body, but this pool is continuously fluxed with vitamin C present in the body before the beginning of the study (Bluck et al., 2005). Ascorbic acid bioavailability after ingestion of a fortified beverage and orange juice was approximately 65%, but the standard deviations in this study have been quite high (Carter et al., 2010).

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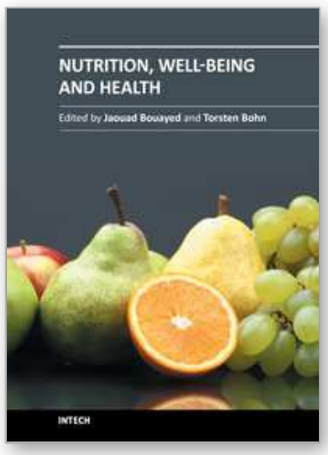

Nutrition, Well-Being and Health

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In our modern society, expectations are high, also with respect to our daily diet. In addition to being merely "nutritious", i.e. supplying a variety of essential nutrients, including macro-nutrients such as proteins or micro-nutrients such as minerals and vitamins, it is almost expected that a good diet offers further advantages - especially well-being and health and the prevention of chronic diseases, which are, as we generally tend to grow older and older, becoming a burden to enjoying private life and to the entire society. These additional qualities are often sought in diets rich also in non-nutritive components, such as phytochemicals. In contrast to drugs, which are taken especially to cure or ameliorate diseases, it is expected that a healthy diet acts in particular on the side of prevention, allowing us to become old without feeling old. In the present book, rather then trying to give an exhaustive overview on nutritional aspects and their link to well-being and health, selected topics have been chosen, intended to address presently discussed key issues of nutrition for health, presenting a reasonable selection of the manifold topics around diet, well-being, and health: from the antioxidants polyphenols and carotenoids, aroma-active terpenoids, to calcium for bone health, back to traditional Chinese Medicine.

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