Beneficial phytochemicals in potato — a review

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ABSTRACT

Potato contains several phytochemicals such as phenolics, flavonoids, polyamines, and carotenoids, which are highly desirable in diet because of their beneficial effects on human health. The concentration and stability of these constituents are affected by several factors such as genotype, agronomic factors, postharvest storage, cooking and processing conditions. The advances in analytical techniques have made possible the identification and understanding the functions of phytochemicals, particularly their antioxidant properties. The potatoes are stored and processed into a variety of products before consumption. In the present review, phytochemicals present in potatoes, factors affecting their content, stability and health benefits are discussed. Processing the potatoes rich in phytochemicals can play an important role in promoting the health of a large segment of population in the countries where potatoes form a substantial part of daily diet.

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1. Introduction

Potato is the fourth most important food crop in the world after rice, wheat and maize, and is the only major food crop that is a tuber. Potato is a very efficient food crop and produces more dry matter, protein and minerals per unit area in comparison to cereals. Potatoes being the staple food in the developed countries account for 130 kcal of energy per person per day against 41 kcal in the developing countries where it is still considered as vegetable. Apart from being a rich source of starch, potatoes contain good quantity of small molecules and secondary metabolites which play an important role in a number of processes (Friedman, 1997). Many of the compounds present in potato are important because of their beneficial effects on health, therefore, are highly desirable in the human diet (Katan & De Roos, 2004). Nutritional deficiencies are not well known in the countries whose population depend on potatoes as their basic food (Katan & De Roos, 2004). One of the global health goals is to increase the availability of nutrients to a large population of the world. A sensible approach to achieve this goal would be to increase the nutritional content of highly consumed crops. Potatoes are grown throughout the world and are consumed in large quantities. Furthermore, potatoes have higher phytonutrient content and are amenable to development through breeding and biotechnology approaches (Nzaramba, Bamberg, & Miller, 2007). The aim of this review is to re-examine the information on beneficial phytochemicals of potatoes.

2. Phytochemicals in potato

In addition to supplying energy, potatoes contain a number of health promoting phytoneutrients such as phenolics, flavonoids, folates, kukoamines, anthocyanins, and carotenoids.

2.1. Phenolics

Polyphenols comprise over 8000 identified substances, which can be divided into groups according to their chemical structure, such as phenolic acids, stilbenes, coumarins, lignins and flavonoids (Ross & Kasum, 2002). Polyphenols are recognized as the most abundant antioxidants in our diet (Manach, Scalbert, Morand, Remesy, & Jimenez, 2004). Potatoes are a good source of these compounds. Phenolic compounds represents a large group of minor chemical constituents in potatoes, which play an important role in determining their organoleptic properties. Further, phenolics have a wide-array of health providing characteristics (Bravo, 1998), therefore, have potential for use as functional food for improving human health. The phenolic content of potatoes was reported to be high, and ranged
from 530 to 1770 μg/g (Al-Saikhan, Howard, & Miller, 1995). Potatoes were considered the third most important source of phenols after apples and oranges (Chun et al., 2005). Talburt, Schwimmer, and Burr (1987) reported presence of lignin, coumarins, anthocyanins and flavones, tannins, monohydric phenols and polyhydric phenols in potatoes. Several unidentified polyphenols were also reported to be present in potatoes, the largest proportion comprised of chlorogenic acid, being more than 90% of phenolics (Malenberg & Theander, 1985). Mattila and Höllström (2007) reported caffeic acid derivatives (chlorogenic acid) as the main polyphenol constituents in potatoes. The phenolics are present in both skin and flesh of potatoes, the concentration being higher in skin. The phenolic content of potatoes varying in flesh colour is tabulated in Table 1. The fresh pulp and skin of potatoes contain 30 to 900 mg/kg and 1000—4000 mg/kg, respectively of chlorogenic acid and minor amounts of other phenolic acids between 0 and 30 mg/kg (Lewis, Walker, & Lancaster, 1999). Potatoes also contain flavones aglycones, a major group of plant phenols, which are potent antioxidants. Lewis, Walker, Lancaster, and Sutton (1998) found that potato tuber skin contained 2000—5000 μg FW phenolic acids and 200—300 μg of flavonoids. Purple- and red-skinned tubers contained twice the concentration of phenolic acids as white-skinned tubers. Tuber flesh contained lower concentrations ranging from 100 to 600 μg of phenolic acids and 0 to 30 μg of flavonoids. It was also reported that purple- or red-fleshed cultivars had three to four times the concentration of phenolic acids of white fleshed cultivars. The predominant phenolic acids were reported to be chlorogenic acid, protocatechuic acid, vanillic acid, and p-coumaric acid. The phenols can be recovered from the skin portion, which is discarded as waste during potato processing and can be used for ‘value addition’ in different food products (Navarre, Goyer, & Shakya, 2009).

2.2. Flavonoids

Flavonoids content in potatoes ranged from 200 to 300 μg/g FW (Lewis et al., 1998). The flavonoids, in order of abundance, were reported to be catechin, epicatechin, erodictyol, kaempferol and naringenin (Brown, 2005). Flavonols such as rutin are also present in potatoes. The flavonoids content of potato is not significantly high, but these could be considered as a valuable source of these compounds because of their high consumption (Tudela, Cantos, Espin, Tomas-Barberan, & Gil, 2002). Anthocyanins are a sub-group within the flavonoids and present in substantial amounts in pigmented flesh potatoes. Anthocyanin levels between 5.5 and 35 mg/100 g FW in potatoes have been reported (Brown, 2005; Lewis et al., 1998) found that purple or red-fleshed cultivars had twice the flavonoid concentration of white-fleshed cultivars and their concentrations are considerably higher in skin, approaching 900 mg in purple-fleshed and 500 mg in red-fleshed types per 100 g FW. Anthocyanin pigments in the periderm of potatoes impart different colours to their skin, purple being the most common colour. The pigmented potatoes may serve as a potential source of natural colourants and antioxidants by the food industry for better human health (Reyes & Cisneros-Zevallos, 2007). Red- and purple-fleshed potatoes had acylated glucosides of pelargonidin, while purple potatoes had, in addition, acylated glucosides of malvidin, petunidin, peonidin, and delphinidin (Brown, 2005; Lachman & Hamonu, 2005). Fossen and Andersen (2000) reported that the anthocyanins of the purple-fleshed (cv Congo) potatoes consisted of ferulyl gluco- and ghanmo-pyranosides of malvidin and petunidin, novel anthocyanins. Potato peel contained quercetin, a flavonol with antioxidant activity and such activity in flavonoids had been attributed to their action as free radical acceptors. Piatta (2000) showed that flavonoids differ greatly in their antioxidant capacity. Quercetin was reported to be three times more effective as an antioxidant than kaempferol and eridictyol, and was twice as effective as catechin. Chu, Chang, and Hsu (2000) found that the flavonoids and flavones extracts had high scavenging activities toward oxygen radicals. Potatoes showed 94% scavenging activity towards hydroxyl radicals, and, along with onions, almost completely inhibition of super-oxide radicals. Transgenic approaches have shown that it is possible to markedly increase the phenolic acids, anthocyanins and flavonoids contents of tubers (Łukaszewicz et al., 2004; Rommens et al., 2008). Łukaszewicz et al. (2004) were able to increase the phenolic acids, anthocyanins content, and antioxidant capacity in transgenic potato plants with expression of genes encoding chalcone synthase, chalcone isomerase and dihydro-flavonol reductase.

2.3. Folate

Potatoes do not have high folate content, but are a major source of this due to their higher consumption. Potatoes supply about 10% of the total folate intake of the people in European countries such as Netherlands, Norway and Finland (Navarre et al., 2009). Folate concentrations in potato vary between 12 and 37 μg/100 g F.W. (Konings et al., 2001). Folate content in more than 70 potato cultivars, advanced hybrids and wild species has been reported to range from 11 to 35 μg/100 g F.W. (Goyer & Navarre, 2007). Higher folate content was generally reported to be present in yellow fleshed potatoes. Antioxidants such as ascorbic acid or thiol compounds were also reported to protect folates against oxidative degradation (McNulty & Pentieva, 2004).

2.4. Kukoamines

Kukoamines are polyamine conjugates and considered to have health promoting effects, which are yet to be well established. Kukoamines in potatoes was first reported by Parr, Mellon, Colquhoun, and Davies (2005). Further studies on these compounds are needed to understand their stability, beneficial effects and their role in other functions. Tuber polyamines have been suggested to play a role in the regulation of starch biosynthesis (Tanemura & Yoshino, 2006) and making the tubers resistant to diseases (Matsuda et al., 2005).

2.5. Carotenoids

Potatoes are a good source of carotenoids, which are lipophilic compounds synthesized in plastids from isoprenoids (Dellapenna & Pogson, 2006). Lutein, zeaxanthin, violaxanthin and neoxanthin are

Table 1

<table>
<thead>
<tr>
<th>Type</th>
<th>Neochlorogenic acid</th>
<th>Caffeoyl putrescine</th>
<th>Chlorogenic acid</th>
<th>Cryptochlorogenic acid</th>
<th>Caffeic acid</th>
<th>Rutinose</th>
<th>Kaempferol-3-rutinose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td>1.1 ± 0.43–20.1 ± 3.59</td>
<td>0.7 ± 0.06–4.5 ± 2.03</td>
<td>22.9 ± 3.4–211 ± 46</td>
<td>3.8 ± 1.1–32.7 ± 7.2</td>
<td>0.5 ± 0.4–9.6 ± 1.3</td>
<td>1.36 ± 0.7–141 ± 8.1</td>
<td>0.31 ± 0.1–4.49 ± 0.27</td>
</tr>
<tr>
<td>White</td>
<td>0.7 ± 0.05–10.7 ± 1.7</td>
<td>0.6 ± 0.12–12 ± 3.97</td>
<td>31 ± 6.7–170 ± 58</td>
<td>2.8 ± 0.3–22.8 ± 0.9</td>
<td>4.7 ± 1.2–144 ± 4.3</td>
<td>0.37 ± 0.1–6.91 ± 3.1</td>
<td>0.13 ± 0.0–1.37 ± 0.19</td>
</tr>
<tr>
<td>White/Purple</td>
<td>0.1 ± 0.01–18.8 ± 6.71</td>
<td>0.2 ± 0.04–16 ± 1.28</td>
<td>21.9 ± 1.1–231 ± 9.8</td>
<td>1.0 ± 0.1–24.7 ± 6.2</td>
<td>2.0 ± 0.2–47.6 ± 3.6</td>
<td>0.29 ± 0.0–1.71 ± 0.1</td>
<td>0.15 ± 0.0–1.25 ± 0.15</td>
</tr>
<tr>
<td>Red/Purple</td>
<td>0.9 ± 0.06–43.7 ± 2.22</td>
<td>13 ± 0.18–8.7 ± 3.44</td>
<td>80.4 ± 9.5–473 ± 14</td>
<td>12.6 ± 1.3–65.9 ± 6.3</td>
<td>5.2 ± 1.3–15.9 ± 0.7</td>
<td>0.48 ± 0.0–3.54 ± 0.2</td>
<td>0.46 ± 0.4–413 ± 2.32</td>
</tr>
</tbody>
</table>

the major carotenoids present in potatoes and \( \beta \)-carotene is present in trace amounts. The orange and yellow colour of the tuber flesh is due to zeaxanthin and lutein, respectively. Potato cultivars with white flesh contained less carotenoids as compared to cultivars with yellow or orange flesh. Total carotenoids content was reported in the range of 50–350 \( \mu \)g/100 g FW and 800–2000 \( \mu \)g/100 g FW, respectively, in white- and yellow-fleshed potato cultivars (Brown, 2008). Carotenoid content of potatoes with varied flesh colour is reported in Table 2. Researchers have been able to increase carotenoid content considerably by using transgenic approaches. Ducrèux et al. (2005) were able to increase tuber carotenoids content from 5.6 to 35 \( \mu \)g/g DW (cv. Desiree) by overexpressing a bacterial phytoene synthase. They also observed large increase in the levels of individual carotenoids, \( \beta \)-carotene (more than 10 fold) and lutein (19 fold). Diretto et al. (2007) claimed that 50% of the RDA of vitamin A can be met by consuming 250 g of carotenoids enriched genetically engineered potatoes.

3. Factors Affecting Phytochemicals Content and Stability

3.1. Genotype

The number of potato varieties known to mankind is vast, estimated to be approximately 5000 (Burlingame, Mouille, & Charraondiere, 2009). About 11 Solanum species are cultivated but most of the potato varieties cultivated throughout the world belong to the species Solanum tuberosum. Apart from these, about 200 wild species are known to exist. The nutrient content of potatoes was reported to be influenced by a number of factors, variety being the most important (Toledo & Burlingame, 2006). Andre, Oufir, et al. (2007) observed an eleven fold variation in the total phenolic content in Andean potato landraces. Using hundreds of potato genotypes, Navarre et al. (2009) found a fifteen-fold difference in their phenolic content. White-fleshed potato varieties were reported to contain lower amount of phenolics (less than 4 \( \mu \)g/g DW) as compared to purple-fleshed wild species (more than 5–6 \( \mu \)g/g DW). An anthocyanin content of up to 7 \( \mu \)g FW in the skin and 2 \( \mu \)g FW in the flesh was reported by Lewis et al. (1998) amongst 26 potato cultivars with coloured flesh. Pelargonidin and peonidin were reported to be present in nearly equal amounts in the red flesh, while petunidin and malvidin were predominant in the purple flesh. Jansen and Flamme (2006) analysed 31 potato genotypes with coloured flesh and found a lower range of 0.5 to 3 \( \mu \)g/g FW in the skin and up to 1 \( \mu \)g/g FW in the flesh, while Brown, Culley, Yang, Durst, and Wroldstad (2005) determined the anthocyanin content in several genotypes and reported a value of up to 4 \( \mu \)g/g FW in whole tubers. Fossen, Øvstedal, Slimestad, and Andersen (2003) reported novel anthocyanins acylated with caffeic acid in purple sprouts of a Norwegian potato cultivar. Eichhorn and Winterhalter (2005) identified major anthocyanins present in four pigmented potato cultivars. Petunidin derivatives were detected in three varieties. Pelargonidin was found to be the only anthocyanin in cv. “Highland Burgundy red”, malvidin was the predominant aglycon of the cv. “Vitolette” and minor amounts of peonidin derivatives were found in cv. “Shetland Black”. Jansen and Flamme (2006) analysed 27 potato cultivars and observed that the average anthocyanins content was the highest in the skin (0.65 \( \mu \)g/g FW). The corresponding values for whole tubers and flesh were 0.31 \( \mu \)g/g FW and 0.22 \( \mu \)g/g FW, respectively. The average anthocyanin content was higher in violet coloured potatoes and lower in red coloured potatoes. More than 20-fold range in carotenoid concentrations has been reported in potato germplasm by Morris et al. (2004). Iwanzik, Tevini, Stute, and Hilbert (1983) reported a range of 27–74 \( \mu \)g/g FW for carotenoids in white fleshed potato cultivars while Brown, Edwards, Yang, and Dean (1993) reported a very high zeaxanthin concentration of 2000 \( \mu \)g/100 g FW in diploid potatoes derived from S. stenotomum and Solanum phureja. Breithaupt and Bamedi (2002) investigated the carotenoid pattern of four yellow-fleshed and four white-fleshed German potato cultivars (S. tuberosum L.). The carotenoid pattern was dominated by violaxanthin, antheraxanthin, lutein, and zeaxanthin, which were present in different ratios, whereas neoxanthin, \( \beta \)-cryptoxanthin, and \( \beta \)-carotene were only minor constituents. Antheraxanthin was found to be the only carotenoid epoxide present in native extracts. The total concentration of the four main carotenoids reached 175 \( \mu \)g/100 g FW, whereas the sum of carotenoid esters accounted for 41–131 \( \mu \)g/100 g FW. Andean potatoes provide a rich and varied source of carotenoids. Andre, Ghislain, et al. (2007) reported a range of 3 to 36 \( \mu \)g/g DW for total carotenoids among 74 Andean landraces. In another study, Andre, Oufir, et al. (2007b) screened 24 Andean cultivars and identified genotypes containing high concentration of lutein (1.12–17.69 \( \mu \)g/g DW) and zeaxanthin (18 \( \mu \)g/g DW) and \( \beta \)-carotene (2 \( \mu \)g/g DW). Burgos et al. (2009) analysed carotenoids content in tubers of 23 accessions of S. phureja and identified two accessions, with a very high concentration of zeaxanthin (1290 \( \mu \)g/g FW). Total and individual carotenoid concentrations were estimated in 152 S. phureja germplasm accessions by Bonierbale et al. (2009). These authors identified two varieties with high zeaxanthin concentrations (above 1000 \( \mu \)g/g FW) and a group of 43 accessions with relatively high \( \beta \)-carotene concentrations (above 10 \( \mu \)g/g FW). The total carotenoid, antheraxanthin, violaxanthin, lutein, zeaxanthin and \( \beta \)-carotene concentrations ranged from 103 to 2135 \( \mu \)g/100 g FW, from 3 to 354 \( \mu \)g/g FW, from trace to 278 \( \mu \)g/100 g FW, from 55 to 189 \( \mu \)g/100 g FW, from trace to 1290 \( \mu \)g/100 g FW, and from trace to 18 \( \mu \)g/g FW, respectively. Brown, Culley, Bonierbale, and Amorós (2007) determined total anthocyanins, total carotenoids and antioxidant values in 38 native South American potato cultivars and found that total anthocyanin ranged from zero to 23 mg cyanidin equivalents/100 g FW, total carotenoid ranged from 38 to 2020 \( \mu \)g zeaxanthin equivalents/100 g FW, the hydrophilic oxygen radical absorbance capacity (ORAC) ranged from 333 to 1408 \( \mu \)mol Trolox equivalents/100 g FW, and the lipophilic ORAC ranged from 4.7 to 30 nM-tocopherol equivalents/100 g FW. A negative correlation between total carotenoids and total anthocyanins was reported.

Total antioxidant activity was evaluated in 40 tuber-bearing Solanum species by Hale, Reddivari, Bamberg, and Miller (2008). Solanum pinnatisectum and S. jamesii accessions consistently ranked the highest in antioxidant activity and phenolic content. Antioxidant

Table 2

Relationship between tuber flesh colour and anthocyanin content, total carotenoids, antioxidant activity, total phenolics and oxygen radical absorbance capacity (ORAC) of potato cultivars.

<table>
<thead>
<tr>
<th>Tuber flesh colour</th>
<th>Anthocyanin content (mg/100 g FW) (^b)</th>
<th>Total carotenoids (µg/100 g FW) (^b)</th>
<th>Antioxidant activity (% inhibition relative to control) (^c)</th>
<th>Total phenolics (µg/g) (^b)</th>
<th>ORAC values (% of white flesh) (^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purple flesh</td>
<td>368</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>250</td>
</tr>
<tr>
<td>Red flesh</td>
<td>22</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>300</td>
</tr>
<tr>
<td>White flesh</td>
<td>–</td>
<td>50–100</td>
<td>65.2–88.1</td>
<td>369.1–527.2</td>
<td>–</td>
</tr>
<tr>
<td>Yellow flesh</td>
<td>–</td>
<td>100–350</td>
<td>68.6–89.2</td>
<td>237.7–407.0</td>
<td>–</td>
</tr>
<tr>
<td>Dark yellow flesh</td>
<td>–</td>
<td>150–1000</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

\(^{a}\) Source: Lewis et al. (1998).

\(^{b}\) Sources: Brown et al., 1993; Lu, Haynes, Wiley, & Clevidence, 2001; Nesterenko & Sink, 2003; Brown, 2005; Brown et al., 2005; Reyes et al., 2005; Brown et al., 2006; Brown et al., 2007; Van Eck et al., 2007; Brown, 2008; Brown et al., 2008.

\(^{c}\) Source: Al-Salikhan et al., 1995.

\(^{d}\) Source: 1. Lewis et al. (1998); 2. Brown (2005).
activity in the wild species ranged from 48 to 824 μg trolox eq/g FW. The phenolic content of these species was primarily composed of chlorogenic and caffeic acids. Other phenolics identified were p-coumaric acid, rutin hydrate, vanillic acid, epicatechin, t-cinnamic acid, gallic acid, and salicylic acid. A large variation exists in the phytonutrients content of tubers of the wild species and better utilization of this largely untapped genetic diversity will help in increasing the phytonutrients content of potatoes.

3.2. Agronomic Factors

Phytonutrients content of potatoes is influenced by developmental stage. Potatoes harvested at a young developmental stage had higher concentrations of some phytonutrients such as folate and chlorogenic acid than mature tubers (Goyer & Navarre, 2009; Navarre, Shalaya, Holden, & Kumar, 2010). Total carotenoids content was found to be higher in immature tubers and it decreased with tuber maturity (Kotikova et al., 2007; Morris et al., 2004). “Baby potatoes” or immature potatoes contain higher amounts of phytonutrients than mature potatoes. Reyes, Miller, and Cisneros-Zevallos (2004) observed that the anthocyanins and total phenolic content in tubers decreased with tuber growth and maturity but total yield per ha of these compounds increased through time. Harvesting at later maturity stages maximized total yield of potatoes, anthocyanin and total phenolic content, and minimized glycoalkaloid content, thus increasing the commercial and nutritional value of purple and red-flesh potatoes. Jansen and Flamme (2006) determined the anthocyanin content of tubers from plants grown at two doses of nitrogen fertilizers i.e. 100 and 200 kg/ha and found no significant difference. Kotikova et al. (2007) investigated the influence of different fertilization levels with different doses of N, P, K and Mg nutrients. The application of fertilizers did not bring any significant change in anthocyanin and carotenoids content of potatoes. It was suggested that application of synthetic fertilizers make the nitrogen available, which is utilized for growth but not allocated for the production of secondary metabolites such as phenols. Where as organic agriculture leads to an enhancement of natural defence substances such as phenolics compounds (Winter & Davis, 2006). Faller and Falho (2009) compared organically grown potatoes with conventionally grown ones and there was no significant difference in their soluble and hydrolyzable polyphenols content. Rosenthal and Jansky (2008) also did not find a consistent effect of production system (organic versus conventional) on antioxidant activity in tubers. Effect of location of crop growth on phytochemicals content has been studied by several researchers. Ezekiel, Singh, Kumar, and Kumar (2008) did not find significant differences in the total phenols content of potatoes of two varieties grown at three locations in the North Indian plains having similar altitude but varying in temperatures during crop growth. Location of crop growth (coastal area and plains) did not have a significant effect on the anthocyanin content of tubers (Jansen & Flamme, 2006). It was concluded that the level of anthocyanins was not affected by the environmental conditions and it was primarily dependent on the genotype. Potatoes grown at two locations differing in altitude showed no significant difference in the total carotenoids content (Kotikova et al., 2007). However, a significant effect of location on anthocyanin and total phenolics was observed by Reyes et al. (2004). The anthocyanins and total phenolic- content of potato tubers was enhanced when tubers were grown in a location with cooler temperatures and longer days (higher solar radiation) and 2.5 and 1.4 times, respectively, higher anthocyanins and total phenolic content were found under such conditions. It appears that temperature during crop growth can affect the phytochemicals content. In a study carried out by Brown, Durst, Wrolstad, and De Jong (2008), potatoes were grown at 3 locations varying in altitude viz, 203, 960 and 1250 masl. Higher anthocyanins content were observed at higher elevations, however, total carotenoids were not affected. Andre et al. (2009) determined the effect of environment and genotype on polyphenols content and in vitro antioxidant capacity of native Andean potatoes and observed a high stability in the ranking of cultivars across environment in terms of phenolic content and antioxidant capacity, indicating that these Andean cultivars could be used in breeding programmes for improving the phenolic content. Conflicting results have been reported with respect to year of crop growth. Jansen and Flamme (2006) compared the anthocyanin contents in tubers of 23 cultivars/clones grown during two years and found that there was no significant difference between years in the anthocyanin content of tubers although the weather conditions during plant growth were different during the two years (the weather during summer was cool and wet during one year and warm and dry during the next year). Kotikova et al. (2007) found that year of cultivation had a significant effect on total carotenoids content. Stushnoff et al. (2008) observed environmental conditions produced year to year variation in total phenolics levels. Rosenthal and Jansky (2008) observed significant effect of the year. They determined antioxidant levels in tubers of 14 specialty potato clones grown at four production sites (two conventional, two organic) for two years. Year of cultivation showed significant effect with antioxidant activity higher in 2006 than in 2005, and attributed the increased levels of antioxidants to cooler late-season temperatures in 2006. Chemical haulm desiccation was reported to have no significant effect on the concentration of antioxidants (Bouno et al., 2009).

3.3. Postharvest Storage

Storage generally increases total phenols content in potatoes but little change or a decrease in phenols content after storage have also been reported in some studies. Ezekiel and Singh (2007) determined total phenols content in four potato cultivars stored for 180 days at 4, 8, 12, 16 and 20 °C. Total phenols increased after storage and the increase was higher at 4 and 16 °C. In another study Ezekiel, Paul, Singh, Peshin, and Shkawat (2000) found that the total phenols in potato tubers continued to increase up to 271 days of storage at 6 °C but at 20 °C, it decreased after 220 days of storage. Potatoes of two cultivars grown at four locations in the North Indian plains did not show significant difference in total phenols content up to 115 days of storage at 4 and 10 °C (Ezekiel, Singh, Kumar, et al., 2008). Kumar and Ezekiel (2009) found that phenols content in the peels and flesh of three Indian potato varieties decreased after 90 days of storage at 2–4 °C, 10–12 °C and in heap storage, a traditional method of storage. The decrease in the peels was minimum at 2–4 °C and maximum in heap storage. Irradiation done to inhibit sprouting of tubers also causes an increase in the total phenols content. Potatoes treated with 0.1 and 0.5 kGy dose of γ-rays and stored for 180 days showed higher total phenols content as compared to untreated potatoes (Ezekiel, Singh, & Datta, 2008). Increase in total phenols content in irradiated potatoes after storage at 10, 20 and 30 °C (Thomas, 1982) and at 5 and 20 °C (Mondy & Gosselin, 1989) has been reported. Effect of storage of potatoes at 4 or 20 °C for 110 days on phenolic content was studied by Blessington et al. (2010). No significant differences in total phenolic content, chlorogenic acid, caffeic acid and vanillic acid were observed after storage at 4 or 20 °C. There was an increase in rutin, p-coumaric acid and quercetin dehydrate contents after storage at 4 or 20 °C. When 4 °C stored potatoes were reconditioned for 10 days at 20 °C, there was a significant increase in total phenolic content, chlorogenic acid, caffeic acid, rutin, vanillic acid, p-coumaric acid, and quercetin dehydrate levels. All the three storage treatments resulted in increased carotenoid content but caused no significant differences in phenolic content and antioxidant activity in most of the eight genotypes studied. Stushnoff et al. (2008) analysed total phenolics from 8 potato genotypes after 112 and 263 days of storage at 5 °C. Two genotypes showed sharp rise in total phenolics after storage, four genotypes showed increase to a lesser extent and two genotypes showed little change. Rosenthal and Jansky (2008) observed that stored tubers had higher levels of antioxidant activity than fresh tubers. Jansen and Flamme (2006) determined the anthocyanin content of tubers in 14 cultivars/
clones immediately after harvest and after 135 days of storage at 4 °C and 86% relative humidity, and did not find any significant change in anthocyanin content of tubers. The fact that cold storage had no significant effect on the anthocyanin content of potatoes indicates that there is no risk of degradation of these compounds during storage of potatoes over a longer period. Cold storage temperature (4 °C) helped in stabilizing anthocyanins in strawberries (Gossinger et al., 2009). Potatoes are stored at 4 °C in cold storage in countries such as India (Gottschalk & Ezekiel, 2006). Although sugar accumulation is favoured by low temperature (4 °C), which could be helpful in anthocyanin retention in stored potatoes. Degradation of anthocyanins is primarily caused by oxidation or cleavage of covalent bonds, which increases with increase in temperature during storage or processing.

3.4. Cooking

Attempts to increase phytoneutrants content in potatoes will become futile if the targeted phytoneutrants do not survive cooking in reasonable quantities (Navarre et al., 2010). Potato peels have been shown to contain a high quantity of phenolics. Boiling and baking potatoes with skin was considered to be a good method of cooking as it helped in retaining most of the nutrients. Lower phenolic content in peeled and cooked potatoes as compared to uncooked potatoes has been reported (Mattila & Hellstrom, 2007). Mondy and Gosselin (1989) found that the potatoes cooked with peel had a greater amount of total phenols in the cortex and internal tissues. This has been attributed to the migration of phenolics from the peel into both the cortex and internal tissues of the tuber. Barba, Calabretti, d'Amore, Piccinelli, and Rastrelli (2008) observed significant losses in phenolic contents between peeled and unpeeled potatoes, and between boiling and baking. Boiling resulted in loss of 85.6% and 94.8%, respectively, in protocatechuic acid and tryptophan in peeled potatoes against a loss of only 25.7% in caffeoylquinic acids. Microwave cooking resulted in loss of 49.6% to 83.2% in protocatechuic acid, 26.8 to 64.4%, in caffeoylquinic acids and 77.3 to 89.2%, tryptophan in peeled potato tubers. However, the losses varied with power level used. The losses were observed to be lower in unpeeled potatoes. For example, the losses in caffeoylquinic acids were 20.6 and 26.8%, respectively in unpeeled and peeled potatoes after microwave baking against losses of 24.1 and 25.7%, respectively, after conventional boiling. The change in phenolic content during processing was attributed to the combination of losses caused by leaching into water, degradation from the effects of heat, oxidation by polyphenol oxidase, and isomerisation (Takenaka, Nanayama, Isobe, & Murata, 2006). Jung, Lee, Kozukue, Levin, and Friedman (2011) determined losses in phenolic compounds in sweet potatoes after different methods of home processing. Maximum losses were reported to occur during boiling followed by deep-frying, steaming and minimum losses occurred during microwave baking. Cooking alters the content as well as composition of polyphenols. Faller and Fialho (2009) reported that boiling, microwave baking and steaming decreased the polyphenols content. However, the recovery of polyphenols was higher after boiling as compared to microwave cooking and it was least in steamed potatoes. They observed that unlike in other vegetables such as carrot, onion and cabbage, cooking caused an increase in antioxidant capacity in potatoes, however different cooking methods did not show significant differences. Their results indicate that though cooking caused a decrease in polyphenols contents, it resulted in an increase in antioxidant capacity in potatoes. In raw vegetables, hydrolyzable polyphenols showed higher correlation with antioxidant capacity whereas in cooked vegetables, soluble phenols showed a better correlation with antioxidant capacity (Faller & Fialho, 2009). Modulation of the quality of the phenolic compounds could affect their antioxidant capacity. The formation of novel substances, such as products of Maillard reaction, could also increase the antioxidant capacity in potatoes (Manzocco, Calligaris, Mastrocola, Nicoli, & Lerici, 2000). Dao and Friedman (1992) observed complete destruction of chlorogenic acid during baking of potatoes and 60% reduction by microwaving, while, Im et al. (2008) observed less than 5% losses in chlorogenic acid during baking of potatoes. Navarre et al. (2010) determined losses in phenolics after cooking by microwaving, steaming, boiling or baking and found that none of these cooking methods decreased the amount of chlorogenic, cryptochlorogenic and neochlorogenic acids. The contents of these compounds and total phenolics either remained the same or increased after cooking. Boiling and microwaving did not cause any changes in the phenolic acids content but caused 16–29% decrease in anthocyanins content (Mulinacci et al., 2008). Baking at 170 °C reduced total phenolics levels the most, while microwave cooking and boiling for 30 min. showed the least reductions (Stushnoff et al., 2008). Flavonols are another class of phenolics and no significant loss in the concentrations of rutin or kaempferol-rutinoside due to cooking was observed by Navarre et al. (2010). The increase in the concentration of these compounds after cooking was attributed to an increase in recoverable compounds, as there is little biosynthesis of these compounds during cooking. Cooking may facilitate the extractability of these compounds by altering the matrix, resulting in higher recoveries and inactivating enzymes that otherwise consume these compounds. An increase in the phenolic content in stir-fried potatoes has also been reported (Navarre et al., 2010). The total phenolic content in stir-fried potatoes was 1.83 mg/g DW as compared to 1.09 mg/g DW in raw potatoes. Antioxidant capacity of baked-, boiled-, microwaved-or steamed-potatoes was reported to be higher as compared to uncooked potatoes, and the highest values was observed for steamed or baked-potatoes. Augustin et al. (1978) observed lower folate concentration after boiling in peeled potatoes as compared to unpeeled potatoes. They also observed higher folate concentration in skin than in flesh, and reported that the loss in folate concentration was less than 30% with different cooking methods. Significant cultivar differences in folate concentration after boiling have also been reported. McKillop et al. (2002) did not observe any decrease in folate content in potatoes after boiling for 60 min. Generally, in most of the studies, higher folate concentration has been reported in unpeeled potatoes irrespective of the cooking method. Blessington et al. (2010) compared the losses in phytoneutrants caused by different cooking methods such as baking, boiling, frying and microwaving. Carotenoid content was observed to be lower in boiled as compared to raw potatoes, however, no significant difference in other methods of cooking was observed. The total phenolic content and antioxidant activity did not show any difference between raw and in boiled potatoes but were higher in baked, fried or microwaved potatoes. Greater amounts of phenolics may be extracted out of the potato matrix into water during boiling and into the oil during frying since phenolic compounds are hydrophilic. Baked, fried and microwaved potatoes had greater levels of caffeic acid and p-coumaric acid, and microwaved potatoes had a higher level of (-)-epicatechin. Baking, boiling, frying and microwaving caused a significant decrease in quercetin hydrate (Blessington et al., 2010). Similar decrease in quercetin derivatives was also observed by Tudela et al. (2002). Brown et al. (2008) measured the effect of cooking on total anthocyanins and hydrophilic oxygen radical absorbance capacity (H-ORAC) in four potato genotypes with varying levels of anthocyanins in the flesh. Boiling and microwaving preserved total anthocyanins while baking and frying caused a decrease. Anthocyanins and carotenoids withstand the usual modes of cooking and retain their antioxidant capacity after cooking (Brown, 2005). The above results suggest that phenolics, anthocyanins, carotenoids and other antioxidants will largely survive cooking.

3.5. Processing

Loss of nutrients during processing is a major concern and it is necessary to minimize nutrient losses during processing of potatoes into various products. Minimal processing such as handling, washing and cutting can cause changes in phytochemicals and can lead to activation of some enzymes which modify the level of phenolic compounds (Tudela et al., 2002). Cutting of potatoes can induce the accumulation of
polyphenols. The activity of phenylalanine ammonia-lyase – the main enzyme that produces phenolic compounds – was reported to increase by damages caused by minimal processing and the resultant pheholic products become the substrates for polyphenol oxidase and peroxidase enzymes involved in the phenolic oxidation and browning reaction (Cantos, Tudela, Gil, & Espin, 2002). Wounding of fresh potatoes has been shown to cause changes in phenolic compounds and antioxidant capacity (Reyes, Villarreal, & Cisneros-Zevallos, 2007). Wounding response was cultivar dependent, which was reported to increase the phenolic content and antioxidant capacity of purple-flesh potatoes (Reyes & Cisneros-Zevallos, 2003) but decreased total soluble phenolics and antioxidant capacity to the extent of 15% and 51%, respectively, in white-flesh potatoes (Reyes et al., 2007). Thermal treatments of vegetables such as potatoes is a real challenge because of their antioxidant phenolic content and other metabolites which need to be protected. Thermal processing increased the digestibility of proteins and carbohydrates, and released folates from the food matrix. French fries, fried- and raw-potatoes were reported to have similar folate content by Konings et al. (2001), while Valtteristo, Leikoinen, Olilainen, and Varto (1997) observed 35 to 52% lower folate content in French fries. Anthocyanins stability during processing was influenced by several factors such as processing temperature, pH, presence of enzymes, proteins and metallic ions (Rein, 2005). Thermal processing was reported to cause anthocyanin degradation (Patras, Brunton, O'Donnell, & Tiwari, 2010). Anthocyanins were enzymatically degraded in the presence of polyphenol oxidase, which can be inactivated by mild heating or blanching. Anthocyanins and other phenolic compounds was easily oxidized and, thus, susceptible to oxidative degradation during various steps of processing (Patras et al., 2010). Earlier, phenolics were considered undesirable because of their role in browning but recent studies have shown that phenolic content is not rate limiting for browning in potatoes (Cantos, Tudela, Gil, & Espin, 2002). No correlation has been found between enzymatic browning and chlorogenic acid or tyrosine (Werij et al., 2007). Total anthocyanins content and hydrogen oxygen radical absorbance capacity (HORAC) in chips and French fries were significantly lower than that in raw potatoes (Brown et al., 2008). Generally, the processing of potatoes lowers the antioxidants. Boiling reduces the anthocyanin content more as compared to microwave heating and frying. Nutritional losses occur during processing of potatoes into dehydrated products such as potato flour, granules, flakes and dice. The addition of sulphites destroys some phytochemicals (McCay, McCay, & Smith, 1987). Nutritional losses were also reported in canned potatoes but invariably the loss was due to leaching into the surrounding liquid and the nutrients can be recovered from cooking. Traditional processing of potatoes to produce products such as chuno, results in nutrients loss (Woolf, 1987). Further research is required to quantify the losses of phytochemicals in traditionally processed potato products.

3.6. Pulsed Electric Fields

Pulsed electric fields (PEF) are reported to affect the stability of bioactive compounds in foods (Soliva-Fortuny, Balasa, Knorr, & Martin Bellos, 2009). There is no evidence that PEF affect the primary structure of proteins, but they are known to affect enzymes like polyphenol oxidase (Giner et al., 2000; Zhong et al., 2007). Pulses of increasing width are known to cause a more severe modification of enzyme structure. PEF was reported to have no significant effect on flavonone and carotenoids contents (Soliva-Fortuny et al., 2009), and their functionality.

3.7. Copigmentation

The stability of anthocyanin colour can be improved by copigmentation, where the anthocyanin molecule reacts with other natural plant components directly or through weak interactions, resulting in an enhanced and stabilized colour (Darias-Martin et al., 2002; Talcott, Brenes, Pires, & Del Pozo-Insfran, 2003).

Zhang, Ma, Zhao, and Mu (2009) evaluated the effect of copigmentation on the stability of anthocyanins from purple potato peel in both liquid and solid states. Copigmentation of citric acid monohydrate and glucose were found to increase the stability of the anthocyanin in the liquid and solid states. Copigmentation of ascorbic acid decreased the stability of the anthocyanin in liquid state and increased in the solid state.

4. Antioxidant Activity

Potatoes have several secondary constituents with antioxidant activity, which contributes to the physiological defence against oxidative and free-radical-mediated reactions. The levels of antioxidants were reported to vary with the flesh colour (e.g., dark yellow or blue) of potatoes (Tables 1 and 2). Potatoes contain water-soluble antioxidants that act as free radical acceptors, e.g. glutathione, ascorbic acid, quercetin and chlorogenic acid. Greater antioxidant activity was observed in skin tissue as compared to flesh. Potato varieties with yellow and white flesh were found to have greater antioxidant activity which indicated that carotenoid pigments were probably not responsible for much of the antioxidant activity. Carotenoids insoluble in water and are effective antioxidants (Byers & Perry, 1992). Potatoes and their processed products such as French fries and chips were reported to be good sources of glutathione, a water-soluble antioxidant and anti-carcinogen that helped maintain functional levels of other antioxidants such as vitamins C and E, and [−]-carotene (Al-saikhan et al., 1995). Water soluble anthocyanins, are potent antioxidants and antioxidant activity is not associated only with coloured flesh of potatoes. The colourless compounds, probably either flavonoids or phenolic acids are potentially potent antioxidants (Brown, 2005). Cyanidin has been found to be three times more effective than pelargonidin as an antioxidant (Pietta, 2000), while another study found malvidin as the most potent antioxidant of the anthocyanidins (Kahlkonen & Heimon, 2003). It has been shown that flavonoids also differ significantly in their antioxidant capacity (Pietta, 2000). Quercetin was found to be three times more effective as an antioxidant than kaempferol and eriodictyol, and was thrice as effective as catechin. Chu, Chang, and Hsu (2000) observed that the flavonoids and flavones extracts from potatoes showed high scavenging activities toward oxygen radicals. Though potatoes contain relatively low amount of total phenolic acids, they have high antioxidant activity compared to other fruits and vegetables (Velioglu, Mazza, Gao, & Oomah, 1998). Dao and Friedman (1992) ranked different phenolic acids for oxidation potential, and caffeic acid and chlorogenic acid were the lowest with values at one third of those compounds with the highest oxidation potential (e.g., 4-hydroxybenzoic acid). Reyes, Miller, and Cisneros-Zevallos (2005) observed a high positive correlation between antioxidant capacity and, anthocyanin and phenolic content, and concluded that these compounds are mainly responsible for the antioxidant capacity. Potatoes can play an important role in increasing the intake of antioxidants. The range of hydrophilic ORAC values reported is 200 to 1400 μmol Trolox equivalents/100 g FW, and the range of lipophilic ORAC values reported is 5 to 30 nmol α-tocopherol equivalents/100 g FW (Brown, 2008).

5. Health Benefits

Consumers are becoming increasingly interested in foods that provide health benefits besides the basic nutrients. Potato peel (PP) is a good source of natural antioxidants, which has been studied in various food systems (Rodriguez de Sotillo, Hadley, & Holm, 1994). PP extract provide protection against acute liver injury (Singh, Kamath, Narasimhamurthy, & Rajini, 2008) and oxidative damage to erythrocytes (Singh & Rajini, 2008). Thompson et al. (2009) have reported that the phytochemicals of freeze-dried potato powder caused a
Oxygen Radical Absorbance Capacity (H-ORAC) is used for hydrophilic anthocyanins, and lipophilic-Oxygen Radical Absorbance Capacity (L-ORAC) is used for lipophilic carotenoids. Brown (2008). Brown (2005) described three commonly used antioxidant assays, (i) ORAC, which has the advantage of combining both inhibition percentage and the length of inhibition time of free radical action by an antioxidant into a single quantity (Cao & Prior, 1998), (ii) FRAP, the ferric reducing ability of plasma assay (Benzie & Strain, 1996), easier and less expensive than ORAC, but presents only a single time point percentage inhibition of oxidation, and (iii) DPPH, the 2,2-diphenyl-1-picrylhydrazyl assay for total antioxidant activity (Brand-Williams et al. (1995)).

7. Conclusions
The research in potato chemistry has established the fact that there is a lot more in potatoes than starch. Phytochemicals content in potatoes can be enhanced by developing new varieties from available germplasm high in these compounds. Natural colourant and antioxidant present in purple- and red-flesh potatoes can be used for developing functional foods/nutraceuticals. Considering the large quantities in which potatoes are consumed throughout the world, potatoes should be a very good vehicle for addressing some health related problems. Available evidence suggests that postharvest storage of potatoes do not significantly affect the content of phytochemicals. Antioxidant levels are generally higher in potatoes grown in high-yielding environments, and increased during storage. Pigmented potatoes may also serve as a potential source of natural anthocyanins for use in food industry since the cost of production of potatoes is relatively low as compared to other horticultural crops. In addition, potato is a high yielding crop and the cultural and storage practices are well established. However, for the economy of the whole process of pigment extraction, potatoes with high concentrations of anthocyanins are desirable. In general, cooking leads to losses of nutrients in potatoes; however, phytoneutrients are either not affected or sometimes increased due to increase in extractability and bioavailability. There is a need for further research to explore the ways by which losses in phytochemicals can be reduced such as co-pigmentation, and their stability can be enhanced. Potatoes contain enough phytochemicals to justify the claim of being health promoters, therefore, should form a substantial part of our daily diet. Different pigmented potato based foods needs to be developed and evaluated especially with respect to the antioxidant capacity and other health benefits.

References


