Phytochemical Profiles of Potato and their Roles in Human Health and Wellness

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ABSTRACT

This review provides updated information related to the chemistry, biochemistry and biological activities of the major phytochemicals including carotenoids, anthocyanins, flavonoids, phenolic acids in potato (Solanum tuberosum L.). The antioxidant activities of these phytochemicals, either in the form of extracts or purified states were discussed. The health beneficial effects of potato phytochemicals, particularly polyphenols and carotenoids and their roles in reducing risks associated with cancer, cardiovascular disease and diabetes were also discussed.

Keywords: anthocyanins, anti-cancer, antioxidants, cardiovascular disease, carotenoids, diabetes, flavonoids, health benefits, phenolic acids, phytochemicals, potato, Solanum tuberosum L.

Abbreviations: DPPH, 1,1-diphenyl-2-picrylhydrazyl; GI, glycemic index; LDL, low density lipoprotein; ORAC, oxygen radical absorbance capacity system; ROS, reactive oxygen species; TEAC, trolox equivalent antioxidant capacity; TOSC, oxyradical scavenging capacity

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INTRODUCTION

The concept that food and medicine share the same origin can be traced back as early as 1000 BC. Traditional medicines are mostly of plant origin, and some such as herbs and certain mushrooms are directly or indirectly used as food or in food preparations. Many food plants are packed with bioactive phytochemicals which in recent years have been proven to play a crucial part in maintaining good health and preventing diseases of humans. Fruits and vegetables in particular are rich in phytochemicals, especially those with antioxidant activity. Polyphenols and carotenoids are two most important phytochemical antioxidant groups in vegetables. They are plant secondary metabolites not essential to human health, but have been found to contribute significantly to the risk reduction of human chronic diseases such as cancer and heart disease. One-third of all cancers are considered avoidable by changing dietary habits alone (Miller 1994). Cardiovascular and heart diseases are also found to be influenced by diet (Duthie and Brown 1994). These chronic degenerative diseases have been linked to oxidative stresses caused by excessive free radicals and reactive oxygen species (ROS) such as the superoxide anion (O2•−), hydroxyl radical (OH•) and the peroxy radical (ROO•), which react with vital biomolecules such as lipids, proteins and nucleic acids (e.g. DNA), causing the aforementioned major health problems. Free radicals and ROS are neutralized by antioxidant defence mechanisms.

Potato (Solanum tuberosum L.) is one of the most important staple food crops of the world among wheat, rice, and maize. It provides humans with good quality macronutrients such as carbohydrates and proteins. However, potato provides more than these essential nutrients. Potatoes showed strong antioxidant capacity among most frequently
consumed vegetables (Wu et al. 2004). A Russet potato, one of the favorite varieties in North America, contains the second highest antioxidants only slightly after broccoli in its hydrophilic antioxidant capacity (Wu et al. 2004). Potato, as a staple crop, is well suited to delivering such antioxidative phytochemicals, and recent development in pigmented potatoes containing high concentrations of anthocyanins and carotenoids has generated even more interests in the potential health promoting role of potato. In this review, the author will examine the phytochemical compositions of potato and discuss how they contribute to the antioxidant capacity, and ultimately to human health and wellness. The term “antioxidative phytochemicals” or “phytochemical antioxidants” used in this paper does not include those essential antioxidants such as ascorbic acid (vitamin C). These phytochemicals are plant secondary metabolites, and their original biological functions in plants are primarily for the defense against plants’ own enemies (insects and diseases) (Friedman 1997). Of the phytochemicals produced by the potato plants, the author will only focus on those with strong antioxidant capacities in the consumable part, i.e. the tuber. It is the author’s intention to summarize the scattered literature on specific groups of phytochemicals so readers have a general picture of the phytochemical composition and the health benefits of potato. Phytochemicals with adverse effect such as the glycoalkaloids found in potato will not be the subject of the discussion in this review.

### PHYTOCHEMICALS IN POTATO

Several different groups of phytochemicals have been reported for potato tubers, among them, polyphenols and carotenoids are the two most diverse and predominant. Polyphenols are a collective term for several sub-groups of phenolic compounds including phenolic acids, flavonoids and anthocyanins. Typical phytochemicals and their concentrations are shown in Figs. 1-7 and Table 1. Caution should be taken in interpretation of the data in Table 1 because different units have been used in reporting the concentrations of the same phytochemicals. Not all compounds are detected or reported in any single studies. Further more, quantitative data is not always available even in recent papers (Table 1). Nonetheless, several individual com-
Phytochemicals in potato. Rong Tsao

Table 1 Phytochemical contents in potato tubers.

<table>
<thead>
<tr>
<th>Phytochemicals</th>
<th>Concentrations</th>
<th>References</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Phenolic acids</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenolic acids</td>
<td>30-900 µg/g FW</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Benzoic acids</td>
<td>0.17 mg/g peel extract DW</td>
<td>2</td>
<td>Mainly gallic acid and protocatechuic acid</td>
</tr>
<tr>
<td>Cinnamic acids</td>
<td>0-4000 µg/g FW; 304-13807 µg/g DW, 72 mg/100 g DM; 9.3 mg/100 g FW; 11.5 mg/100 g FW</td>
<td>1, 3, 4, 5, 6</td>
<td>Mainly chlorogenic acid.</td>
</tr>
<tr>
<td><strong>Flavan-3-ols</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catechin</td>
<td>11.4 mg/100 g FW</td>
<td>6</td>
<td>Major flavan-3-ol</td>
</tr>
<tr>
<td>Epicatechin</td>
<td>trace</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Flavonols</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quercetin-3-rutinoside (rutin)</td>
<td>0-196 µg/g DW</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Kaempferol-3 rutinoside</td>
<td>0-227 µg/g DW</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td><strong>Anthocyanins</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plargonidins</td>
<td>200-2000 µg/g FW</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Petunidins</td>
<td>1000-2000 µg/g FW</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Delphinidins</td>
<td>NQ</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Cyanidins</td>
<td>NQ</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Pecidins</td>
<td>20-400 µg/g FW</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Malvidins</td>
<td>20-5000 µg/g FW</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Tocopherols</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>α-Tocopherol</td>
<td>2.7-20.8 µg/g DW</td>
<td>3</td>
<td>Mainly in yellow and orange-fleshed potatoes</td>
</tr>
<tr>
<td><strong>Carotenoids</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>β-Carotene</td>
<td>0-2.0 µg/g DW</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Cryptoxanthin</td>
<td>0.5-5.8 µg/g 100 g FW</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Lutein</td>
<td>1.1-17.7 µg/g DW; 16.8-48.9 µg/100 g FW</td>
<td>3, 8</td>
<td>Major</td>
</tr>
<tr>
<td>Zeaxanthin</td>
<td>Trace-17.7 µg/g DW; 2.7-107.4 µg/100 g FW</td>
<td>3, 8</td>
<td>Major</td>
</tr>
<tr>
<td>Violaxanthin</td>
<td>0.1-13.3 µg/g DW; 4.9-70.6 µg/100 g FW</td>
<td>3, 8</td>
<td>Major</td>
</tr>
<tr>
<td>Antheraxanthin</td>
<td>0-10.0 µg/g DW; 7.7-66.1 µg/100 g FW</td>
<td>3, 8</td>
<td>Major</td>
</tr>
<tr>
<td>Neoxanthin⁴</td>
<td>0.4-5.3 µg/g DW</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td><strong>Phytic acid</strong></td>
<td>0.11-0.27% DW</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Folic acid</td>
<td>521-1373 ng/g DW; 125 µg/100 g FW</td>
<td>9, 10</td>
<td></td>
</tr>
</tbody>
</table>

⁴FW, Fresh weight; DW, Dry weight; NQ, not quantified. Trace, <0.4 µg/g DM.

Phenolic compounds are distributed throughout the potato tuber, but the peel and adjoining tissues contain about 50% of the total with the remainder decreases in concentration from the outside toward the center of potato tubers (Hasegawa et al. 1966). Although other phenolic acids are found in potato, the majority are cinnamic acid derivatives (Fig. 1). Like in other plants, these benzoic acids or cinnamic acids are synthesized in potato via the shikimate pathway (Friedman 1997; Herrmann 1995; Schmidt and Ampeh 1995). Chlorogenic acid (5-O-cafeoylquinic acid) is an ester formed between the carboxyl group of caffeic acid and the 5-hydroxy group of quinic acid (Fig. 1). The hydroxyl group at 4- or 3- position of quinic acid also forms esters with caffeic acid, resulting in isomers cryptochlorogenic acid and neochlorogenic acid, respectively, i.e. 4-O- or 3-O-cafeoylquinic acid (Fig. 1).

Phenolic acids play a significant part in the first line defense mechanism of potato against insects and pathogenic microbes. Compounds such as chlorogenic acids are particularly important in the development of host resistance of potato against phytopathogens such as Erwinia spp. (Friedman 1997). Phenolic compounds can either directly function as antimicrobials by inhibiting bacterial growth, or indirectly by affecting other biochemical processes of both the host plant (potato) and the pathogen in favor of the plant (Friedman 1997).

In foods, phenolic acids are found in nearly all plant-based diets, particularly fruits, vegetables and whole grains (Tsao and Akhtar 2005; Kim et al. 2006). Phenolic acid concentrations of the potato tuber are found to be in the range of 1-171 mg/100 g fresh weight (FW), but the highest amounts are often present in red and purple potatoes (del Mar Verde Méndez et al. 2004; Im et al. 2008). A normal potato peel, however, can contain as much as 177 mg gallic acid equivalent /100 g FW peel (Makris et al. 2007). The total phenolic content of potato depends on both genetic and environmental factors, however, other factors such as extraction and analytical methods may also influence the outcome of the results. A large portion of the phenolic acids are not extractable by conventional solvents, leading to significant underestimation of the total phenolics available in potato (Chu et al. 2002; Nara et al. 2006). Chu et al. (2002) hydrolyzed the insoluble residue of potato, and released nearly 40% more total phenolics. Nara et al. (2006) studied the bound phenolics in both the flesh and peel of potato, and found that the peel not only contained significantly higher concentrations of free phenolics (1.68 vs. 2.66 mg ferulic acid equivalent/g dry weight (DW) in the flesh and peel, respectively), but also in bound phenolics (0.02 and 1.26 mg ferulic acid equivalent/g DW in the flesh and peel, respectively). The major bound phenolic compound was identified as ferulic acid (Nara et al. 2006). Similar results were found by Leo et al. (2008).

**Catechins**

Catechins belong to flavan-3-ols which are often found in tea or fruits such as apple and grape (mainly in the skins)
Flavonols

Flavonols such as quercetin and kaempferol are nearly ubiquitous throughout the plant kingdom, and are a particularly important phytochemical group in our diets (Tsao and Akhtar 2005). In potato, flavonols are not the predominant polyphenol group, and not all reports in the literature have found these compounds in potato. Andre et al. (2007), however, indeed found rutin (quercetin-3-rutinoside) and kaempferol-3-rutinoside in 23 native Andean potato cultivars (Fig. 3). The highest concentration of these two flavonols was 191 and 227 µg/g DW, respectively (Andre et al. 2007). Fresh-cutting induced the biosynthesis of three flavonols, quercetin3-rutinoside, quercetin 3-diglucoside, and quercetin 3-glucosylrutinoside in the potato tubers (Tudela et al. 2002). The flavonols were detected from day 3 in the cold storage and the content increased significantly from barely detectable levels to 6-14 mg/100 g FW on day 6 (Tudela et al. 2002).

Anthocyanins

Anthocyanins are a major subgroup of flavonoid polyphenols that are responsible for most of the red, blue and purple colors seen in fruits and vegetables, flower petals and autumn leaves (McCullum et al. 2007) (Fig. 4). Anthocyanins in fruits mainly exist in glycosidic forms, and the color of a specific anthocyanin compound depends on the hydroxylation or methoxylation patterns on the B ring. In pigmented potatoes, the anthocyanin composition is further complicated by acylation in the glycoside ring. In fact, studies on red and purple fleshed potatoes (S. tuberosum) indicated that these acylated anthocyanins predominated the pigment profiles (Naito et al. 1998; Eichhorn and Winterhalter 2005; Fossen et al. 2003) (Fig. 4). Anthocyanins are chemically stable, particularly under acidic conditions, therefore they are good natural food colorants (Rodriguez-Saona et al. 1999). More importantly, in recent years, anthocyanins have been ascribed as the major components responsible for the health benefits of fruits such as blueberry and strawberry (Wang et al. 2008). This has instigated research programs in developing red and purple fleshe d potato cultivars. In purple potatoes, the predominant anthocyanin was petunidin-3-p-coumaroyl-rutinoside-5-glucoside (commonly known as petanin) (Andre et al. 2007) (Fig. 4).

Tocopherols

Tocopherols are essential vitamin antioxidants (Vitamin E);
Discussions of this paper (as antioxidants in human health, they have been included in however owing to their phenolic feature and the importance noids have been found in yellow-fleshed potatoes (Fig. 6 orange-fleshed cultivars (Brown 2005). Different caroteenoid contents range from 50-100 /g541g/100 g FW in white fleshed varieties to 200 /g541g/100 g FW in deeply yellow to tenoid content in yellow fleshed potatoes can be as high as carotenoids, and depending on the variety, the total carotenoid content in yellow fleshed potatoes is 521 to 1373 ng/g FW (Tsao and Yang 2007). In general, the total carotenoid contents range from 50-100 µg/100 g FW in white fleshed varieties to 2000 µg/100 g FW in deeply yellow to orange-fleshed cultivars (Brown 2005). Different carotenoids have been found in yellow-fleshed potatoes (Fig. 6). Al-Saikhan et al. (1994) analyzed 10 yellow and orange fleshed Texas grown potato varieties and found lutein and zeaxanthin to be the predominant carotenoid in an Ontario-grown Yukon Gold potato at 400 µg/100 g FW, and certain Yukon Gold potatoes contained up to 350 µg violaxanthin/100 g FW (Tsao and Yang 2006).

**Anthocyanins**

<table>
<thead>
<tr>
<th>Anthocyanins</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>petunidin-3-rutinoside-5-glucoside</td>
<td>OCH₃</td>
<td>OH</td>
<td>OH</td>
</tr>
<tr>
<td>petunidin-3-cafeoyl-rutinoside-5-glucoside</td>
<td>OCH₃</td>
<td>OH</td>
<td>Caffeic acid</td>
</tr>
<tr>
<td>petunidin-3-coumaroyl-rutinoside-5-glucoside</td>
<td>OCH₃</td>
<td>OH</td>
<td>p-Coumaric acid</td>
</tr>
<tr>
<td>petunidin-3-feruloyl-rutinoside-5-glucoside</td>
<td>OH</td>
<td>OH</td>
<td>Ferulic acid</td>
</tr>
<tr>
<td>delphinidin-3-coumaroyl-rutinoside-5-glucoside</td>
<td>OH</td>
<td>H</td>
<td>p-Coumaric acid</td>
</tr>
<tr>
<td>cyanidin-3-coumaroyl-rutinoside-5-glucoside</td>
<td>OCH₃</td>
<td>H</td>
<td>OH</td>
</tr>
<tr>
<td>peonidin-3-rutinoside-5-glucoside</td>
<td>OCH₃</td>
<td>H</td>
<td>p-Coumaric acid</td>
</tr>
<tr>
<td>peonidin-3-coumaroyl-rutinoside-5-glucoside</td>
<td>OCH₃</td>
<td>OCH₃</td>
<td>OH</td>
</tr>
<tr>
<td>malvidin-3-rutinoside-5-glucoside</td>
<td>OCH₃</td>
<td>OCH₃</td>
<td>p-Coumaric acid</td>
</tr>
<tr>
<td>malvidin-3-coumaroyl-rutinoside-5-glucoside</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 4 Anthocyanins in red and purple-fleshed potatoes.**

however owing to their phenolic feature and the importance as antioxidants in human health, they have been included in discussions of this paper (Fig. 5). Potatoes contain very little fat-soluble content thus only minimum amount of tocopherols, mainly α-tocopherol (5-21 µg/g DW) was found in potato tubers (Andre et al. 2007).

**Carotenoids**

In addition to the pigments in red and purple potatoes, some potatoes such as the Yukon Gold variety have yellow-colored flesh. The yellow pigments in these potatoes are carotenoids, and depending on the variety, the total carotenoid content in yellow fleshed potatoes can be as high as 54 µg/g DW (Andre et al. 2007). In general, the total carotenoid contents range from 50-100 µg/100 g FW in white-fleshed varieties to 2000 µg/100 g FW in deeply yellow to orange-fleshed cultivars (Brown 2005). Different carotenoids have been found in yellow-fleshed potatoes (Fig. 6). Al-Saikhan et al. (1994) analyzed 10 yellow and orange fleshed Texas grown potato varieties and found lutein and zeaxanthin to be the major carotenoids. The orange-fleshed varieties were much higher in both compounds at 120-148 and 1242-2055 µg/100 g FW, respectively for lutein and zeaxanthin. Other carotenoids have been reported in recent studies (Breithaupt and Bamedi 2002; Tsao and Yang 2006). Breithaupt and Bamedi (2002) identified 4 major violaxanthin, antheraxanthin, lutein, and zeaxanthin; total concentration 175 µg/100 g FW) and 3 minor carotenoids (neoxanthin, β-cryptoxanthin, and β-carotene). They also found carotenoid esters at 41-131 µg/100 g FW. We found lutein to be the predominant carotenoid in an Ontario-grown Yukon Gold potato at 400 µg/100 g FW, and certain Yukon Gold potatoes contained up to 350 µg violaxanthin/100 g FW (Tsao and Yang 2006).

**Phytic acid and folic acid**

Phytic acid or inositol hexaphosphate (InsP₆ or IP₆) exists in many foods, particularly in grains and oil seeds (Fig. 7). Potatoes (S. tuberosum) contained 0.035-0.073% phytate on a wet basis (Phillippy et al. 2003), and 0.111% to 0.269% of dry weight (Phillippy et al. 2004). Despite the anti-nutrient image of phytic acid due to the chelating ability to important minerals such as calcium, magnesium and iron (Porres 2004), IP₆ or its lower phosphorylated forms (IP₁-₅) has been shown in recent years to possess several health beneficial properties such as antioxidant (Graf and Eaton 1990), anti-cancer (Shamsuddin et al. 1997; Zhang and Song 2005), hypocholesterolemic (Lee et al. 2005; Lee et al. 2006) and hypolipidemic effects (Lee et al. 2007).

Folic acid (vitamin B9) is an essential micronutrient in the human diet (Fig. 7). A deficiency of folicates in the diet is associated with the increased risk of neural tube defects, cardiovascular diseases, anemia, and some cancers (Scott 1999; Bailey et al. 2003; Finglas et al. 2006). Even though folic acid is found in most fruits, vegetables and grains, and is fortified in breakfast cereals in some developed countries, current folate intake is suboptimal in most of the world’s populations (Scott et al. 2000). Potato contains 521 to 1373 ng/g DW of folate which was genotype and location dependent (Goyer and Navarre 2007). The highest folate concentration was found mostly in color-fleshed potatoes, and the skin contained 30% higher folate concentrations than the flesh (Goyer and Navarre 2007).

**FACTORS AFFECTING PHYTOCHEMICALS IN POTATO**

The phytochemical composition of potato tuber can be affected by several factors, including genetics, growth period, growing season, geographic location, post-harvest storage and processing conditions (Reddivari et al. 2007a). Detailed
discussions on these factors are beyond the scope of this mini review; however, the author would like to analyze the effect of food processing conditions on the quantity and quality of potato phytochemicals, as these conditions directly relate to what we consume as food. Because potato is consumed cooked, the effect of cooking or processes involved in food preparations on the phytochemical micronutrients is important.

Irradiation of potato peel with \( \gamma \) rays at 150 Gy was found to significantly increase the total phenolic contents by 26% (Kannat et al. 2005). The irradiation had even greater impact on the major phenolic acid, chlorogenic acid (increased by 60%). Physical damage such as fresh-cutting and subsequent cold storage can stimulate the production of flavonols such as quercetin glycosides in potato tubers, however, domestic cooking such as boiling, microwaving, and frying caused a partial loss of the flavonols, (Tudela et al. 2002). Similar results were found for caffeic acid derivatives in the same study.

Most recently Barba et al. (2008) studied the influence of boiling and microwave baking on the amount of several phenolic acids in peeled and non-peeled potatoes (\( S. \) tuberosum cv. ‘Agria’). They found that in general, greater loss was found in peeled potatoes regardless of the heating method. Loss of phenolics can be reduced by using less time in combination with appropriate power input during microwave baking. Reyes and Cisneros-Zevallos (2007) studied the effect of pH and heating on the stability of anthocyanins extracts from purple- and red-fleshed potatoes. They found that potato anthocyanins had the potential to be used as natural colorants for the food industry, particularly the red-fleshed potato anthocyanins, which was found to be more stable than that from the purple-fleshed potato.

Phillippy et al. (2004) studied the phytate content in raw and cooked potatoes, and found that potato phytate was generally stable during common home cooking procedures such as boiling, baking and microwaving. Processed foods such as French fries, dehydrated potato flakes and potato chips were also found to retain much of their original phytate in the same study. Folic acid in potato seemed less

Fig. 6 Carotenoids in yellow and orange-fleshed potatoes.
affected by cooking. Boiling for 60 min did not result in a significant change in folate content of whole potatoes (125.1 and 102.8 mg/100 g for raw and boiled potato, respectively), nor in that of potatoes with or without skin during boiling (McKillop et al. 2002).

Cooking significantly increased the hydrophilic antioxidant capacity of potato, but significantly reduced the lipo-philic antioxidant capacity (Wu et al. 2004), however, it was unclear whether or not the increase was caused by release of more hydrophilic antioxidants such as phenolics, or the decrease was caused by degradation of antioxidants such as carotenoids and tocopherols.

**EFFECT OF PHYTOCHEMICALS ON HUMAN HEALTH AND WELLNESS**

Many chronic diseases such as cancer, cardiovascular and coronary heart disease, diabetes and Alzheimer's disease have all been associated with the excessive free radicals and reactive oxygen species (ROS) (Willcox 1999; Christen 2000; Liu 2003; Willcox et al. 2004). These diseases have been the leading cause of death in industrialized countries. Research has also shown that both Type 1 and Type 2 diabetes are at least partially associated with oxidative stresses caused by free radicals (Maritim et al. 2003; Willcox et al. 2004). Neurodegenerative disorders such as Alzheimer’s disease and other degenerative diseases, particularly age-related macular degeneration have also been associated with free radical damages (Hughes 1999; Christen 2000; Willcox et al. 2004).

Antioxidants thus play a significant role in alleviate these diseases as they can neutralize the act of free radicals and ROS. Ample evidence has been accumulated in recent years supporting strongly the positive correlation between dietary intake of phytochemical antioxidants and chronic diseases (Block et al. 1992; Anderson et al. 2000; Liu 2003; Willcox et al. 2004). Many of the studies have attributed the disease-fighting capability to the phytochemicals with antioxidant capacity. Also, although individual or groups of phytochemical compounds have been studied separately, increasingly more evidence suggests that it is a joint effort among the phytochemical antioxidants of different chemical genres in fighting the diseases, either additively or synergistically (Liu 2003).

**Antioxidant capacity**

Antioxidants play significant roles in preventing oxidation of food and in maintaining good human health. Potato peel extracts indeed were found to prevent soybean oil oxidation, and phenolic acids (chlorogenic and protocatechuic) were the main active antioxidants (Onyeneho and Hettiaachchy 1993). Similar results were obtained in other studies (Rodriguez de Sotillo et al. 1994a, 1994b; Al-Saikhan et al. 1995). These results suggest that potato peel extracts can be used as a potential preservative for the prevention of oxidative rancidity of oil or fat-rich foods. On the other hand, recent research discoveries suggest that the antioxidant capacity of potato phytochemicals may be of more interest in promoting human health.

Vinson et al. (1998) examined the total phenolic content of 23 commonly consumed vegetables and evaluated the antioxidant quality by the inhibition of low density lipoprotein (LDL) oxidation mediated by cupric ions. They developed an antioxidant index measuring both the quantity and the quality of antioxidants present, and found that potato contained the lowest quantity of total and free dry weight phenolics, yet had the second best antioxidant quality based on the total phenolic contents (Vinson et al. 1998). Phenolic acids are found in many dietary sources including fruits, vegetables and whole grains, and have been shown physiological and pharmacological functions (Shahidi and Wanasundara 1992; Mukhtar et al. 1994). In addition to the strong radical scavenging effect and antioxidant capacity, they have also been found to act as effective anti-inflammatory, anti-allergic, anti-mutagenic agents, and good protectant against oxidative DNA damage (Nardini et al. 1998; Tseng et al. 1998; Lodovici et al. 2001, 2003). Among the most important dietary benzoic acids and cinnamic acids, caffeic acid, ferulic acid and gallic acid were found to exhibit over 85 and 60% inhibitory effect toward UVB-induced oxidation in erythrocytes and LDL, respectively (Hsieh et al. 2005).

Andre et al. (2007) analyzed several major phytochemical groups in 74 native Andean cultivars including total phenolic, total carotenoid, and total vitamin C contents. A high linear correlation between the antioxidant capacity measured by the hydrophilic oxygen radical absorbance capacity system (H-ORAC) and the total phenolic content of potato was found. They concluded that such linear correlation suggests that the presence of the phenolic compounds, not the vitamin C, largely accounts for the hydrophilic antioxidant capacity of the potato tubers (Andre et al. 2007). However, the antioxidant capacity depends heavily on the assay system used. High H-ORAC value by the presence of phenolics only gives a partial view of the total antioxidant capacity of potato. For this reason, a lipophilic anti-
oxidant capacity system (L-ORAC) was developed and it was interesting to note that although cooking significantly increased the H-ORAC, it did the opposite to the L-ORAC value of potato (Wu et al. 2004).

Potato peel extracts rich in chlorogenic acid and caffeic acid showed excellent antioxidant activity as determined by β-carotene bleaching and radical scavenging activity of 1,1-diphenyl-2-picrylhydrazyl (DPPH). The antioxidant activity of the potato peel extract was also comparable to the synthetic food antioxidant butylated hydroxytoluene (BHT) in preventing lipid peroxidation of irradiated meat (Kannat et al. 2005). A linear correlation was also found between the total phenolic content and both the TEAC value (trol ox equivalent antioxidant capacity) and the oxyradical scavenging capacity (TOSC) indicating phenolic acids are the major contributing phytochemicals to the total antioxidant capacity of potato peel. The phenolic content of potato flesh presented ORAC values ranging from 4.6 to 15.3 nmoles α-tocopherol equivalents per 100 g FW (Brown 2005). In red and purple potatoes with solidly pigmented flesh with levels of total anthocyanins ranging from 9 to 38 mg/100 g FW, ORAC ranged from 7.6 and 14.2 μmole/g FW of Trol ox equivalents (Brown 2005).

Phytic acid, although a minor phytochemical in potato, was found to be a strong antioxidant against lipid peroxidation (Graf 2007). The study showed that phytic acid formed an iron chelate which greatly blocked iron-driven hydroxyl radical generation thus suppressed the lipid peroxidation. A similar mechanism of antioxidant activity was found by Midorikawa et al. (2001).

**Anti-cancer activity**

Despite the ample evidence that food phytochemicals contribute significantly to the lowered risks of cancer, only a handful of studies have been conducted on the anti-cancer activity of potato phytochemicals. Kim et al. (1994) investigated the effect of potato extracts on the induction of glutathione S-transferase P-positive (GST-P+) altered hepatic foci in newborn Sprague-Dawley rats given single treatment with 60Co gamma irradiation. The potato extract was given at a dose of 2 mg/ml in drinking water for 3 weeks. The extract decreased significantly the number, area and Dmax of GST-P+ hepatic foci compared to the corresponding control. They therefore concluded that potato extracts can be used as radio-protective agent against carcinogenic gamma irradiation (Kim et al. 1994).

Phenolic extracts from four specialty potato cultivars and their organic acid, phenolic acid and anthocyanin fractions were examined against two tumor cell lines. LNCaP (androgen dependent) and PC-3 (androgen independent) in a study by Reddivari et al. (2007b). Potato extracts and their anthocyanin fractions inhibited cell proliferation and increased the cyclin-dependent kinase inhibitor p27 levels, and induced apoptosis in both LNCaP and PC-3 cells. The cytotoxic activities of potato extract and the anthocya-nin fraction in cancer cells were found to be due to activation of caspase-independent apoptosis (Reddivari et al. 2007b). Similar activity was shown against stomach cancer both in vitro and in vivo (Hayashi et al. 2006). Anthocya-nins prepared from colored potatoes induced apoptosis in cultured human stomach cancer KATO III cells, and feeding the cooked red potato or purple potato, or 1% solution of red or purple potato anthocyanin extract significantly suppressed the growth of mouse stomach cancer as compared with the feeding with white-fleshed Irish Cobbler potato (by 37-48%). They concluded that anthocyanins were responsible for the anti-cancer activity (Hayashi et al. 2006).

Phenolic acids such as chlorogenic acid and caffeic acid have been reported to protect cells from carcinogens. The exact mechanisms of the protective property of phenolic acids are not known, however, deactivation through binding to the carcinogen or free radicals may be possible explanations for the protective effect of potato chlorogenic acid and caffeic acid esters (Camire et al. 1995; Nakayama et al. 1997). Chu et al. (2006) suggested that although the anti-oxidant activity and anti-proliferation of cancer cells by potato extracts were not as strong as by other vegetables, due to the high bound phenolic content, potato could release half of their phenolics locally in the colon, thus contributing to the prevention of colon cancer. Most recently, Leo et al. (2008) showed that proliferation of human mammary mamalian cancer (MCF-7) cells was significantly inhibited in a dose-dependent manner after exposure to potato extracts.

Phytic acid IP₆ and its lower phosphorylated forms (IP₋₃) as well as inositol (Ins) are important in regulating vital cellular functions such as signal transduction, cell proliferation and differentiation in mammalian cells (Shamsuddin et al. 1997; Zhang and Song 2005). A striking anti-cancer action of IP₆ has been demonstrated both in vivo and in vitro, which is based on the hypotheses that exogenously administered IP₆ may be phosphorylated, dephosphorylated to IP₅₋₃, and inhibit cell growth (Shamsuddin et al. 1997). There is additional evidence that Ins alone may further enhance the anti-cancer effect of IP₆. Besides decreasing cellular proliferation, IP₆ also causes differentiation of malignant cells often resulting in a reversion to normal phenotype (Shamsuddin et al. 1997).

Midorikawa et al. (2001) monitored the formation of 8-oxo-7,8-dihydro-2′-deoxyguanosine in cultured cells treated with an H₂O₂-generating system, and found a strong inhibitory effect of phytic acid on DNA damage by H₂O₂ and Cu(II).

**Cardiovascular and heart diseases**

Oxidation of LDL cholesterol is linked to atherosclerosis, arterial blockage, heart attacks and strokes. Due to the antioxidative nature of potato phytochemicals, and the fact that certain potatoes contain very high levels of these antioxidants, consumption of good quality potato can contribute to the prevention of LDL oxidation, therefore lower the risk of cardiovascular and heart diseases. Vinson et al. (1998) indeed showed that potato extracts rich in phenolics effectively prevented the Cu-induced LDL oxidation. In vivo study using rats showed that consumption of potato peel induced a lowering of cholesterol (Lazarov and Werman 1996). Even though the authors in the in vivo study ascribed this to the fibre content of the peel, as discussed above, the peel contains a variety of phytochemicals which are strong antioxidants that may contribute to the observed effect.

Robert et al. (2006) investigated in the rat the effect of a potato-enriched diet on lipid metabolism and antioxidant protection, and found that feeding for 3 weeks led to a significant decrease in cholesterol and triglyceride levels in plasma (respectively, -30% and -36%) and cholesterol level in liver (-42%), and significantly improved the antioxidant status in plasma. These effects could be interesting for prevention of cardiovascular disease. Although the authors did not attribute their finding to any specific bioactive components, they did suggest that a combination of dietary fibre and phenolic content should be examined (Robert et al. 2006). A subsequent study by the same group indeed showed that a combination of different antioxidant micronutrients enhanced the antioxidant defences and improved lipid metabolism in rats as compared with starch or sucrose fed rats (Robert et al. 2008).

Similarly, Han et al. (2007) examined the antioxidant effects of polyphenol/anthocyanin-rich potato (S. tuberosum cv. ‘Shadow-Queen’) flakes in male rats fed a high-cholesterol diet. The thiobarbituric acid reactive substance (TBARS) levels in the serum and liver of the Shadow-
Queen potato were significantly lower than those in the control and the white-fleshed potato flake groups. The serum urate levels were significantly lower, the hepatic glutathione levels, and activities of hepatic glutathione reductase and glutathione-S-transferase were significantly higher than in the control and the white-fleshed potato groups as well. The authors suggested that the purple potato flake diet containing polyphenols/anthocyanins may play an important role in the protection against oxidative stress induced by oxidative damage in rats fed a high-cholesterol diet.

Shih et al. (2008) showed carotenoids such as β-carotene and canthaxanthin may also play an important role in altering the pro-oxidation and antioxidation balance and suppressed cholesterol-induced oxidative stress via modulation of antioxidant system and cholesterol metabolism in a similar study. This implies that yellow or orange-fleshed potatoes may act similarly, and together with the polyphenols/anthocyanins in red or purple-fleshed potatoes, carotenoids may be as important in lipid metabolism and in preventing cardiovascular diseases.

Diabetes

To date, several epidemiological studies have described associations between the dietary glycemic index (GI) and risks of type 2 diabetes (Salmeron et al. 1997a, 1997b; Hodge et al. 2004; Liu et al. 2004; Schulze et al. 2004). Furthermore, recent weight-loss intervention studies suggest that a diet with a low GI may represent a promising alternative to a low-fat diet (Slabber et al. 1994; Spieth et al. 2000; Ebbeling et al. 2003). Several prominently cited studies have reported that potatoes are characterized by a high GI value which leads to increased incidence of type 2 diabetes (Soh and Brand-Miller 1999; Foster-Powell et al. 2002; Montonen et al. 2005; Halton et al. 2006). For this reason potatoes have been ranked among the foods to be eaten sparingly, and sometimes given unjustified labels that all potatoes have a high GI (Buyken and Kroke 2005). When examined closely, however, contradictory results to the above have been reported in the past. Some research results showed no association between potato consumption and diabetes (Hodge et al. 2004; Liu et al. 2004) and others an association with lower 2-h glucose values during follow-up (Feskens et al. 1995). Intake of potato and its effect on glucose metabolism also depends on the gender and the amount consumed (Ylönen et al. 2007). Many factors can affect the GI values of potatoes. Cooking method, processing, variety and the composition of the meal (Lunetta et al. 1995; Foster-Powell et al. 2002; Fernandes et al. 2005) can all affect the GI values. Methods such as baking and microwave cooking tend to lead to high GI values whereas conventionally boiled potatoes appear to have a GI value on average below 70. The values of conventionally boiled potatoes again can vary considerably depending on the genetic (Buyken and Kroke 2005).

The physicochemical properties of carbohydrates certainly play significant parts in maintaining the GI of potatoes. Other phytochemicals in the potato tubers may also contribute significantly to lowering GI. Phytochemicals, particularly phenolic antioxidants in common foods have been shown to strongly inhibit the carbohydrate digestive enzymes such as α-amylase and α-glucosidase activities, suggesting that these phytochemicals can be potentially contributing to the inhibition of carbohydrate breakdown and control of GI of food products (Matsui et al. 2001; McCleary et al. 2005; Nasu et al. 2003). Worth mentioning is the anti-hyperglycemic effect of acylated anthocyanins in purple sweet potatoes (Ipomoea batatas). Although the purple sweet potatoes belong to a different family than the white-fleshed common potatoes (S. tuberosum), the acylated anthocyanin composition are similar (Matsui et al. 2002; Lachman and Hamour 2005). In a subsequent in vivo study, Matsui et al. (2002) showed that enzyme inhibitory activity against α-glucosidase led to significant reduction of blood glucose level of male 8-week-old Sprague-Dawley rats administered with a single dose of peonidin 3-O-[2-O-(6-O-E-feruloyl-β-D-glucopyranosyl)-6-O-E-cafeoyl-β-D-glucopyranosido]-5-O-β-D-glucopyranoside isolated from the purple sweet potato tubers. A reduction of serum insulin secretion was also observed corresponding to the decrease in blood glucose level. They then suggested that the anti-hyperglycemic effect of the anthocyanins was achieved by maltase inhibition, not by sucrase or glucose transport inhibition at the intestinal membrane (Matsui et al. 2002). Potato polyphenols have also been shown to negatively correlate with the blood glucose response (GI value) of normal and diabetic subjects in a controlled human clinical study (Thompson et al. 1983). The inhibitory activity of polyphenols against key enzymes such as α-amylase, α-glucosidase and phosphorylase that are important in starch and sugar metabolism is considered to be important in lowering the GI, and more importantly in reducing risks associated with diabetes.

Potatoes present a very significant source of antioxidants in human nutrition, e.g. among fruits and vegetables they insure an average daily intake of about 64 mg polyphenols per capita in the U.S.A. and occupy the second place after tomatoes (Al-Saikhan et al. 1995). Polyphenol-rich potatoes, particularly those containing high concentrations of anthocyanins, are therefore promising in reducing the risks of diabetes because of the advantage of potato being a staple vegetable food. With more research focused on developing potato varieties with high anthocyanin content and on appropriate growing conditions for the enhancement of natural pigment and antioxidant yields, purple- and red-fleshed potatoes can potentially be the favorite of health-conscious consumers and the food and nutraceutical industry (Brown et al. 2003).

CONCLUSION

Potatoes (Solanum tuberosum L.), being one of the most important staple food crops of the world, contains diverse biologically active phytochemicals, in addition to carbohydrates and proteins as major source of energy for human. Potatoes are a rich source of phenolic acids, flavonoids, folates, phytates and carotenoids. Anthocyanins are the major pigments responsible for the red and purple fleshed potatoes. In recent years, effort has been made in developing phytochemical-rich cultivars and in optimizing agronomic practices to increase the phytochemical content of potatoes. However, food processing conditions such as different heating methods can also significantly affect the phytochemical composition. As strong antioxidants, these phytochemicals, together with other essential nutrients such as tocopherols, have been shown in both in vitro and in vivo studies to have anti-proliferation, anti-LDL peroxidation and GI lowering activities. These have significant implications in reducing the risks of cancer, cardiovascular diseases and diabetes. Reviewing the phytochemical composition of potato and the roles these bioactive agents play in human health and wellness, has led us to suggest that future research efforts should be made in developing phytochemical-rich varieties, particularly those deeply colored ones rich in phenolic acids, anthocyanins and carotenoids. Cooking or processing methods that maximize the retention of phytochemical nutrients should also be further examined, in addition to human clinical trials that help to understand how these phytochemicals are delivered and absorbed in our body.

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