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

Rong Tsao*

Guelph Food Research Centre, Agriculture & Agri-Food Canada, 93 Stone Road West, Guelph, Ontario, N1G 5C9, Canada

Correspondence: * **caor@agr.gc.ca**

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

CONTENTS

INTRODUCTION 125
PHYTOCHEMICALS IN POTATO 126
Polyphenols 127
Phenolic acids 127
Catechins 127
Flavonols 128
Anthocyanins 128
Tocopherols 128
Carotenoids 129
Phytic acid and folic acid 129
FACTORS AFFECTING PHYTOCHEMICALS IN POTATO 129
EFFECT OF PHYTOCHEMICALS ON HUMAN HEALTH AND WELLNESS 131
Antioxidant capacity 131
Anti-cancer activity 132
Cardiovascular and heart diseases 132
Diabetes 133
CONCLUSION 133
REFERENCES 133

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 (Milner 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 ($^{\bullet}O_2^-$), hydroxyl radical ($OH^{\bullet}$) and the peroxy radical ($ROO^{\bullet}$), 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

Received: 24 September, 2008. Accepted: 27 November, 2008.

Invited Review

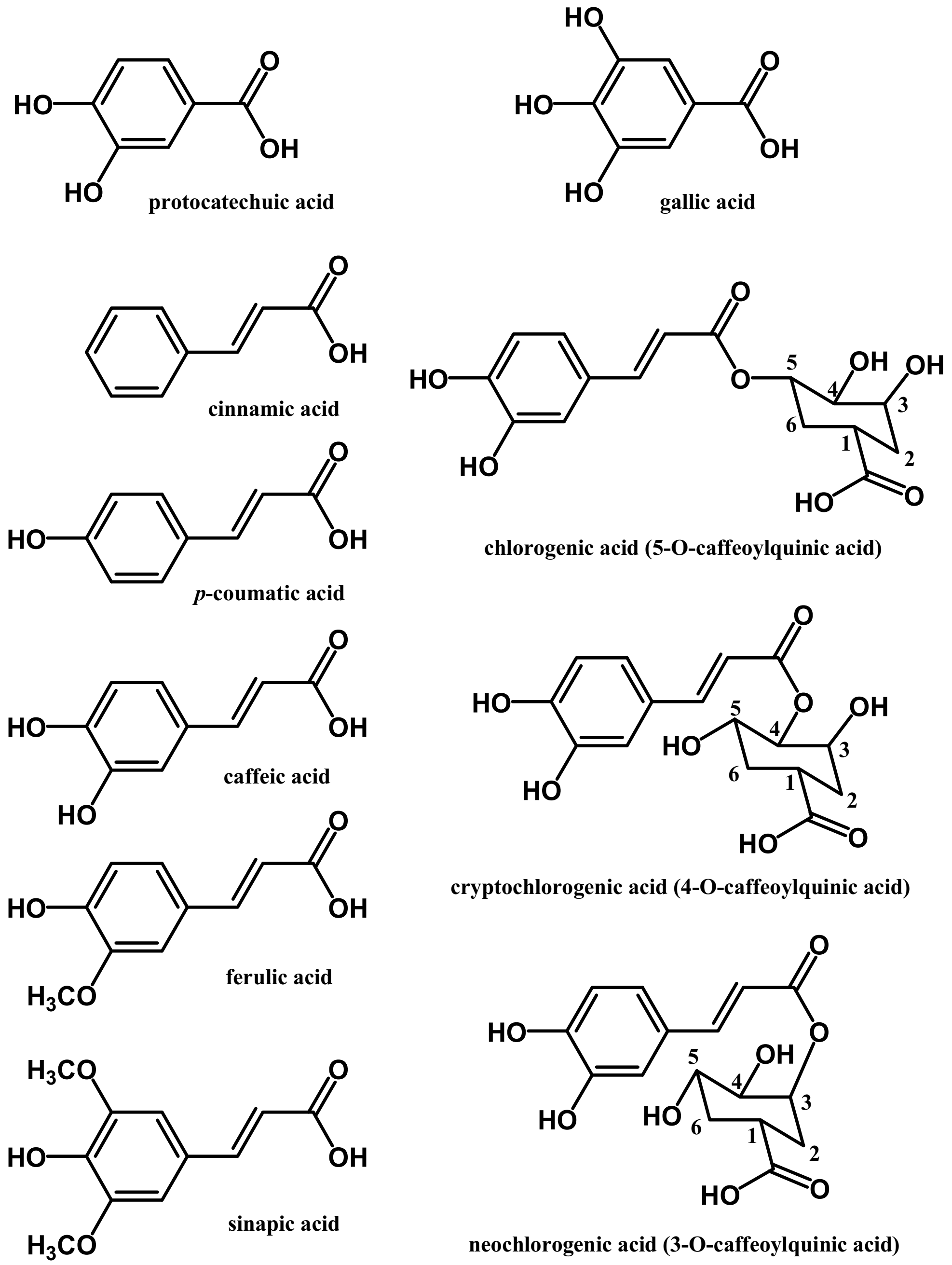


Fig. 1 Phenolic acids and derivatives from potato.

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 date is not always available even in recent papers (**Table 1**). Nonetheless, several individual com-

Table 1 Phytochemical contents in potato tubers.

Phytochemicals	Concentrations	References	Notes
Phenolic acids	30-900 μg/g FW	1	
Benzoic acids	0.17 mg/g peel extract DW	2	Mainly gallic acid and protocatechuic acid
Cinnamic acids	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	1, 3, 4, 5, 6	Mainly chlorogenic acid.
Flavan-3-ols			
Catechin	11.4 mg/100 g FW	6	Major flavan-3-ol
Epicatechin	trace	1	
Flavonols			
Quercetin-3-rutinoside (rutin)	0-196 μg/g DW	3	
Kaempferol-3 rutinoside	0-227 μg/g DW	3	
Anthocyanins	0-16330 μg/g DW	3	Mainly in red or purple fleshed potatoes
Plargonidins	200-2000 μg/g FW	1	
Petunidins	1000-2000 μg/g FW	1	
Delphinidins	NQ	1	
Cyanidins	NQ	1	
Peoidins	20-400 μg/g FW	1	
Malvidins	20-5000 μg/g FW	1	
Tocopherols			
α-Tocopherol	2.7-20.8 μg/g DW	3	
Carotenoids			Mainly in yellow and orange-fleshed potatoes
β-Carotene	0-2.0 μg/g DW	3	
Cryptoxanthin	0.3-5.8 μg/100 g FW	8	
Lutein	1.1-17.7 μg/g DW; 16.8-48.9 μg/100 g FW	3, 8	Major
Zeaxanthin	Trace-17.7 μg/g DW; 2.7-107.4 μg/100 g FW	3, 8	Major
Violaxanthin	0.1-13.3 μg/g DW; 4.9-70.6 μg/100 g FW	3, 8	Major
Antheraxanthin	0-10.0 μg/g DW; 7.7-66.1 μg/100 g FW	3, 8	Major
Neoxanthin[a]	0.4-5.3 μg/g DW	3	
Phytic acid	0.11-0.27% DW	7	
Folic acid	521-1373 ng/g DW; 125 μg/100 g FW	9, 10	

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

1. Lewis *et al.* 1998; 2. Rodriguez de Sotillo *et al.* 1994b; 3. Andre *et al.* 2007; 4. Griffiths and Bain 1997; 5. Friedman 1997; 6. del Mar Verde Méndez *et al.* 2004; 7. Phillipp *et al.* 2004; 8. Breithaupt and Bamedi 2002; 9. Goyer and Navarre 2007; 10. McKillop *et al.* 2002.

pounds or groups of compounds are universal in all potato varieties, or different types of potatoes. For example, chlorogenic acid is the main phenolic acid found in all potato tubers; anthocyanins are only found in red and purple-fleshed potatoes; carotenoids are only found in yellow and orange-fleshed potatoes (**Table 1**).

Polyphenols

Phenolic acids

The major phenolic acids in potato are cinnamic acid and its derivatives, although benzoic acids such as gallic and protocatechuic acid are also found to be present. The phenolic acid profile in potato was reported to contain chlorogenic acid (50.3%) caffeic acid (41.7%), gallic acid (7.8%), and protocatechuic acid (0.21%) (Rodriguez de Sotillo *et al.* 1998). In some cases, chlorogenic acid constitutes up to 90% of the total phenolic content (Friedman 1997). **Fig. 1** shows the chemical structures of potato phenolic acids.

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 Amrhein 1995). Chlorogenic acid (5-*O*-caffeoylquinic acid) is an ester formed between the carboxyl group of caffeic acid and the 5-hydroxyl 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*-caffeoylquinic 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 Mendez *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)

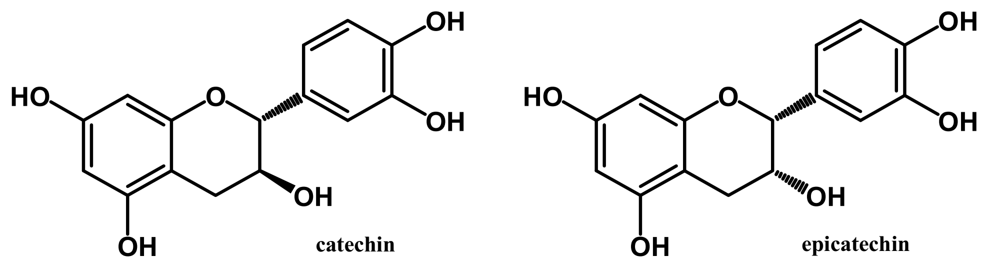


Fig. 2 Structures of major flavan-3-ols (catechins): catechin and epicatechin.

(Tsao *et al.* 2005; Si *et al.* 2006) (**Fig. 2**). Catechins are known as strong antioxidants which have been associated with several potential health benefits. Catechin is only a minor constituent in potato (10-13 mg/100 g FW), as was found in some cultivars by del Mar Verde Mendez *et al.* (2004). Its isomer, epicatechin (**Fig. 2**) was also found in potato tuber in trace amount (Lewis *et al.* 1998).

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 (McCallum *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 with 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 fleshed 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);

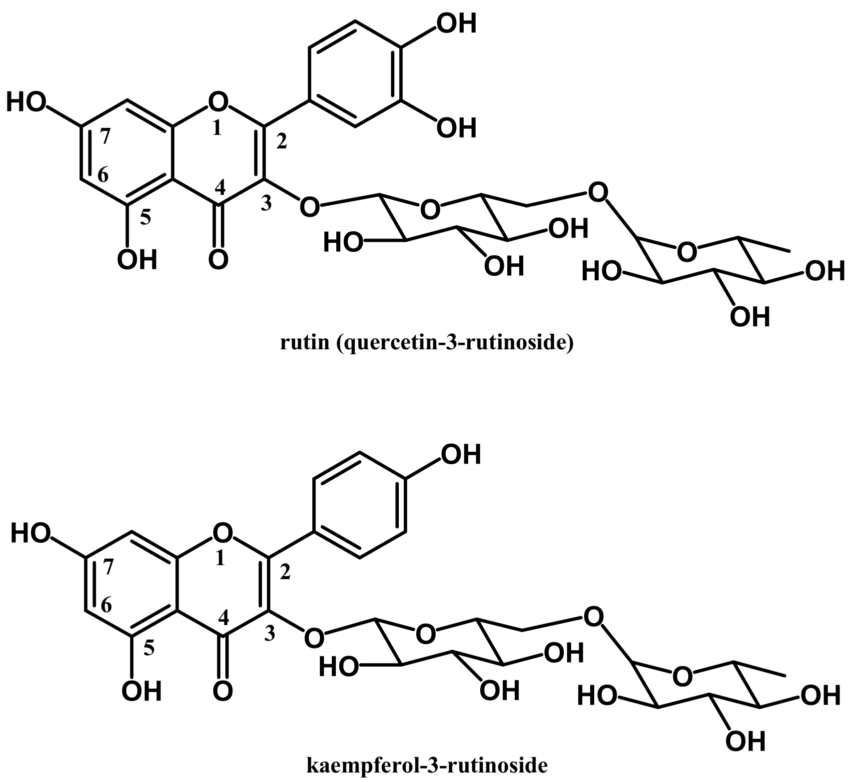
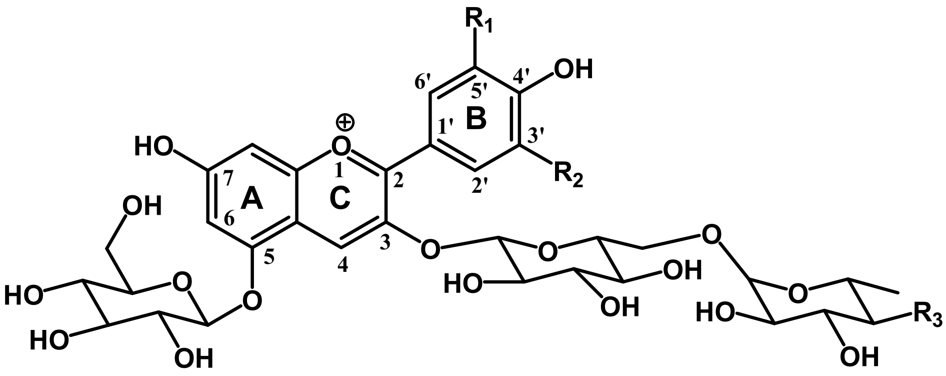


Fig. 3 Structures of major flavonols: quercetin and kaempferol glycosides.



Anthocyanins	R_1	R_2	R_3
petunidin-3-rutinoside-5-glucoside	OCH_3	OH	OH
petunidin-3-caffeoyl-rutinoside-5-glucoside	OCH_3	OH	Caffeic acid
petunidin-3-coumaroyl-rutinoside-5-glucoside	OCH_3	OH	*p*-Coumaric acid
petunidin-3-feruloyl-rutinoside-5-glucoside	OCH_3	OH	Ferulic acid
delphinidin-3-coumaroyl-rutinoside-5-glucoside	OH	OH	*p*-Coumaric acid
cyanidin-3-coumaroyl-rutinoside-5-glucoside	OH	H	*p*-Coumaric acid
peonidin-3-rutinoside-5-glucoside	OCH_3	H	OH
peonidin-3-coumaroyl-rutinoside-5-glucoside	OCH_3	H	*p*-Coumaric acid
malvidin-3-rutinoside-5-glucoside	OCH_3	OCH_3	OH
malvidin-3-coumaroyl-rutinoside-5-glucoside	OCH_3	OCH_3	*p*-Coumaric acid

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

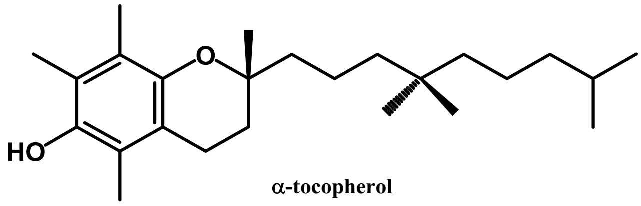


Fig. 5 α-Tocopherol is the major vitamin E found in potato.

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 (3-21 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 (InsP_6 or IP_6) 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 the chelating ability to important minerals such as calcium, magnesium and iron (Porres *et al.* 2004), IP_6 or its lower phosphorylated forms (IP_{1-5}) 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 *at al.* 2007).

Folic acid (vitamin B9) is an essential micronutrient in the human diet (**Fig. 7**). A deficiency of folates 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

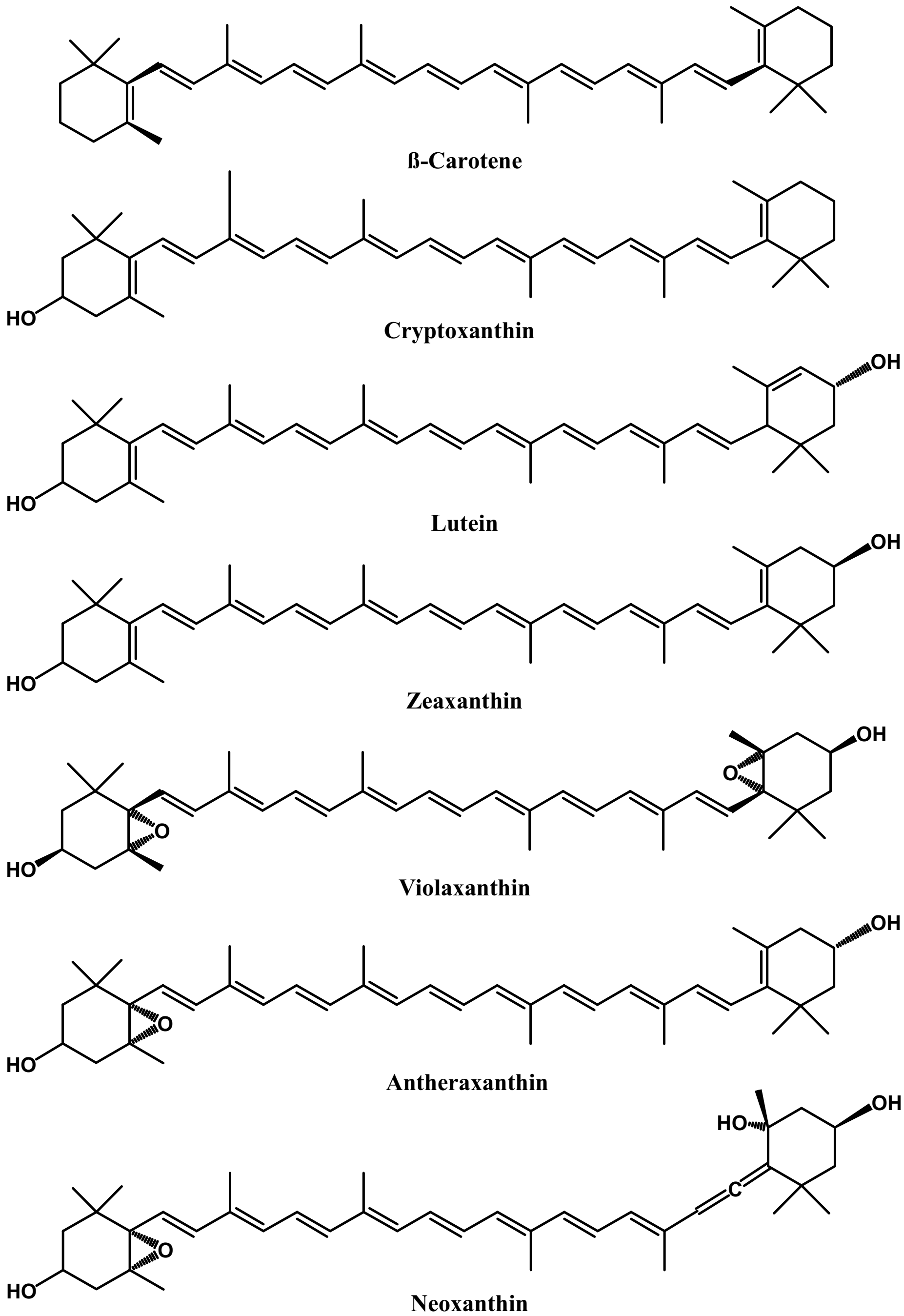


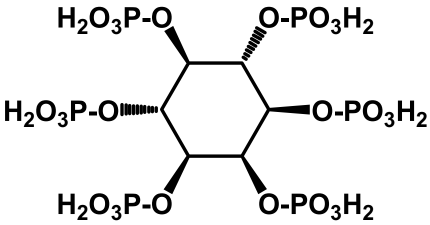
Fig. 6 Carotenoids in yellow and orange-fleshed potatoes.

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.

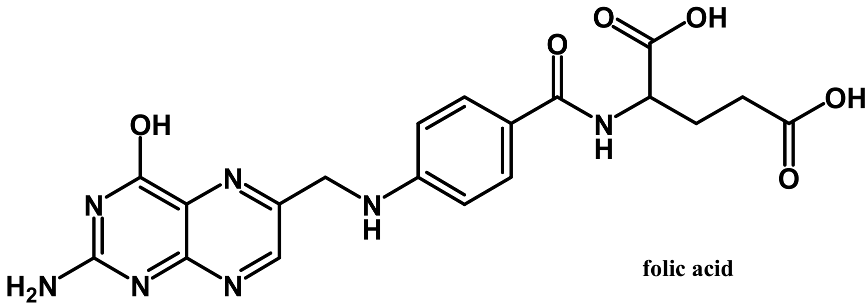
Irradiation of potato peel with γ rays at 150 Gy was found to significantly increase the total phenolic contents by 26% (Kannat *et al.* 2005). The irradiation had even greater impact on the major phenolic acid, chlorogenic acid (increased by 60%). Physical damage such as fresh-cutting and subsequent 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-flesh 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



phytic acid (inositol hexaphosphate)



folic acid

Fig. 7 Structures of phytic acid (inositol hexaphosphate) and folic acid.

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 lipophilic 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 *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 antioxidant 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 phenolics-rich extract was also found to be 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 (trolox equivalent antioxidant capacity) and the oxyradical scavenging capacity (TOSC) indicating phenolic acids are the major contributing phytochemicals to the total antioxidant capacity of potato (Leo *et al.* 2008). Nara *et al.* (2006) identified major phenolics in both free and bound forms and found the total amount of chlorogenic acid and caffeic acid in the free-form phenolics was highly correlated with the DPPH radical scavenging activity. Ferulic acid was identified as the active radical scavenging compound in the bound-form phenolics from the peel.

In potatoes with total carotenoids ranging from 35 to 795 μg/100 g FW, the lipophilic extract 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 umole/g FW of Trolox equivalents (Brown 2005).

Phytic acid, although a minor phytochemical in potato, was found to be a strong antioxidant against lipid peroxidation (Graf *et al.* 1987). 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 contributes significantly to the lowered risks of cancer, only a handful 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 ^{60}Co 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 D_{max} 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 prostate cancer 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 anthocyanin 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). Anthocyanins 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.* 1996). Chu *et al.* (2002) suggested that although the antioxidant 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 mammalian cancer (MCF-7) cells was significantly inhibited in a dose-dependent manner after exposure to potato extracts.

Phytic acid IP_6 and its lower phosphorylated forms (IP_{1-5}) 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 IP_6 has been demonstrated both *in vivo* and *in vitro*, which is based on the hypotheses that exogenously administered IP_6 may be internalized, dephosphorylated to IP_{1-5}, and inhibit cell growth (Shamsuddin *et al.* 1997). There is additional evidence that Ins alone may further enhance the anti-cancer effect of IP_6. Besides decreasing cellular proliferation, IP_6 also causes differentiation of malignnant 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 H_2O_2-generating system, and found a strong inhibitory effect of phytic acid on DNA damage by H_2O_2 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 adverse effects related to 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 genetics (Buyken and Kroke 2005).

The physicochemical properties of carbohydrates certainly play significant parts in maintaining the GI of potatoes, however, other phytochemicals in the potato tubers may also contribute significantly to lowing 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; McCue *et al.* 2005; Nasu *et al.* 2005). Worthy 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 purple-fleshed common potatoes (*S. tuberosum*), the acylated anthocyanin composition are similar (Matsui *et al.* 2002; Lachman and Hamouz 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*-caffeoyl-β-D-glucopyranoside]-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 will therefore play an important role 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-flesh potatoes can potentially be the favorite of health-conscientious 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 potato, 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 great potentials in human health. As antioxidants, they help fight the harmful free radicals and excess reactive oxygen species. Potato phytochemicals 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 bioactives 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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