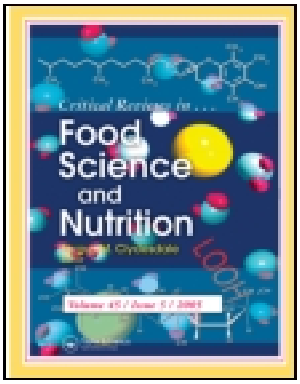

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Potatoes and Human Health

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The potato (Solanum tuberosum L.) tuber follows only rice and wheat in world importance as a food crop for human consumption. Cultivated potatoes have spread from the Andes of South America where they originated to 160 countries around the world. Consumption of fresh potatoes has declined while processed products have increased in popularity. As the potato becomes a staple in the diets of an increasing number of humans, small differences in potato nutritional composition will have major impacts on population health. The potato is a carbohydrate-rich, energy-providing food with little fat. Potato protein content is fairly low but has an excellent biological value of 90–100. Potatoes are particularly high in vitamin C and are a good source of several B vitamins and potassium. The skins provide substantial dietary fiber. Many compounds in potatoes contribute to antioxidant activity and interest in cultivars with pigmented flesh is growing. This review will examine the nutrient and bioactive compounds in potatoes and their impact on human health.

Keywords Cardiovascular disease, glycemic index, chlorogenic acid, obesity

This review does not intend to replace the numerous reviews on potato as nutrient or food item but only to summarize the contribution of potato to long-term human health. This humble tuber has sustained many generations and new research has revealed possible directions for breeding programs to enhance the nutritional composition of potatoes to meet the needs of specific groups of consumers.

ORIGIN OF POTATO AS HUMAN FOOD

The cultivated potato (*Solanum tuberosum* L.) originated in South America where it has been used for food for over 10,000 years (CDC, 1999a) and domesticated during pre-Columbian times over 8,000 years ago (CIP, 2008a). Pre-Columbian food preparation involved the production of *chuño*, which was used in soups and stews, much as it is still produced in the Andes today (Woolfe, 1987). Harvested potato tubers are piled on the ground and repeatedly frozen over several nights. Skin removal (through trampling) is followed by soaking or leaching in running river water. This serves to remove the bitter flavors caused by glycoalkaloids. The final step involves sun-drying which preserves the *chuño* for up to several years. Another product, *papa seca*, is produced by boiling, peeling, slicing, then sun-drying and grinding and is also used in stews and soups. Potatoes were first spread to European countries, including Spain and England, in the late 1500s (CDC, 1999b). The potato may have been instrumental in preventing scurvy among early consumers, including sailors, due to its relatively high vitamin C content (Buckenhüskes, 2005). Potatoes became so widely distributed and important, especially in certain parts of Europe, that they are often referred to as “European” or “Irish” potatoes. Potatoes are now grown in 160 countries (AAFC, 2007) with over 4,000 cultivars (Hils and Pieterse, 2007). Potatoes are eaten fresh or following storage; prepared in a multiplicity of different ways at home or commercially processed into many different foods.

Despite its apparent diversity, the cultivated potato contains only a fraction of the potential biodiversity that is present in South American cultivars and cross-compatible wild species (reviewed by Bradshaw, 2007). In a comparison of 205 cultivars and 1220 genotypes of wild and cultivated species for dry matter, starch, resistant starch, starch granule diameter, and protein content, Jansen et al. (2001) found more variability in wild than cultivated potatoes for all characters. For this reason, and because the potato genome is known, there exists enormous capacity through breeding to improve potato towards an increasingly more healthy food item. The need for new cultivars is primarily driven by goals of stable or improved yields under more sustainable growing conditions (primarily lower fuel and fertilizer inputs), environmental stresses, and disease and pest pressures. Where daily per capita availability of nutritious food is below recommended phytochemical intake, diet diversification, and improved preparation and processing to increase micronutrient bioavailability is needed (Hanson et al., 2004),

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and improved potato cultivars may have a significant role here. Where food security is not an overwhelming issue, consumer demand is for more convenience foods, improved nutritional and health properties, including organically-grown produce, better flavor, and novel foods.

POTATO PRODUCTION – CURRENT AND FUTURE TRENDS

The potato has achieved worldwide prominence as a food item, in part, due to its tremendous yield per unit area compared with many other food crops. Average potato yield in metric tons per hectare ($mtha^{-1}$) in North America (40.6) is far in excess of those achieved in Europe (17.3), Latin America (16.6), Asia (15.7), or Africa (10.8) (2005 figures, CIP 2008b). There would seem to be much potential for increased yield in many potato growing areas. Higher production in parts of North America is favored by many factors, including cool climate with ample rainfall, mechanization and efficiencies of scale, relatively high inputs (fertilizer, pesticides), long growing season which favors the higher yielding long-season cultivars, and production systems involving rotation with cereals and forages that improve soil structure and discourage disease.

World potato growing areas are in a state of dynamic change. Global production statistics collected by FAO were tabularized and mapped by CIP (2008b). The production levels in the developed nations of Europe, North America, and the former Soviet Union have declined by 30 million metric tons (mmt) within the past 16 years (183 and 156 mmt in 1991 and 2007, respectively). During this same interval, production has doubled in countries of the developing world including Asia, Africa, and Latin America (85 and 165 mmt in 1991 and 2007, respectively). The top three world leaders in potato production in 2007 included China (72.0 mmt), the Russian Federation (35.7 mmt), and India (26.3 mmt). Production in China is forecast to reach 81 mmt in 2010 (Wang and Zhang, 2004). Asian production, overall, is increasing at about 6% annually (Bamberg and del Rio, 2005). Demand is fueled by increasing numbers of potato-consumers in both production and non-production areas, interest in processed potato products for a developing food service industry, use as animal feed for a growing livestock industry, and anticipated export potential to neighboring countries including Japan and South Korea. It is expected that China will increasingly export fresh potatoes and import processed potato product. The situation is similar in India, where both internal and export markets continue to increase (CommodityOnline, 2008).

Almost half of the global potato supply is now consumed in Asia. The consumption per capita in Asia is on the increase as of 2005, but is still relatively low (26 kg) compared with Europe (96 kg) or North America (58 kg) (CIP, 2008b). This suggests that demand for potato in Asia could double or triple over the next few years. As prosperity increases, consumption may both increase and shift to include processed food products (CIP, 2008c). As consumption increases, relatively small improvements in nutrition impact increasingly on consumer health compared with major gains in the minor food items (Bamberg and del Rio, 2005).

Undermining the overall gains in Asian and African prosperity over the past decade are recent soaring food prices resulting from diversion of grain from feed to biofuels and associated speculation in the commodities markets (Fresh Plaza, 2008a). Fuel and fertilizer shortages are also impacting agricultural production. Potato increasingly contributes to world food security and has a critical role to play in developing nations facing hunger. Potatoes supplement or replace grain-based diets where rice, wheat, or corn availability has lessened or price has become unaffordable. The potato now ranks third, behind rice and wheat, for human food as the use of corn for biofuels and animal feed has lessened its human food applications.

Predicted global climate change for 2010–2039, with associated increased temperatures, is expected to cause upheaval in most agricultural, including potato, growing areas (Hijmans, 2003). Major cultural adaptations involving planting time and cultivar choice (particularly more heat-tolerant cultivars) will need to be implemented to mediate impact of increased temperatures. However, effects will vary with different geographic areas where potato is grown. Areas expected to be least affected are at high latitudes (Canada, China, Russia, Scandinavia) or high altitudes in the tropics (Peruvian/Bolivian Altiplano) where production area may increase. Areas expected to be most affected, with predicted large yield declines, comprise a zone that includes southeastern Europe, Russia, and Kazakhstan. Subtropical areas such as India and Bangladesh where potatoes are already grown during the coolest season will be greatly affected without much scope to mediate yield.

POTATO VARIETIES AND CLASSIFICATION FOR FOOD USES

Potato varieties can be classified using a broad range of criteria. One common classification is based on the number of days to maturity following planting of whole or cut seed tubers. For example, potatoes are classified as very early (65–70), early (70–90), mid-season (90–100), late (110–130), or very late ($>$130) (CFIA, 2008). Cultivars with longer maturity times generally out-yield the shorter maturity cultivars. “New” potatoes are often short-season cultivars that are harvested early as small, tender potatoes and usually boiled for table use.

Varieties may be classified based on tuber quality traits suited to specific cooking or processing activities (boiling, baking, dehydrating, frying, etc.). These may be divided further. For example, cultivars preferred for frying are generally separated into chipping (round) or French fry (elongate) types. Further to this, cultivars can be classified based on storage properties. Some cultivars must be eaten or processed following harvest, and others maintain their starch properties longer in storage. During storage, or prolonged storage, starch may be converted to reducing sugars that caramelize during the frying process. Cultivars that can be stored for longer are advantageous to the food industry.

Consumer preference may relate to tuber periderm (skin) and/or flesh color. The most common colors include brown, red, white, or yellow skin with white or yellow flesh. Skins that are russet (brownish or reddish-brown with a raised "fish net") can be clearly distinguished from those that are not. The "specialty" or "novelty" potatoes reflect the variation seen among South American wild species that possess a broader range of pigmentation. For example, phenotypes occur with colors such as purple and blue skin and/or flesh color. Potato pigments include anthocyanins, carotenoids, and precursor flavonoids and phenolics (van Eck, 2007). These pigments are secondary metabolites that are important in plant defense (Hahlbrock and Scheel, 1989). These substances and others contribute as antioxidants, with important health properties that are discussed in a later section.

POTATO NUTRITIONAL VALUE

The potato has been widely accepted throughout the world as a staple food and is available in many forms yet many consumers are unaware of the healthful attributes of the tubers. The potato has greater dry matter and protein per unit growing area compared with the cereals (Bamberg and del Rio, 2005). Despite this, consumers tend to believe that potatoes are high in calories and in fat compared with other carbohydrate sources such as rice or pasta; an incorrect assumption since potato has negligible fat and a low energy density similar to legumes (Priestley, 2006). Educational and research efforts are underway to convert consumers to the merits of potatoes or potato products as a replacement for cereals or cereal products in cooked and processed food items. The reader is directed to recent reviews on nutritional aspects of potato, including Buckenhüskes (2005) and the Symposium: Enhancing the Nutritional Value of Potato Tubers (Suttle, 2008 and others). Potatoes are usually eaten cooked, and most often eaten boiled and unpeeled in many regions of the world. The various nutrient components of a 100-gram serving of baked, boiled, and French-fried potatoes are presented in Table 1.

Carbohydrates

Cooked potatoes are a good dietary source of carbohydrates, which make up about 75% of the total dry matter of the tuber. Starch is the predominant carbohydrate in potatoes and serves as an energy reserve for the plant. While cultivated potato averaged 11.0–30.4% starch on a fresh weight basis (mean of 18.8%), wild species ranged from 3.8 to 39.6 with a mean of 18.1% (Jansen et al., 2001). However, these data were not grouped based on maturity type. Maturity type is far more important than remaining genetic variation for tuber yield and starch content (van Eck, 2007). The late-maturing cultivars tend to produce much greater tuber and starch yield compared with the early-maturing cultivars.

Starch is packed in granules that typically contain amylose and amylopectin in a ratio of 1:3. Amylose content in the wild species was 23–37% of the total starch (mean of 29.7%) and 21.9 to 42.7 (mean of 31.2) in the cultivars (Jansen et al., 2001). This indicates some potential for increased amylose through selection among cultivated potato, and potential improvement through breeding. As the crystalline structure of native potato starch is generally impervious to the action of amylolytic digestive enzymes, there is a substantial resistance of raw potato starch to digestion and so it acts physiologically as a "resistant starch." The resistance to amylase digestion is greatly diminished when potato starch is gelatinized following cooking as gelatinization causes loss of crystallinity leading to the solubilization of the starch polymers. Starch quality traits of cooked potato that impact on health include the amylose:amylopectin ratio and the degree of phosphorylation. The branched structure of amylopectin allows for greater digestibility than the linear chain structure of amylose, which leads to a higher glycemic response. Nutritionally, a greater proportion of resistant starch (or more slowly digested starch) is considered advantageous as it provides similar health benefits to fermentable fiber. Resistant starch refers to the summation of starch and starch degradation products that are not absorbed in the small intestine. Upon cooling following cooking, higher-amylose starches have greater retrogradation following processing compared with those with more amylopectin. Retrogradation causes the starch to become more crystalline leading to resistance to digestive enzymes. Higher amylose starches also reduce oil penetration, so are favored for use in snack foods to decrease consumer fat intake (Tarn et al., 2006). Covalently-bound phosphorus is present in potato starch at greater levels (0.08%) than in other plant starches (0.02% in corn) (Li et al., 2006) and is important to the physicochemical properties of starch, affecting its gelatinization and pasting properties (Tarn et al., 2006). Additionally, the phosphorylated glucosyl residue is not susceptible to cleavage by amylolytic enzymes, leading to the release of phosphorylated oligosaccharides and reduced digestibility of gelatinized and raw starch (Kamasaka et al., 1995). Sucrose is the major disaccharide of potatoes while glucose and fructose are the major monosaccharides. The equilibrium between free sugars and starch changes during tuber storage and impacts processing. Too much reducing sugar leads to browning when potatoes are fried.

Protein

Potato protein ranged from 1–1.5% of tuber fresh weight in the 20 cultivars tested (Ortiz-Medina, 2007). Compared with other raw vegetable sources, potatoes are not typically considered to be a good dietary protein source due to their low overall protein content. However, potato protein has excellent biological value (BV), with a BV of 90–100 compared with whole egg (100), soybean (84), and beans (73) (Kasper, 2004; cited in Buckenhüskes, 2005). Patatin is the major storage protein and an allergen for some people. This allergenicity is significantly reduced by heating (Koppelman et al., 2002). The second major potato tuber protein after patatin is a diverse group of low molecular weight proteins that inhibit proteases of the

Table 1 Nutrient content of 100 g (FW) of potato prepared in common styles[a]

Nutrient	Units	Baked, flesh + skin[b]	Boiled in skin, flesh only[c]	French fries, frozen then oven-heated	Daily Reference Value or Reference Daily Intake
Proximates					
Water	g	74.89	76.98	61.51	
Energy	kcal	93	87	172	
Energy	kJ	390	365	721	
Protein	g	2.50	1.87	2.66	50
Total lipid (fat)	g	0.13	0.10	5.22	
Ash	g	1.33	0.92	1.90	
Carbohydrate, by difference	g	21.15	20.13	28.71	300
Total dietary fiber	g	2.2	1.8	2.6	25
Total sugars	g	1.18	0.87	0.28	
Sucrose	g	0.40	0.19	0.18	
Glucose (dextrose)	g	0.44	0.37	0.11	
Fructose	g	0.34	0.30	0.00	
Starch	g	17.27		20.13	
Minerals					
Calcium, Ca	mg	15	5	12	1000
Iron, Fe	mg	1.08	0.31	0.74	18
Magnesium, Mg	mg	28	22	26	400
Phosphorus, P	mg	70	44	97	1000
Potassium, K	mg	535	379	451	3500
Sodium, Na	mg	10	4	32	2500
Zinc, Zn	mg	0.36	0.30	0.38	15
Copper, Cu	mg	0.118	0.188	0.135	2
Manganese, Mn	mg	0.219	0.138	0.210	2
Selenium, Se	mcg	0.4	0.3	0.2	70
Vitamins					
Vitamin C, total ascorbic acid	mg	9.6	13.0	13.3	60
Thiamin	mg	0.064	0.106	0.128	1.5
Riboflavin	mg	0.048	0.020	0.031	1.7
Niacin	mg	1.410	1.439	2.218	20
Pantothenic acid	mg	0.376	0.520	0.522	10
Vitamin B-6	mg	0.311	0.299	0.184	2.0
Folate, total	mcg	28	10	28	400
Vitamin A, RAE	mcg_RAE	1	0		
Carotene, beta	mcg	6	2		
Vitamin A, IU	IU	10	3		5000
Lutein + zeaxanthin	mcg	30	9		
Vitamin E (alpha-tocopherol)	mg	0.04	0.01	0.11	
Vitamin K (phylloquinone)	mcg	2.0	2.1	2.5	
Lipids					
Fatty acids, total saturated	g	0.035	0.026	1.029	20
Fatty acids, total monounsaturated	g	0.003	0.002	3.237	
Fatty acids, total polyunsaturated	g	0.058	0.043	0.321	
Cholesterol	mg	0	0	0	300

[a]Data obtained from the USDA National Nutrient Database for Standard Reference, Release 21 (2008), accessed November, 2008.
[b]A medium baked potato 2.25–3.25 inches in diameter weighs 173 g. The standard U.S. labeling portion is 148 g.
[c]A 2.5 inch diameter boiled potato weighs 136 g without the skin.

Kunitz-type and other enzymes (Pots et al., 1999). Lysine is at greater levels compared with cereal proteins and the sulfur containing amino acids (methionine and cystine) are at lower levels. Chakraborty et al. (2000) described genetically modified (GM) potato transformed with the amaranth gene *AmA1*. These GM potato produced 35–45% more protein than control with 2.5 to 4-fold increased lysine, methionine, cysteine, and tyrosine. These potatoes are being grown in India and are reaching the final testing stages (Gilani and Nasim, 2007).

Lipids and Dietary Fiber

Lipids are only a tiny fraction of potato weight, amounting to approx. 0.15 g/150 g fresh weight (FW); less than cooked rice (1.95 g) or pasta (0.5 g) (Priestley, 2006). Dietary fiber is supplied by cell walls, especially the thickened cell walls of the periderm (peel) which makes up 1–2% of the tuber. These non-lignified fibers may have a role to play in reducing cholesterol levels (Lazarov and Werman, 1996).

Minerals

The minerals present in greatest concentrations in raw potato include (mg/g FW): potassium (564), phosphorus (30–60), calcium (6–18) (Burton, 1989; Buckenhüskes, 2005). The % RDA for these minerals is 22, 6, and 6, respectively (White and Broadley, 2005). Skin-on potatoes are considered a good dietary source of potassium. Rats fed a diet high in sodium (2% sodium chloride) were better able to retain calcium and magnesium and increase urinary pH when fed cooked potato instead of wheat starch due to the high potassium citrate content of the potato (Narcy et al., 2006). Potatoes contain relatively little phosphorus in the form of phytate. Since phytate forms unabsorbable complexes with key minerals such as zinc and iron, potatoes have better bioavailability for those minerals relative to many other plant foods with substantially higher phytic acid content. Biofortification is a relatively recent initiative to improve health in impoverished populations through breeding of micronutrient-rich staple food crops (White and Broadley, 2005). It may be possible to increase the mineral fraction of potato tubers through improved selection among cultivars. For example, zinc is critically important to cognitive skills; its range among cultivars was found to be much wider than previously known, (12.5–20 μg/g DW = 160% spread) (Brown, 2008). Similarly, iron deficiency is common among impoverished populations and not uncommon in the developed world. Brown (2008) determined that iron levels varied significantly among cultivars (18–65 μg/g DW = 373% spread); well beyond previous estimates. Curiously, a link was determined between greater iron levels and red-skinned cultivars. Improved breeding and mineral fertilization are alternative means to increase potato mineral status (White and Broadley, 2005; Brown, 2008).

Vitamins

The predominant vitamin in potatoes is vitamin C (ascorbic acid), which ranges in content between 84 to 145 mg per 100 g dry weight depending on cultivar, planting site, and storage conditions (Augustin, 1975). Vitamin C is important to iron availability, a mineral that tends to be limiting in the human diet (Brown, 2008). Potatoes constitute an important dietary source of vitamin C in many areas of the world. Also present are several B vitamins (folic acid, niacin, pyridoxine, riboflavin, and thiamin) and potatoes can be described as a good dietary source of pyridoxine (vitamin B_6).

Carotenoids and their derivative xanthophylls are diverse lipid-soluble pigments. In potato, xanthophylls are the most abundant carotenoids (Brown, 2008). Two of these pigments, present in low concentration in cultivated potato (β-carotene and lutein), have an important role to play in eye health. Vitamin A deficiency is widespread; more than 124 million children around the world are deficient in vitamin A (Humphrey et al., 1992) leading to various ailments, including blindness, and resulting in premature death. The most potent dietary source of vitamin A (pro-vitamin A) is β-carotene. Lutein is an oxygenated xanthophyll that protects against macular degeneration, the leading cause of visual impairment and blindness in older North American adults (Seddon et al., 1994). Potatoes with yellow flesh contain primarily lutein, with a trace of β-carotene and various other pigments including violaxanthin, zeaxanthin, and others (Brown, 2008) (Table 2). Carotenoid content ranges from 57–750 μg/150 g FW; there are more carotenoids in yellow than white fleshed varieties (Buckenhüskes, 2005). The orange-fleshed potatoes contain zeaxanthin in addition to lutein (Brown et al., 2003). Breeding may increase carotenoid content, as wild species may contain these pigments in greater concentrations (Brown, 2008). In lettuce, both β-carotene and lutein were highly correlated, so selection for higher levels of one could lead to increase in both (Mou, 2005). This relationship has not been examined for potato. It may also be possible to transform potato to increase β-carotenoid content. To this end, Ducreux et al. (2005) reported the transformation of two cv., Desiree and Mayan Gold, with a phytoene synthase gene from *Erwinia* using a patatin promoter. Subsequently, Van Eck et al., (2007) enhanced β-carotene content by RNAi-mediated silencing of the β-carotene hydroxylase gene that converts β-carotene to the less useful zeaxanthin. However, the β-carotene to retinol conversion efficiency (21 μg of β-carotene per 1 μg retinol) proposed for developing countries suggests that a combination of strategies will be necessary to sufficiently improve the pro-vitamin A content of potato for populations at risk of vitamin A deficiency (Van Eck et al., 2007).

Table 2 Antioxidant compounds in potatoes

Category	Individual compounds
Proteins	patatin
Vitamins	ascorbic acid
	dehydroascorbic acid
	folic acid
Phenolic acids	caffeic acid
	chlorogenic acid
	p-coumaric acid
	ferulic acid
	gallic acid
	protocatechuic acid
	vanillic acid
Flavonoids (Flavan-3-ols, Flavonols and Anthocyanins)[a]	catechin
	cyanidin
	delphinidin
	malvidin
	malvidin-3-(*p*-coumaroyl rutinoside)
	pelargonidin
	peonidin
	petunidin
	rutin
Carotenoids (Xanthophylls)[b]	antheraxanthin
	B-carotene (trace)
	lutein
	neoxanthin
	violaxanthin
	zeaxanthin

[a]In potatoes with red, blue or purple color.
[b]With the exception of lutein, B-carotene, and violaxanthin found in potatoes, with yellow- orange flesh.

Phytochemicals

Phytochemicals are secondary products of plant metabolism, many of which are implicated in human health as antioxidants. These vary in amount and composition among potato cultivars (Al-Saikhan et al., 1995; Brown et al., 2003; 2005; 2008). Chu et al. (2002) estimated 124.5 mg vitamin C equivalent/150 g FW potato; 13% from vitamin C and the balance from carotenoid and phenolic substances.

Anthocyanins are red, blue, and purple pigments that can be found in the skin and flesh of certain cultivars. These are important in plant and human health, contributing important antioxidant properties (Brown et al., 2003; Brown, 2005; 2008). Total anthocyanin concentrations in Andean potatoes ranged from 14–16,330 μg/g DW (Andre et al., 2007). Anthocyanins are water-soluble and usually occur in their glycosylated and acetylated forms. Reyes and Cisneros-Zevallos (2007) evaluated extracts from red and purple potatoes and concluded that they were a potential source of natural color. The genetic systems influencing anthocyanin production in potatoes have been summarized by De Jong (1991) and Brown (2005). Usually, cultivars high in anthocyanins are low in carotenoids and vice versa, although breeding efforts were able to overcome this negative correlation (Brown, 2008).

Phenolic acids and polyphenols play important roles in plant health, cooking properties, and human health (Friedman, 1997). Chlorogenic acid is the predominant phenolic compound in potatoes, as in other Solanaceous species such as eggplant (Prohens et al., 2007). Chlorogenic acid, catechin, caffeic acid, ferulic acid, gallic acid, and malvidin were the major phenolics isolated from methanol/water extracts (Reddivari et al., 2007; Leo et al., 2008). Total antioxidant activity was correlated with total phenolic content. In addition to the free-form phenolic compounds such as chlorogenic acid and caffeic acid, bound-form phenolics such as ferulic acid that is ester-linked to cell wall polysaccharides is also present in potatoes and contributes to the radical scavenging activity of potato (Nara et al., 2006).

Natural Toxicants and Allergens

Glycoalkaloids are nitrogenous compounds contained by potatoes and other members of the Solanaceae family. The primary glycoalkaloids in potatoes are α-chaconine and α-solanine. The ratio of these compounds varies and they are localized in the skin. New cultivars are screened for their total glycoalkaloid content (TGA) due to concerns about the effects of these compounds on human health. Friedman (2006) reviewed these compounds and noted that their effects in humans can be both deleterious and beneficial (Table 3). Grunenfelder et al. (2006) dispelled the myth that green potatoes contain higher levels of glycoalkaloids. Chlorophyll and glycoalkaloids both accumulate in potato skins in the presence of light but they do so independently.

Lectins are glycoproteins that bind chitin and therefore serve as plant protectants. *S. tuberosum* agglutinin (STA) is the primary potato lectin. Wounding of the tubers produced additional chitin-binding compounds (Millar et al., 1992). Recently, a mechanism of lectin interaction with immunoglobulin E was proposed to explain the non-allergic hypersensitivity of some consumers to potatoes (Pramod et al., 2007).

Table 3 Potential health effects of glycoalkaloids, primarily α–solanine and α–chaconine

Beneficial effects	Harmful effects
decreased serum glucose	cholinesterase inhibition
antibiotic	teratogenicity
cancer cell growth inhibition	intestinal inflammation
reduced serum cholesterol levels	nausea
anti-inflammatory	
anti-pyretic	

Allergies to potatoes appear to be relatively uncommon. Patatin (Sol t 1) is the primary storage protein (Shewry, 2003) and the major allergen in potatoes. Patatin may induce allergic symptoms during potato peeling (Seppälä et al., 1999). Four other proteins (Sol t 2, Sol t 3.0101, Sol t 3.0102, and Sol t 4) are related to soybean trypsin inhibitors and may cause reactions in atopic children (Seppälä et al., 2001). Patatin may be cross-reactive for persons with allergy to latex, and children with atopic dermatitis appear to have increased sensitivity to this potato protein (Schmidt et al., 2002). Twelve infants with atopic dermatitis and suspected potato allergy were found to have positive responses to both raw and cooked potato (Majamaa et al., 2001). De Swert and colleagues (2007) reported that most infants with potato allergy develop tolerance to cooked potato at 4 years of age and that potato allergy could be a risk factor for future pollen allergy. An investigation of extracts from wild and GM potatoes revealed an incidence of positive skin prick responses in 5.7% of persons with diagnosed allergy disorders (Lee et al., 2006). No differences were observed between the wild and GM potato extracts. Boiling and exposure to simulated gastric fluid greatly reduced protein and IgE-binding. This agreed with previous reports of allergic responses to consumption of raw potatoes. Potatoes were recommended as a "safe" food for persons with an allergy to lipid transfer protein, a highly cross-reactive plant allergen (Asero et al., 2007).

POTATOES AS FOOD

Potatoes are prepared by consumers in an overwhelming variety of means. Baking, boiling, dehydrating, and frying are employed world-wide. Commercial processes are addressed in many texts including Woolfe (1987), Lisińska and Leszczyński (1989), and Gopal and Khurana (2006). Examples of commercial potato products are listed in Table 4.

Processing Effects on Nutrient Composition

Cooking or processing of potatoes greatly improves the digestibility of potato starch, which has very low digestibility in

Table 4 Processed potato products

Category	Products
Fresh/refrigerated	hash browns
	gnocchi
	steamed or baked whole, halved, cubed
	steamed and mashed
	pancakes and latkes
	cake
	knishes
Frozen	cakes
	French fries, home fries
	hashed browns
	pierogies
Dried	cubes
	flakes (instant mashed)
	flour
	granules
	starch
	slices
Shelf-stable	bread
	chips/crisps
	extruded snacks
	sticks
Beverages	vodka
	wine

the raw state since potato starch granules have a β-crystalline structure that is resistant to amylase digestion (Englyst et al., 1992). In general, unpeeled potatoes that undergo cooking have better nutrient retention than do peeled potatoes and size reduction brings about further losses. Boiling cut or peeled potatoes leads to loss of water-soluble vitamins and minerals due to their leaching out into the cooking water. Losses of minerals occur only via boiling with the greatest losses occurring for potassium and copper (Finglas and Faulks, 1984). Baking, roasting, and frying generally result in lower losses of vitamins than boiling. Conventional frying or chipping of potatoes in oil such as for French fries and chips typically increases fat content within a short period. The fiber content of potatoes, which is nutritionally significant, is reduced greatly by peeling. Ascorbic acid concentration is reduced as cooking time and temperature increase (Han et al., 2004). Microwave cooking produced the smallest losses of ascorbic acid in three Korean cultivars; boiling caused losses of 77.2–88.4%.

Persons who undergo kidney dialysis must limit their potassium consumption. Patients have been advised to soak potatoes in water to help leach some of this mineral out. However,

Table 5 Strategies for controlling acrylamide formation in potato products[a]

Intervention
Selection of cultivars low in asparagine and glucose
Removal of precursors prior to processing
Optimization of food processing to prevent acrylamide formation
Addition of ingredients that inhibit acrylamide formation
Removal of acrylamide post-processing

[a] Adapted from Friedman and Levin (2008).

leaching alone does not result in significant losses of potassium (Bethke and Jansky, 2008). Boiling cubed potatoes reduced potassium levels by an average of 50%; shredding potatoes to increase surface area before cooking resulted in 75% loss of the mineral. Conversely, persons with normal kidney function who wish to maximize potassium should cook whole potatoes and minimize boiling time to reduce leaching. Due to their naturally high ratio of potassium to sodium content, potatoes are useful in sodium-restricted diets.

Fresh-cut, minimally-processed potatoes are available in many forms, including diced, sliced, and shredded. Polyphenol oxidase may react with substrates (tyrosine, chlorogenic acid) to discolor the cut pieces. Enzymatic browning could lead to substantial losses of amino acids, which could be minimized by immediate cooking of the cut potatoes or their immersion in water. Cutting potatoes increased the activity of phenylalanine ammonia lyase (PAL) with subsequent increase in antioxidants (Reyes et al., 2007). Quercetin glycosides, total flavonols, and caffeic acid derivatives increased in fresh-cut potatoes stored at 4°C for 6 days (Tudela et al., 2002). Light inhibited wound-induced phenolic biosynthesis, suggesting that opaque packaging may be desirable for fresh-cut potatoes to maximize antioxidants in products destined to become home fries and mashed potatoes. Wounded *cv.* All-Blue retained more anthocyanins when stored in the dark than in the presence of light (Reyes and Cisneros-Zevallos, 2003). New potatoes produced fewer phenolic compounds than did potatoes from long-term storage. Cutting potatoes leads to loss of ascorbic acid in the presence of oxygen. Excessive enzymatic browning coupled with the loss of vitamin C makes the normal atmosphere impractical for commercial use (Tudela et al., 2003). Vacuum packaging of fresh-cut potatoes retained up to 89% of the original vitamin C content and light color was maintained.

Compared with uncooked potatoes, all methods of cooking produced significant losses of total flavonoids (Tudela et al., 2002). Boiling, steaming, and frying led to retention of 4–16 mg of quercetin derivatives and 6–30 mg of caffeic acid derivatives per serving; microwaving resulted in fewer flavonoids than did boiling and steaming. Boiling potatoes in varying volumes of water did not seem to affect the magnitude of chlorogenic acid that leached into the cooking water (Andlauer et al., 2003). Despite losses, cooked potatoes contribute substantial amounts of flavonols to the diet. Brown (2005) reviewed storage and cooking factors impacting potato antioxidants. After-cooking darkening (ACD) is a defect for some cultivars that are exposed to air after processing (boiling, baking, frying, and dehydrating). This color change involves oxidation of ferrous-chlorogenic acid to a bluish-grey ferri-dichlorogenic compound that depends on the ratio of chlorogenic to citric acid (Wang-Pruski and Nowak, 2004). Cultivar and storage duration were more important than management practices in affecting ADC (Wang-Pruski et al., 2007).

Glycoalkaloid content is affected by certain types of processing. Friedman and McDonald (1999) reviewed the effect of processing methods on glycoalkaloids in potato products. Peeling and slicing contributed most to reducing total glycoalkaloid (TGA) content during French fry production (Pêska et al., 2006). However, washing and blanching significantly reduced nitrates. Early-season cultivars tended to have lower TGA levels, and a doubling of nitrogen fertilizer increased TGA by 10% (Tajner-Czopek et al., 2008). Peeling and cooking resulted in greater losses of the more toxic solanine compared with chaconine.

Use of Processed Peels as a Food Item

Potatoes used for chipping usually have thin skins that are relatively easily removed through abrasion. In the French fry industry, potato peels are removed through steam-peeling. Since dried peels are 50% dietary fiber (Camire et al., 1993) and a good source of phenolic acids and other antioxidants (Kanatt et al., 2005), several researchers have investigated their use as food additives to improve nutritional quality or to retard lipid oxidation. Potato peel aqueous extract was demonstrated to be equally effective to BHA in preventing oxidation of sunflower oil, which was attributed to the high content of polyphenolic compounds. For example, freeze-dried aqueous potato extract contained phenolic acid content of 3.43% that consisted of chlorogenic, caffeic, gallic, and protocatechuic acids at concentrations of 50.3%, 41.7%, 7.8%, and 0.21%, respectively, of the total phenolic content (Rodriguez de Sotillo et al., 1994). Extruded peels were more effective in minimizing peroxide values in oatmeal cookies than dried peels at the same levels of addition (10%) (Arora and Camire, 1994). Potato peel extracts were used to limit lipid oxidation in irradiated lamb meat (Kanat et al., 2005).

Peels processed by extrusion cooking after drying bound bile acids (Camire et al., 1993) and the carcinogen benzo[a]pyrene in vitro (Camire et al., 1995). An extract from potato peels ameliorated oxidative damage to rat erythrocytes and human erythrocyte membranes (Singh and Rajini, 2008). Inclusion of 10% potato peels in a diet fed to diabetic rats helped normalize some aspects of oxidative stress (Singh et al., 2005).

While potato flesh contains free phenolics, peels contain bound:free phenolic acids in a ratio of about 1:3 (Nara et al., 2006). The bound forms are present as β-glycosides that are resistant to upper gastrointestinal digestion but can be absorbed following colonic microbial metabolism (Chu et al., 2000). Peels may not contain the only antioxidant by-products of potato processing. Hydrolyzed potato protein, a by-product of the potato starch industry, retarded oxidation in beef patties by $>40\%$ (Wang and Xiong, 2005).

Sensory Qualities

Potato sensory properties and methods of analysis have been reviewed by Arvanitoyannis et al. (2008). Much of the literature on sensory properties of potatoes has been conducted as part of established potato breeding programs. Typically, new cultivars are screened to have safe glycoalkaloid levels before consumers evaluate them. High glycoalkaloid content results in bitter taste and even burning sensations (Friedman, 2006). Phenolic acids contribute to bitter flavors in some potatoes. Taste thresholds of chlorogenic and ferulic acid in dehydrated mashed potatoes were 82 and 62 mg/L, respectively (Work and Camire, 1996). Addition of margarine to the mashed potatoes increased the taste threshold for chlorogenic acid only. Glutamate, aspartate, and nucleotides contributed to off-flavor in boiled potatoes (Morris et al., 2008).

Food Safety Concerns

Reported food safety issues have been relatively rare for potatoes and their products. Quality assurance procedures are in place in many potato-producing nations to address food safety concerns for products such as potato. For example, the Can-Trace initiative in Canada enables identification and response to food safety issues and concerns from the farm-level through to the retail and food service industries (AAFC, 2007). Prior to harvest, various chemical fertilizers are incorporated into the soil to stimulate plant growth. Pesticides are applied to the leaves of plants to deter predation from Colorado potato beetle and other insects, and inhibit fungal growth, including late blight. Post-harvest, sprout inhibitors may be applied. Isopropyl N-(3-chlorophenyl) carbamate (also called chlorpropham or CIPC) is the primary sprout inhibitory agent used (Kleinkopf et al., 2003). At the time of harvest, the peel may have residual nitrates and chemical sprout inhibitors (Lang, 1992). Washing, blanching, and cooking all helped to reduce pesticide levels in Egyptian potatoes (Soliman, 2001).

Contaminants Following Cooking

A review on the microbiology of potato products noted that many pathogenic bacteria and fungi have been isolated from potato (Doan and Davidson, 2000). The surface of raw tubers may be contaminated with pathogens from the soil in which the potatoes were grown or during handling following harvest. Microbial problems in cooked potatoes are not common, although they can be problematic in some processed products. *Bacillus cereus* was found in 10–40% of dehydrated potatoes, and poses a problem for reconstituted mashed potatoes (King et al., 2007). *Salmonella* strains were identified in potatoes prepared for home dehydration (DiPersio et al., 2005). Blanching prior to dehydration greatly reduced microbial counts.

Similarly, microbial problems in prepared foods containing potato are unusual, unless these products are improperly handled. For example, *Clostridium botulinum* growth in gnocchi made with potato flakes was controlled by 8°C storage and inclusion of sorbate at 0.09% (w/w) (Del Torre et al., 2004). A heat-resistant type of *Staphylococcus aureus* was associated with the illness of more than 100 persons in India who consumed fried potato balls; the food handler apparently spread the bacteria to the food (Nema et al., 2007). Several recalls of refrigerated potato products such as mashed potatoes and home fries due to contamination with *Listeria monocytogenes* have occurred in the U.S. in the past few years. Ozone treatment of potatoes offers promise as a means to control pathogens in processed potatoes (Selma et al., 2006).

Acrylamide

Swedish researchers first reported that acrylamide, a common industrial chemical, can be found in many heated carbohydrate-rich foods (Tareke et al., 2002). French fries and potato chips had some of the highest acrylamide levels reported, spurring numerous studies on the mechanisms of acrylamide formation in foods as well as its mitigation (Lineback et al., 2006). There is generally consensus that asparagine as a free amino acid reacts with reducing sugars in the presence of heat to form acrylamide through a complex pathway involving Maillard and related reactions (Stadler et al., 2002; Zyzak et al., 2003). Although potatoes generally contain both free asparagine and reducing sugars, there exists a wide variability in these acrylamide precursors among potato cultivars. Kennebec and White potatoes have very low levels of both asparagine and reducing sugars (Vivanti et al., 2006). Friedman and Levin (2008) have summarized intervention strategies to control acrylamide levels in potatoes and other foods (Table 5). While it appears prudent to limit acrylamide in heat processed potato products, there is still controversy surrounding the role of dietary acrylamide in carcinogenesis. Epidemiology has revealed no association with dietary acrylamide and risks for breast (Hogervorst et al., 2007; Olesen et al., 2008), bladder and prostate (Hogervorst et al., 2008a), or gastrointestinal cancers (Hogervorst et al., 2008b). Some increased risk for endometrial and ovarian (Hogervorst et al., 2007), and renal cell cancers (Hogervorst et al., 2008a), have been identified. Mucci and Wilson (2008) noted that none of these studies found a risk due to consumption of a specific group of foods, including potato products. Physiologically-based pharmacokinetic/pharmacodynamic modeling could not support a link between dietary acrylamide exposure and human neurotoxicity; lifetime excess risks ranged $1.0\text{-}3.9 \times 10^{-4}$ average human tumor incidence (Doerge et al., 2008). The U.S. Food and Drug Administration researchers concluded that consumers should continue to follow the advice to eat a balanced and varied diet that is low in trans fat and saturated fat and rich in whole grains, fruits, and vegetables.

CONTRIBUTION OF POTATOES TO HUMAN HEALTH

Beyond the nutritional properties of a quality staple food, potato may have a role to play in human health over a lifetime of consumption. Potato has been implicated in contributing to diabetes and obesity because of its high glycemic index. On the other hand, it is lauded for its contribution to preventing malnutrition and promoted as a healthy food item. This is primarily due to the presence of vitamins and minerals, and the content of antioxidants, with their free-radical scavenging characteristics. These antioxidants may slow the onset of age-related chronic diseases including certain cancers, cardiovascular disease, and diabetes.

Potato and Energy Metabolism

The glycemic index (GI) is a research tool developed by Jenkins et al. (1981) to assess the impact on blood sugar levels from a serving of any food containing 50 grams of carbohydrate. Procedures for GI and related measures have been reviewed (Kendall et al., 2006; Monro and Shaw, 2008). GI values for potato vary greatly due to compositional differences among cultivars and methods of food preparation. For example, GI values ranged from 56 to 94 for eight British cultivars (Henry et al., 2005). Lower GI values were reported for waxy than for firm or floury types. New potatoes, which are smaller than most potatoes, had lower GI compared with other cultivars (Sohl and Brand-Miller, 1999). When boiled red potatoes were served hot to volunteers, a GI of 89.4 was found based on glucose = 100 scale (Fernandes et al., 2005). When cooking is followed by cooling, amylose retrogrades to produce resistant starch. The GI response was only 56.2 when cooking was followed by refrigeration of 12–24 hours. This phenomenon slows postprandial glucose release from cooked potatoes. Low GI diets have been associated with decreased risk of obesity, cardiovascular disease, and type-2 diabetes. In addition, intervention trials have demonstrated improvements in certain metabolic risk factors (Aston, 2006). However, despite commercial efforts to exploit GI, the value of GI to prevent or treat obesity and diseases remains controversial. The need for improved methodology was cited by van Bakel et al. (2009) to obtain better estimates of GI and glycemic load (GL) for epidemiology research.

Potatoes may have a role in controlling appetite and therefore weight gain, by contributing to satiety. Satiety is the feeling of fullness and the loss of hunger that occur after eating. Many factors influence satiety, including the rate of gastric emptying, and the proportion of macronutrients in the food. Foods that increase satiety are thought to promote weight control by delaying subsequent meals and total calories consumed. A study with 13 volunteers compared the effects of isocaloric test meals containing potatoes prepared by several methods: oven-baked French-fries, boiled and mashed with varying quantities of water (Leeman et al., 2008). Postprandial satiety after 3 hours was least for the French fries and greatest for the boiled potatoes on an equivalent-energy basis, but no differences were found when various types of potato were fed as carbohydrate-equivalent meals. Men fed several test meals consumed less energy during the boiled potato arm of the study than when pasta or white rice was eaten as the side dish (Erdmann et al., 2007). The potato meal resulted in lower post-prandial serum insulin and higher ghrelin levels. This latter study contrasts with short-term intervention studies. These have generally indicated that high GI meals decrease satiety, and increase the return of hunger and energy intake at a later meal, in comparison with low glycemic index meals containing potatoes (Roberts, 2000). Conversely, longer-term studies on the effects of low and high GI diets, matched for fiber and macronutrient composition, among free-living subjects have not shown effects on body weight. For example, a randomized crossover intervention study that included two consecutive 12–week periods showed that lesser or greater *ad libitum*-fed glycemic index diets made equivalent in macronutrient composition, fiber content, or energy density, had no impact on body weight, fat mass, satiety, or energy intake in overweight/obese women (Aston et al., 2008). A systemic review of 31 short-term and 20 long-term clinical intervention trials demonstrated no consistent impact of low versus high GI diets on either satiety or body weight control (Raben, 2002).

In a short-term study, obese children consumed significantly more energy after a test lunch containing rapidly-digested carbohydrates (mashed potato, meat, nectar) than after one with more slowly digested carbohydrates (spaghetti, meat, orange) (Alviña and Araya, 2004). It seems that appetite was stimulated and increased caloric intake promoted by the more rapidly digested meal. However, more research is required to determine whether high GI meals can generate similar findings on energy intake on a longer-term basis.

Potato chips and French fries have been implicated by several nutritionists as major contributors to obesity as these products contain a high fat and caloric content. In a Canadian study of elementary school-aged children in a First Nations community, obese children ate 50% more French fries on a weight basis ($p \leq 0.05$, analysis of covariance) than the normal-weight children (Receveur et al., 2008). Children's preference for French fries may be related to food neophobia and avoidance of vegetables (Dovey et al., 2008).

In summary, potato is a healthy component of a varied diet. As a starch food item, it should be consumed in moderation and without excess lipid additions. A meal containing potato contributes to satiety. Potato servings do not in themselves promote obesity; excess starchy food and especially food laden with high-calorie lipid additions is the culprit. Excluding potatoes from the diets of persons attempting weight loss is not warranted based on their carbohydrate content. Samaha et al. (2007) concluded that carbohydrate restriction would be of greatest benefit for persons with insulin resistance syndromes.

Prevention of Nutrient Deficiencies

Vitamin C is often lacking in the diet of individuals without access to fresh produce. Potato had a role in prevention of scurvy from its first contact with Europeans. Despite destruction of ascorbic acid during cooking and a moderate content compared with some other fruits and vegetables, potato plays a critical nutritional role as the primary source of vitamin C in many countries. The importance of potato in contributing vitamin C is partly because they can be stored, allowing potatoes to be a regular item in the diet. It is estimated that potatoes provide, on average, over 50% of the daily ascorbic acid requirement in the USA and about 20% of the dietary intake in Europe (Love and Pavek, 2008). In developing countries, seasonal variations in plasma ascorbate have been related to deterioration in ascorbic acid content of potatoes in locations where refrigeration is relatively unavailable (FAO, 2002). In Glasgow, Scotland, the WHO MONICA project compared plasma vitamin C levels with items from a food frequency questionnaire (Wrieden et al., 2000). Citrus products and other vegetables were major sources of vitamin C for persons with optimal levels of the vitamin, but potatoes and fried potatoes (chips) contributed about 17–18 mg per day of ascorbic acid in the diets of adults with low and marginal vitamin plasma C. The researchers concluded that dietary advice to avoid eating fried potatoes should also contain recommendation of other foods to replace the vitamin C provided by the chips. Cooked, peeled, or unpeeled potatoes, offer 11–12 mg vitamin C per 100 g product (Biesalski, 2005; cited in Buckenhüskes, 2005). Potatoes are a component of many traditional Indian recipes. Vegetable dishes containing potatoes contribute about 34 mg of ascorbic acid per 100 g in the Punjab region (Gupta and Bains, 2006). Loss of vitamin is affected by cooking method, so opportunity may exist to increase nutrient retention via education about different cooking procedures.

Potatoes contain significant amounts of folic acid (folate; vitamin B_9). Potato consumption was significantly associated with adequate serum folate status in Cretan adults (Hatzis et al., 2006). Consumption of at least 122 g of potatoes produced the same odds ratio (0.41) for low serum folate as did consumption of at least 190 g of other vegetables, suggesting that potato should be promoted more heavily for its folate contribution.

Human dietary intake of vitamin A and the essential minerals iron and zinc is often insufficient. These deficiencies or low intakes usually occur in populations where diets are primarily plant-based (Nicolle et al., 2004). Increased level of micronutrients in vegetables such as potato would most benefit these populations. Iron deficiency is a global health concern for children and premenopausal women. Although potato is not typically considered a good source of dietary iron, iron uptake is enhanced by ascorbic acid. So, increasing ascorbic acid levels in vegetables such as potato may contribute to alleviating human iron deficiencies (Nicolle et al., 2004; Brown, 2008). Alternatively, several native Andean varieties contained significant levels of iron and zinc (Burgos et al., 2007). Genotype had a greater influence on mineral content than environment, suggesting that new varieties could be developed with enhanced iron and/or zinc content. Cooking did not generally reduce concentrations of either mineral. The researchers calculated that consumption of genotypes with the highest iron level could provide 6.88 and 1.72 mg per day for women and children, respectively. Provision of 38% of the Daily Value for iron would qualify this potato for the following U.S. iron content claims: excellent source of iron, rich in iron, and high in iron.

Zinc deficiency impairs development. Andean potato varieties vary in their zinc content, but some are relatively high in this mineral (Burgos et al., 2007). Based on a daily consumption of 200 g by Peruvian children aged 1–3 years, and 800 g by women, the variety with the greatest zinc content could theoretically provide 29% and 87%, respectively, of the corresponding recommended nutrient intake (RNI) for those demographic groups.

Potato has an important role to play in preventing malnutrition, especially in impoverished areas of the world. Although potato has a relatively low energy density, it has negligible fat, contains quality protein, fiber, and vitamins, especially vitamin C and the B-group vitamins, minerals, especially potassium, and important phytochemicals, many of which have antioxidant properties. Potato is important to global nutrition and health.

Antioxidants and their Relation to Health

Reactive oxygen species are indicated to be key modulating factors responsible for the development of many important age-related and inflammatory disease conditions such as arthritis, atherosclerosis, cancers, cardiovascular diseases, diabetes, gastrointestinal disorders and neurodegenerative dysfunctions (Packer, 1995). Potatoes contain a diverse mixture of antioxidants (Brown, 2005; 2008) (Table 3), which exhibit multiple antioxidant activities including superoxide scavenging capability, ferrous ion chelating effects, and strong reducing capacity (Singh and Rajini, 2004). Polyphenolic compounds provide a large portion of the antioxidant action of potatoes and their extracts by scavenging and neutralizing free radicals, decomposing lipid peroxides, and quenching singlet oxygen (Cao et al., 1997). Although phenolic compounds contributed greatly to the total antioxidant activity in four Italian early potato cultivars, carotenoids and ascorbic acid were also major contributors (Leo et al., 2008). Differences in antioxidant content were found due to cultivar and growing site.

Potato cultivars and wild *Solanum* species with flesh that is purple or red and solidly-pigmented are particularly high in anthocyanin content (Brown, 2005). Antioxidant capacity has been directly related to anthocyanin content in potatoes (Brown et al., 2003). Drum-dried potato flakes from both a light purple (KM) and darker purple (H92) potato cultivar had significant in vitro antioxidant activity, but only the antioxidant activity of sera from rats fed the darker flakes were higher than those of rats fed a control diet (Han et al., 2006b). Liver lipid oxidation was also lower in the H92-fed animals. In a related study, rats fed a purple potato (cv. Shadow-Queen) diet had lower oxidation levels in both sera and liver, but white potatoes (cv. Toyoshiro) also reduced serum urate levels (Han et al., 2007a). Extracts from a red potato cultivar (Hokkai no. 91) ameliorated galactosamine-induced liver damage in rats (Han et al., 2006a). Potato flakes from the red cv. Northern-Ruby reduced serum lipid oxidation and increased hepatic superoxide dismutase (SOD) mRNA (Han et al., 2007b).

Consumption of foods rich in antioxidants is expected to increase antioxidant levels in vivo. Malondialdehyde (MDA) levels as an index of *in vivo* lipid peroxidation were higher in the plasma of elderly Spanish citizens who ate 29.8 grams of potatoes or more daily (Lasheras et al., 2003). Glycoalkaloids or other toxins in potatoes and differences in cooking methods were proposed as sources of the oxidative damage. A review of MDA as a biomarker for oxidative stress concluded that day-to-day and within-subject variation limited the applicability of the assay for assessment of individuals (Nielsen et al., 1997). While the assay may be suitable for estimating oxidative stress in a population, it is not clear whether the 162 subjects in the Spanish study were an adequate sample of the population. However, residents of the Canary Islands consume an average of 143.2 grams of potatoes per person per day, which is higher than that for the general Spanish population (del Mar Verde Méndez et al., 2004). Potatoes contribute an estimated 19% and 14% of the recommended amount of flavonoids for men and women in the Canary Islands, based upon the levels of (+)-catechin measured.

Potato and Prevention of Cancer

Consumption of produce is associated with reduced risks for prostate cancer, which is a leading cause of cancer deaths among men in the United States. Extracts from four specialty potatoes and the anthocyanin fraction from genotype CO112F2-2 reduced cell growth and induced apoptosis in both androgen-dependent (LNCaP) and androgen-independent (PC-3) prostate cancer cell lines (Reddivari et al., 2007). The anthocyanins appear to cause mitochondrial release of the proteins Endo G and AIF that promote apoptosis. Likewise, intake of anthocyanins from purple and red potatoes might play a protective role against stomach cancer. Intake of steamed purple and red potatoes repressed the growth of mouse stomach cancer induced by benzo(a)pyrene (Hayashi et al., 2006). Isolated anthocyanins induced apoptosis in human stomach cancer cell lines as well as suppressing benzo(a)pyrene-induced mouse stomach cancer proliferation indicating that anthocyanins were the bioactive anti-tumor components. No induction of apoptosis was observed upon exposure to normal lymphocytes prepared from healthy volunteers. The exact anthocyanins involved in the anti-tumor properties remain to be delineated as there are approximately ten and eight different types of pigment present in the purple and red potato anthocyanin fractions, respectively.

The role of vegetable consumption in prevention of cancer has not reached consensus in the scientific community. Methanol-water extracts from four Italian short-season potato cultivars inhibited the proliferation of MCF-7 breast cancer cells (Kallio et al., 2008). Extracts from cv. Nicola were most effective, but concentrations above $1 \times 10^{-3} \mu g$ gallic acid equivalents μL^{-1} stimulated cell growth. Potato glycoalkaloids inhibited the growth of human colon (HT29) and liver (HepG2) cancer cells (Lee et al., 2004), and human cervical, liver lymphoma, and stomach cancer cells (Friedman et al., 2005). Alpha-chaconine reduced lung cancer metastasis in vitro by suppressing metabolic pathways (Shih et al., 2007) and induced apoptosis of human colon cancer cells via activation of caspase-3 and inhibition of signaling compound ERK 1/2 (Yang et al., 2006.)

Although cooking inactivates lectins, these compounds may also help to reduce cancer risks. Lectins induce apoptosis and limit the synthesis of proteins, DNA, and RNA in cancer cells (De Mejía and Prisecaru, 2005). Potato lectin reduced the viability of human hepatoma, human choriocarcinoma, mouse melanoma, and rat osteosarcoma cells, but was not as effective as other lectins with different carbohydrate-binding characteristics (Wang et al., 2000). While in vitro assays have limitations, these findings suggest that glycoalkaloids and lectins in potatoes may not be as menacing as once thought.

Fried potato products may contain acrylamide. For example, Korean potato chips were found to contain as much as 4.0 μg/kg acrylamide (Lee and Shim, 2007). The controversy surrounding the risks of consumption of dietary acrylamide were discussed previously.

In summary, relatively little has been published regarding the long-term cancer–related health effects of potato in diets of consumers around the world. Scattered, relative short-term studies have implicated potato anthocyanins, glycoalkaloids, and lectins as anti-tumor agents while concerns have been expressed regarding trace quantities of acrylamide in cooked starches.

Potato and Prevention of Cardiovascular Disease

Although many factors affect the status of the heart and circulatory system, maintenance of normal serum lipids and blood pressure are essential for health. The many adverse effects of dietary fat on the cardiovascular system were reviewed by Damjanovi and Barton (2008). Potato products with high lipid content should be minimized in the diet. Ideally, for cardiovascular benefit, potato should be prepared to contain low fat and sodium. Relatively high levels of potassium are needed to counteract the effect of sodium and protect against hypertension. Like leguminous seeds and various root vegetables (Nicolle et al., 2004), potato is an excellent potassium source. Retention of potassium during cooking was best in whole boiled potatoes compared with cut boiled product (McGinnis, 2008).

Rats fed potato peels for 4 weeks showed less plasma cholesterol (40% decrease) and less hepatic fat cholesterol (30% decrease) compared with cellulose-fed rats (Lazarov and Werman, 1996). Rats fed a diet with 78% potato for 3 weeks to evaluate the vegetable's role in lipid metabolism had lower plasma cholesterol and triglycerides and reduced liver cholesterol than control rats (Robert et al., 2006). The test animals excreted more neutral sterol, particularly coprostanol, indicating a possible mechanism for cholesterol reduction. Plasma vitamin E and FRAP antioxidant levels were greater in the potato-fed rats, demonstrating additional cardiovascular benefit to potato consumption. Drawbacks to this study included the differences in rat lipid metabolism compared with that of humans, and the extremely high levels of potato in the test diet. The lowered plasma cholesterol concentrations in potato-fed rats could be partly related to lipid lowering properties of potato protein (Morita et al., 1997). Potato protein was demonstrated to exert potent fecal bile acid and neutral steroid excretion properties relative to other proteins including soy and casein, which was related to the relatively lower methionine content and methionine-to-glycine ratios in potato protein.

Another rat feeding study compared three diets: potato-, starch-, and sucrose-based (Robert et al., 2008). Rats on the potato diet for 3 weeks had lower cholesterol and triglycerides than those fed the control or sucrose diets. Antioxidant status and short chain fatty acids were greater in the potato-fed animals. Potato starch phosphorylation may also play a role in controlling serum lipids. Kanazawa and colleagues (2008) fed rats on diets containing different types of starch. Serum-free fatty acids, triglycerides, and liver triglycerides were less in the animals fed a Hokkaikogane potato starch with a phosphorus content of 8,136 mg/L. Triglyceride HDL was also less in that treatment group. Potato starch increased fecal bile acid excretion but starch type had no effect on cecal short chain fatty acid synthesis or pH. So, it appears that potato starch that contains a high level of phosphorus exhibits lipid-lowering properties but not the cecal fermentation-promoting effects of resistant starch. The plasma lipid-lowering effects could be attributable to slower digestion of gelatinized high-phosphorus potato starch. The phosphate residue on the carbon-3 hydroxyl group imparts relative resistance to hydrolysis by α-amylase (Takeda et al., 1983).

Potato processing by-products can be rich sources of dietary fiber. Potato peels from a French fry processing plant were evaluated for their ability to bind bile acids in vitro (Camire et al., 1993). Although dried peels bound some bile acids, extrusion cooking enhanced peel binding of cholic, deoxycholic, and glycocholic acids; binding of deoxycholic acid was highly correlated with total dietary fiber and insoluble dietary fiber content. All peels bound a smaller percentage of bile acids than did the drug cholestyramine. Residue from potato starch production in Japan had different effects on lipid metabolism of rats fed the pulps at a 15% level for 4 weeks (Hashimoto et al., 2006). Residue from *cv.* Benimaru potatoes increased fecal bile acid production while *cv.* Hokkaikogane pulp inhibited fatty acid synthesis.

Inflammation is another risk factor for cardiovascular disease. Although many biomarkers for inflammation exist, high-sensitivity C-reactive protein (CRP) has received the most attention as a predictor for cardiovascular disease. When BMI was controlled for in a study of Australian adults, potato intake was associated with lower CRP levels (Hickling et al., 2008). Potato antioxidants may be responsible for lowering inflammation. Rats fed isolated potato peptides showed greater serum HDL-cholesterol and fecal steroid output and less non-HDL cholesterol (Liyanage et al., 2008). The results were attributed to inhibition of cholesterol absorption, possibly via suppression of micellar solubility of cholesterol.

Peptides isolated from potato tubers exhibited angiotensin-converting enzyme (ACE) inhibition in vitro (Pihlanto et al., 2008). Inhibition was lowest in isolates from immature (new) potatoes, and increased in isolates from mature tubers, sprouted potatoes, and commercial potato processing by-products. ACE inhibition was 44–94%, with IC_{50} values of 0.018–0.086 mg/mL.

Little has been published on the role of potato in prevention of cardiovascular disease. For maximum health, potato should be prepared with conservative lipid additions and the peels should be eaten for their fiber content. There is some evidence that potato protein, resistant starch, and phosphorylated starch also contribute to cholesterol lowering properties. Phytochemicals, especially antioxidants, were implicated in reducing inflammation, a risk for cardiovascular disease.

Potato and Prevention of Diabetes

The incidence of diabetes (diabetes mellitus) is increasing world-wide both in the developed and developing economies. Type-2 diabetes involves 90% of diabetics, and is characterized by insulin resistance and often associated with obesity and dyslipidemia. The development of diabetes and its progressive complications come about through unregulated elevated blood sugar levels (hyperglycemia). Management of diabetes involves oral administration of synthetic hypoglycemic agents. However, these are not always effective, may have side-effects, and may not prevent long-term vascular complications (nephropathy, neuropathy, retinopathy, etc.) (Spiller and Sawyer, 2006). Hyperglycemia induces oxidative stress; circulating markers of free-radical-induced damage are increased and antioxidant defenses are reduced.

The combination of available carbohydrates and anti-diabetic factors such as antioxidants complicates evaluation of the role of potatoes in prevention and management of diabetes. Potato, and especially French fry consumption, was modestly associated with an increased risk for type-2 diabetes in the Nurses' Health Study (Halton et al., 2006). For potatoes in general, but not French fries, the highest quintile of potato consumption was associated with greater relative risks (1.22) in obese women (BMI $\geq$ 30), but not (0.95) for women who were not obese (BMI $<$ 30 kg/m^2). Risks associated with French fry consumption were significant for all women. In contrast, despite an association of GI and glycemic load with risk for developing diabetes, potato intake was associated with a lowered risk of type-2 diabetes in the Shanghai Women's Health Study, which was a population-based prospective cohort study of 74,942 women aged 40 to 70 years (Villegas et al., 2007). The contrasting findings were explained based on a relatively low intake of potato in the Chinese population and a differing pattern of potato preparation involving less fat and frying compared with Western dietary patterns. Other studies have reported no association between potato intake and incidence of type-2 diabetes (Williams et al., 1999; Hodge et al., 2004; Liu et al., 2004).

The diets of adults in the Attica region of Greece were examined for patterns associated with measures of metabolic syndrome (Panagiotakos et al., 2007). Principal component analysis grouped fried, baked, and boiled potatoes together with beef, pork, and poultry for a component (numbered 2) that explained 11.7% of the variance in the model. Multivariate regression found a positively significant association between component 2 and waist circumference and a negatively significant one for high-density lipoprotein cholesterol. Associations between component 2 and systolic blood pressure, blood glucose, and triglycerides were not significant. Since potatoes are often consumed with meats, these trends are not unexpected. Consumption of potatoes does not necessarily lead to increased girth; persons who eat a "meat and potatoes" diet may have other life patterns that affect health.

An examination of the diets of adolescents with the suggestive subtitle of "Trading candy for potato chips?" reported that teens with type-1 diabetes consumed more fat and less carbohydrate compared with their non-diabetic peers (Helgeson et al., 2006). Twenty-four hour diet recalls were used to estimate the nutrient intake of the adolescents, a problematic assessment technique, particularly when dealing with this age group. Consumption of potato chips or any other specific food was not reported in the publication.

Potato peel extracts, which contain a rich content of polyphenolic antioxidants reduced hyperglycemia, oxidative stress, and overall food consumption in diabetic rodents when fed at 10% of the diet (Singh et al., 2005a). Plasma glucose levels in diabetic rats fed 5% and 10% potato peel powder were 16% and 33% lower than the control diabetic animals. Other significant improvements in the peel-fed animals included reduced urine output and serum alanine amino transferase (ALT). The combined dietary fiber and polyphenol content of peels merits further investigation as a therapeutic aid for diabetes. Two antioxidants, caffeic and chlorogenic acids, both found at high concentrations in potato extracts, were implicated in prevention of type-2 diabetes (Paynter et al., 2006) and cardiovascular disease (Morton et al., 2000). Chlorogenic acid appears to slow gut glucose absorption because 3 weeks of intravenous infusion of chlorogenic acid to obese, hyperlipidemic, insulin resistant (fa/fa) Zucker rats lowered the postprandial peak response to a glucose challenge (Rodriguez de Sotillo and Hadley, 2002). Administration of chlorogenic acid appears to increase insulin sensitivity rather than affecting insulin release. Svetol® is a trade-marked item containing chlorogenic acid, now approved in Norway and the UK for addition to coffee, gum, and mints, to promote weight loss (Svetol, 2008). Chlorogenic acid selectively inhibits hepatic glucose-6-phosphatase (Arion et al., 1997), a rate-limiting enzyme in gluconeogenesis. A potato protein, proteinase inhibitor 2 (PI2) is incorporated into a weight loss supplement, Slendesta®, as this protein acts as an appetite suppressant by stimulating the release of the peptide cholecystokinin, that increases satiety (Hill et al., 1990).

The incidence of obesity and diabetes are on the increase world-wide. More studies are needed to confirm the link between potato dietary fiber and polyphenolic content in prevention or therapy for diabetes.

Other Health Effects

An analysis of dietary factors associated with the onset of overactive bladder in men revealed a hitherto unknown relationship between urinary incontinence and potato consumption (Dallosso et al., 2004). The odds ratio increased from 1.00 for 0–5 servings per week to 1.48 for 8 or more servings per week ($p = 0.05$). The researchers could offer no firm explanations for the finding, but the effects of high potato consumption on urinary control, and possible prostate involvement, merits further investigation.

SUMMARY

The potato stem tuber is one of the world's most popular food items, now grown in more than 160 countries around the world. Potatoes can be prepared in a plethora of different ways. As a staple in the diets of an increasing number of humans, small differences in potato nutritional composition impacts on population health. The potato is a nutrient dense food that supplies significant nutrients without too many calories. It has a role in preventing malnutrition in impoverished areas, and contributes to health where food is ample. In populations where potato consumption is high, potatoes can make an important dietary contribution of phenolic compounds, ascorbic acid, potassium, as well as moderate contributions of dietary fiber (when skins are eaten), magnesium, phosphorus, and B-vitamins. Selection for cultivars with greater iron and zinc content is likely to significantly improve the coonsumption of these important minerals especially in view of the relatively low phytate content of potatoes—of particular importance where food choice is limited. These nutritional contributions make the potato an important and generally underestimated foodstuff in the diet of many populations worldwide and underline its potential role in fighting malnutrition in impoverished areas. A meal containing potatoes contributes to satiety. Potato servings do not in themselves contribute to obesity, which is a complex problem with numerous contributing factors.

Relatively little has been published regarding the long-term health effects of potato in diets of consumers around the world. Scattered, relatively short-term studies have implicated potato anthocyanins, glycoalkaloids, and lectins as anti-tumor agents in cancer cell lines while concerns have been expressed regarding trace quantities of acrylamide in cooked starches. For maximum cardiovascular health, potato should be prepared with conservative lipid additions and the peels should be eaten for their fiber content. There is some evidence that potato protein, resistant starches, and phosphorylated starches also contribute cholesterol-lowering properties. Phytochemicals, especially antioxidants, were implicated in reducing inflammation, a risk for cancer, cardiovascular disease, and diabetes. The incidence of diabetes is on the increase world-wide. More studies are needed to confirm the link between potato dietary fiber and polyphenolic content in prevention or therapy for diabetes.

Increased knowledge of the composition of phenolic components and antioxidant activity of various potato cultivars will lead to greater awareness by the food industry and consumers regarding potatoes as "functional foods" and possibly change food industry practices and consumer habits regarding utilization of specific "high antioxidant" potato cultivars. Emerging research perspectives suggest that the polyphenolic components are key food constituents involved in the prevention of chronic diseases. This research could drive the development of informative consumer labeling regarding polyphenolic content. Such labeling will lead to consumer trends towards the purchase of potato cultivars with higher polyphenolic content and lead processors to attempt to maintain or enrich these components within potato products. The optimal phytochemical panel still needs to be evaluated since a variety of phenolic compounds coexist within potato cultivars. However, only limited knowledge is available about their synergistic or antagonistic interactions, including with ascorbic acid. More information is required regarding nutrient interactions within the complex mixtures found in various potato cultivars and co-consumed foods since the effects of these compounds cannot be considered in isolation from one other. More information on the bioavailability of phenolic compounds in potatoes is also needed.

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