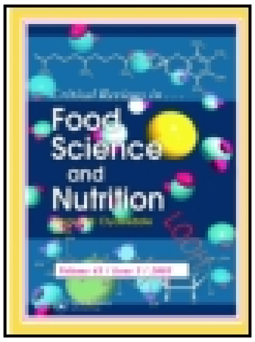

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Potato Bioactives Processing and Health

Impact of Potato Processing on Nutrients, Phytochemicals and Human Health

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ABSTRACT

Potatoes (*Solanum tuberosum*) are an important global crop that can be transformed into many products impacting several health dimensions ranging from under-nutrition, food security and disease prevention to issues of over-nutrition including obesity, diabetes, heart disease. Processed potato products are typically categorized as high fat and sodium foods, as well as being classified as a significant source of carbohydrate, in the form of starch. Conversely, potato products are less known for their contribution of key micronutrients (vitamin C, potassium, magnesium), fiber, and phytochemicals (phenolics and carotenoids). More recent insight into the nutritional value of potatoes and the potential of potato phytochemicals to modulate oxidative and inflammatory stress as well as the potential to alter glycemic response has resulted in increased interest in strategies to improve and leverage the nutritional quality of processed potatoes. This review summarizes critical information on nutritional profiles of potatoes and their processed products and describes the state of the science relative to the influence of in-home and common commercial processing on nutritional quality and potential impacts on human health.

Key Word

Potatoes; Nutritional quality; Processing; Phytochemicals

Introduction

The potato (*Solanum tuberosum*) is the fourth most important agricultural crop grown for human consumption after rice, wheat, and corn, (USDA Economic Research Service 2014). Well known for high agricultural yields and significant nutritive value, potatoes are a source of macronutrients (carbohydrate and protein), micronutrients (vitamin C, potassium, magnesium) and potentially healthful phytochemicals (Camire et al., 2009). This, combined with the ability of potato varieties to be grown, processed and transformed in many temperate as well as tropical/subtropical regions of the world (Govindakrishnan and Haverkort, 2006), gives this tuber the potential to impact several dimensions of health and nutrition.

Since initial domestication by natives of the Central Andes of South America almost 8000 years ago (FAO, 2008a) the potato has been consistently bred and improved resulting in over 4500 diverse cultivated varieties. Two main subspecies of potatoes exist, *S. tuberosum: andigena*, known as Andean; and *S. tuberosum*, or Chilean (Zaheer and Akhtar, 2014). *S. tuberosum* varieties remain the most commonly grown and consumed representing ~10% of cultivated species and over 200 wild species (FAO, 2008). Tremendous variation in physical (size, shape and color), organoleptic, and nutritional quality exists in potatoes. In the developing world, the potato is a critically important "food security" crop. Since it is not traded as a commodity and it is less vulnerable to world food price increases and addresses the need for diet diversification with nutritious and high yielding crops (Bradshaw, 2007). Many countries have begun to use potatoes to reduce their dependence on commodity crops. In 2005 the share of potatoes produced by developing nations surpassed that of developed nations for the first time (FAO, 2008). In the developed world, high-yielding, pest-resistant, and sustainably-produced

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varieties of potatoes are leveraged to meet the convenience, specific health, and quality demands of consumers (Bradshaw, 2007).

While global consumption of potatoes is increasing, in developed markets such as the US, consumption of fresh potatoes is actually decreasing relative to consumption of commercially processed potatoes (frozen, fried, chips and snacks) (USDA ERS, 2014). This increase in consumption of processed products is often criticized due to the perception that processed potatoes do not deliver the same nutritional value as freshly prepared products. While potatoes in their raw state are an excellent source of nutrients and phytochemicals, traditional (in home) and to a larger extent, commercial processing methods are believed to result in loss of micronutrients and other negative nutritional changes including addition of fat and salt (Ek et al., 2012). However, the extent to which nutritional value is truly impacted is unclear. Further, opportunities do exist to leverage food science and technology principles to improve the nutritional profile and functional attributes of potatoes products.

The purpose of this review is to summarize information on potatoes and potato products commonly consumed as key source of nutrients and biologically active phytochemicals and describe the state of the science relative to the impact of processing (in-home and commercial) on potato nutritional quality and potential impacts to human health. As several reviews already exist on potato genetics and agronomic characteristics (Arvanitoyannis et al., 2008; Mori et al., 2015; Watanabe, 2015), nutritional quality of potato (Brown, 2005; Camire et al., 2009; Ezekiel et al., 2013; King and Slavin, 2013; McGill et al., 2013), and overall contribution of potato products to the human diet (Keijbets, 2008; Zaheer and Akhtar, 2014), this review focuses on building on these efforts to include discussion of research gaps, technologies opportunities to enhance the value of potato products in all forms in the human diet.

Potato Varieties, Cultivation, and Forms in the Diet

Potato Variety and Selection

Potato cultivars vary significantly in physical and chemical characteristics making it possible to breed for specific functional and nutritional qualities critical to producers and consumers alike. Potato varieties are commonly characterized by features of the plant and tuber including: tuber shape, number of buds, or ‘eyes’, skin texture, skin and/or flesh color and distribution of pigmentation, maturity type, and disease resistance (Burton, 1989). Potatoes are also categorized based on composition, cooking quality characteristics, and use. In 1926, Salaman described four categories: floury (often burst spontaneously, crumble easily), close (do not burst, readily break, don’t crumble), waxy (firm flesh, only breaks down by kneading), and soapy (same as waxy, but also watery and translucent).

Differences in texture correspond to differences in starch type, content and contribute to performance in certain products and potential nutritional impact. Floury potatoes contain more starch than other varieties (20-22%) with a high proportion of amylose, giving them a drier, mealier texture. Waxy potatoes contain lower amounts of starch (16-18%) with a high proportion of amylopectin. The US Potato Board summarizes 15 major varieties used for chip stock in the United States: Alturas, Andover, Atlantic, Chipeta, Dakota Pearl, Ivory Crisp, Kennebec, LaChipper, Marcy, Megachip, NorValley, Norwis, Pike, Reba, and Snowden (United States

Potato Board, 2007a). Common varieties, like Russet Burbank and Shepody, are more suitable for French fry production (Keijbets, 2008).

Breeding and selection of varieties is dependent on several factors that can be broadly separated on the intended use of the potato, specifically for fresh market or further processing. For common fresh market potatoes varieties (Table 1), critical characteristics include shape and overall appearance (free from blemishes and defects). Consumers have rated appearance of the skin and location of growth (interest in “locally grown”) as important factors in potato purchasing (Jemison et al.,2008). Cooking quality is important as it relates to color, texture, and flavor of the final dish. For example, selection is often based on stability to preparation and absence of cooking defects such as enzymatic browning and stem-end blackening (Burton, 1989; Storey, 2007).

Selection of commercial varieties can be more complicated considering both the commercial process and intended in-home use. While all “fresh market” characteristics are important for commercial potato processing, specific factors uniformity, lack of sprouts or blemishes, and specific size ranges for intended process remain critical. For example, a short, oval shape with a transverse axis ratio less than 1.33:1 is desired for chip manufacturing. In French fry manufacturing, long varieties are desirable (transverse axis greater than 50 mm). Dry matter concentration is also important; dry matter less than 19.5% and 20% for French fry and chip manufacturing, respectively, is considered unacceptable (Kirkman, 2007).

Final color (control of excessive browning) is a critical component of quality in fried potato products. While many factors can contribute to browning, it is a result of reactions occurring during heating between both reducing sugars and sucrose (especially at higher temperatures) with amino acids such as glutamine, asparagine and arginine (Shallenberger et al., 1959; Khanbari and Thompson, 1993). Thus, minimizing free sugar content in addition to certain amino acids in commercial varieties is highly desirable trait to breed for in an effort to limit darkening and other undesirable reactions such as acrylamide formation (Tareke et al., 2000). Additional important functional and nutritional factors commonly highlighted in selection of potato varieties for commercial processing include type of starch, yield, improved micronutrient and antioxidant content, reduction in anti-nutritional components such as glycoalkaloids and resistance to various environmental stresses, pests, and diseases (Jansky, 2009; Bradshaw and Bonierbale, 2010).

Cultivation, Harvest, and Storage

Potatoes are grown from “seed potatoes”, which can comprise 5-15% of a year’s crop. They can be grown in a variety of climates, but cannot flourish at temperatures less than 10°C (50°F) or more than 30°C (86°F) (FAO, 2008a). Typical yields (tonnes/hectare) for potatoes are reported to be highest in North America (41), followed by Europe (17), Latin America (16), Asia (15), and Africa (10) (FAO, 2008b). The size of the potato harvest in the United States continues to expand, due to both increases in land area and average yields. In 2013, US farmers harvested 467 million hundredweight (cwt) of potato tubers (Wells et al., 2013). Potato tubers are harvested when at maturity, usually determined by a sucrose rating test (levels should be < 1 mg/g fw). 90% of potato harvest occurs in the fall, but many varieties are suited for long-term storage in climate-controlled conditions. This allows them to be sold throughout the year to both the fresh and processing markets.

Fresh market potatoes are sold on the open market upon harvest, while potatoes intended for commercial processing are usually contracted before spring planting (USDA ERS, 2014). Potatoes that are meant to be stored can be left in the soil to allow skins to thicken, which helps to prevent moisture loss (FAO, 2008a). Potatoes intended for processing are typically stored in the dark at high relative humidity, and between 6-8°C to prevent greening or quality loss (FAO, 2008a; Bradshaw and Ramsay, 2009). Colder temperatures during storage lead to accumulation of reducing sugars, which, as described above, can promote darkening during processing and contribute to acrylamide formation (Amrein et al., 2003; Kirkman, 2007).

Value-Added Commercial Processing of Potatoes

Earliest examples of processed potatoes can be traced to the Incan Empire (~1400 A.D.). A dehydrated product known as chuño was made through a natural freeze drying process facilitated by the conditions of the Andean region (Bradshaw and Ramsay, 2009). “Modern” processing of potatoes appeared in France around 1780 in the form of dehydrated potato biscuits (Burton, 1989) Dehydrated potatoes remained the most common processed product until the second half of the 20th century (Bradshaw and Ramsay, 2009). Currently, ~50-60% of fresh potatoes undergo commercial processing to products such as: chips, frozen potato products (mostly French fries), dehydrated potato products (including flakes, granules, flour, meal, and dried potatoes), chilled-peeled potatoes (mostly in Europe), canned potatoes, and other potato products (Bradshaw and Ramsay, 2009; USDA ERS, 2014). Potato products with significant market presence driven by consumer and restaurant demand are summarized in Table 2. Frozen French fries are the United States' top potato export product (valued at $635 million), followed by potato chips ($178 million), and dehydrated potato products ($82 million) (USDA ERS, 2014).

Beyond typical application in potato based food products, potatoes are also processed into potato starch and fermented into alcoholic beverages or used as feedstock for pharmaceutical, textile, paper, and other industrial and food ingredients including high quality protein, fuel alcohol, bioactive polyphenols, micronutrients and fiber (FAO, 2008a; Kärenlampi and White, 2009; Toma et al.,, 1979; Mattila and Hellström, 2007; Tarazona-Díaz and Aguayo, 2013).

In-Home Processing

A significant portion (40~50%) of potatoes are designated for fresh market sales to be used in-home and for food service applications. Fresh market potatoes are processed/prepared, in order of popularity, via boiling/steaming, baking/roasting, frying, microwaving, and other methods (Vreugdenhil et al., 2011). Variations within each of these methods can produce hundreds of recipes, including soups, salads, mashed potatoes, baked potato dishes, dumplings, pancakes, French fries, and on. Other than differences in scale and intensity, approaches in-home are similar to those employed in commercial operations relying on similar unit operations such as peeling, size reduction (slicing, cubing, etc.), thermal treatment (roasting, baking, boiling and frying). One exception is commercial French fry processing. Industrially, French fries often undergo par frying and a secondary frying before consumption, which means there are two opportunities for heat and mass (water for oil) transfer at the surface of the potato that can impact nutritional attributes including uptake of oil.

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Nutritive Value and Perception of Potatoes & Potato Products

Consumers may misunderstand the nutritional values of potatoes. Based in part on the manner in which potatoes are processed, prepared and foods they are associated with generally lead to the assumption that all potatoes products are high in carbohydrates, low in micronutrients and contribute directly to obesity. A study by Monteleone et al., (1997) reported participants viewed potatoes generally as “filling”, and boiled and baked potatoes were seen as “healthy.” However, chipped and roasted potatoes were viewed as more flavorful, but were also rated as highly fattening. In regards to carbohydrate content, a study of UK consumers revealed that participants believed starch-rich foods like potatoes were high in energy and would not help in weight management (Stubenitsky and Mela, 2000). Oakes (2004) reported that foods with added fat and sugar (e.g. baked potato with sour cream) were considered to be lower in micronutrients than the corresponding primary food alone (baked potato, skin on). Overall, these studies highlight that perception of potato nutritional value is strongly influenced by factors, possibly historical, social, and cultural, other than their nutrient content. In addition, perception is strongly influenced by presence of added fat.

In reality, potatoes are an inexpensive staple food that is a source of energy, modest amounts of high-quality protein, dietary fiber and, are good source of vitamin C, potassium, and other key micronutrients. Interestingly, when compared to other common starchy foods such as cooked pasta or brown rice, a serving of potatoes (with skins) contains less energy and carbohydrates and contains more fiber, iron, Vitamin C, folate, and Vitamin B6 (Table 3; USDA, 2014). However, complexity and variation in preparation, make it difficult to capture the true nutritional profiles of potato products as consumed. This is especially true especially for those with salt and fat added to enhance palatability. It is also important to note that USDA nutritional data commonly cited, do not fully take into account the considerable diversity that exists in raw potato nutritional quality. Therefore, the discussion that follows should be considered in the context of opportunities to leverage breeding/selection, agronomic practices and processing technologies that may maximize the nutritional value of potato products for consumers.

Sugars, Starch, Resistant Starch and Fiber

Content and Digestibility

Carbohydrate composition in potatoes is primarily defined by the starch content which typically ranges between 16-20% starch (FAO, 2008a) and primarily in the form of highly branched amylopectin (70-80%), and more linear amylose (~20-30%) (Hoover, 2001). Potato starch is unique in that significant amounts of mono-phosphate esters are covalently bound to amylopectin (Hoover, 2001) allowing water to more easily penetrate the structure resulting in a very high swelling power (Ek et al., 2012). This combined with the high content of smooth, medium (11-25 μm), and large (>25 μm) starch granules, long amylopectin chains, and high-molecular-weight amylose provides unique functionality for food applications including the ability to act as thickeners, stabilizers, bulking agent, or water-holding agent (Bertoft and Blennow, 2009).

Native potato starch is classified as resistant starch, or starch that is undigested within 120 minutes of consumption and passes on to be fermented in the large intestine. Resistant starch is considered a type of dietary fiber and has demonstrated benefits for colonic health (Nugent, 2005). Resistant starch is classified into four groups: RS1- physically entrapped starch; RS2-

ungelatinzed starch granules that are resistant to digestive action of amylases; RS3- retrograded starch resulting from cooling after gelatinization; and RS4- starches that have been chemically modified in a way that reduces digestibility (Englyst et al., 1992; Sajilata et al., 2006). Native potato starch is characterized as RS2. It is crystalline in nature (B-type) and highly compact, which protects it from action by amylases and digestive enzymes. Extent of resistance is dependent on several factors including size, shape and porosity of the potato starch granule, extent of molecular association, amylose:amylopectin ratio, amylose chain length, and presence of amylose-lipid complexes (Hoover, 2001; Ek et al., 2012). Starches with B-type crystallinity have been found to be more resistant to digestion than those with A-type crystallinity because enzymatic damage is confined to the surface of granules (Sajilata et al., 2006). Native potato starch has been found to be less digestible than other starches, such as maize, likely due to its high phosphorous and amylose content as well as the large size of the starch granules (Noda et al., 2008).

In addition to starch potatoes contain appreciable levels of simple sugars and fiber. Glucose, fructose and sucrose are common potato sugars (Wilson et al.,1981; Zhu et al., 2010), with content varying significantly between and within varieties, within a tuber and typically decrease over tuber development (Watada and Kunkel, 1955; Navarre et al., 2013). For example, Amrein et al., (2003) reported free sugar content of 17 varieties with a range of 30-1537, 97-2550 and 430-1597 mg/kg fw for fructose, glucose and sucrose respectively. In regards to dietary fiber, potatoes contain approximately 1-2% dietary fiber by weight, which is concentrated in the peels. While potato cannot be considered a good source of fiber, a medium potato with skins can

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provide up to 3 g per serving. Considering the level of potato consumption in many diets, potato fiber can provide a significant portion of overall dietary fiber (Kolasa, 1993).

Effect of Storage and Processing

The starch to sugar ratio in potatoes can be impacted by storage. Cold induced sweetening of potatoes occurs during refrigerated storage that initates an enzymatic conversion of starch to glucose (Watada and Kunkel, 1955). This process has detrimental impact on finished product quality by promoting excessive brown color and acrylamide formation (Shallenberger et al., 1959; Zhu et al., 2010). Currently strategies including biotech approaches are being leveraged to limit cold sweetening and enable refrigerated storage of potatoes for fresh market and processing (Sowokinos, 2001; Rommens et al., 2008).

In regards to starch, gelatinization occurs upon heating of potatoes converting native starch granules to rapidly digestible starch (RDS), meaning it can be digested to glucose in 20 minutes or less (Englyst et al., 1992). The amount of RDS present in potato products will largely determine glycemic response (Raigond et al., 2014) and drives the notion that potatoes are all high glycemic foods. However RDS present in cooked potatoes (especially amylose) has a tendency to retrograde upon cooling generating appreciable amounts of slowly digestible starch (SDS) or resistant starch (RS3 type) that contributes to dietary fiber content (Thed and Phillips, 1995; Sajilata et al., 2006). Therefore, while potatoes may only contain 1-2% of fiber, method of processing/preparation and consumption of cooled potato products can have a significant impact on final fiber content and potentially impact health endpoints including as glycemic response (Slavin, 2013). Strategies to leverage this behavior may be beneficial in modulating glycemic response

Protein

Potatoes contain between 2-2.5% protein with 40% of the soluble protein classified as the glycoprotein storage protein class know as patatins (Shewry, 2003). Potatoes are one of richest protein source of any root or tuber crop (FAO, 2008a). Protein content is generally dependent on potato cultivar/variety and maturity. However, potato amino acid profiles are generally high in asparagine, glutamic acid, and aspartic acid, and low in methionine, cysteine, and histidine (Brierley et al., 1996; Zhu et al., 2010) allowing them to be considered a very high quality plant protein (Desborough et al., 1981; Kärenlampi et al., 2009).

Asparagine, the most abundant amino acid in potatoes, has been positively correlated to acrylamide formation during frying (Zhu et al., 2010) stimulating interest in methods to modify its levels in tubers. While approaches to limit excess nitrogen fertilization are often mentioned (Morales et al., 2008), Amrein et al., (2003) reported asparagine content of potatoes in Switzerland to range between 2010 and 4250 mg/kg FW with differences between varieties but generally no impact of farming system or fertilization (organic or conventional/integrated). Additional, processing approaches to reduction of asparagine include addition of asparaginase to convert asparagine to aspartic acid, yeast fermentation, lowering pH to protonate and/or partially hydrolyze asparagine, blanching, addition of glycine or lysine to compete with asparagine for binding, and addition of metal ions, among others (Friedman and Levin, 2008; Pedreschi et al., 2014). More recently, transgenic approaches have been applied to reduction in free asparagine up to 95% (Rommens et al., 2006). In March of 2015 the FDA issued an evaluation of J.R. Simplot’s submission of potatoes genetically engineered to reduce levels of asparagine and reducing sugars. It was concluded that these genetically engineered potatoes are as safe for human consumption or feed as parent varieties (US FDA, 2015).

Lipids -- Natural content and addition through processing

Potatoes have very little natural lipid with levels typically ~0.1% fw across varities. The large majority (90%) of fatty acids in potato are palmitic, linoleic, and linolenic acids. Combined, polyunsaturated lipids make up approximately 70-76% of potato lipids and are mostly associated with lipoprotein membrane structures (Galliard, 1973). However, potato products often have added lipid through frying, panfrying or roasting with oil. Added fat contributes palatability but, as described earlier, raises concern for added calories and potential undesirable health effects, especially for fried products. Oil absorption during frying is of particular concern. This is mainly a surface phenomenon with the majority of lipid absorption occurs after product removal from frying (Aguilera and Gloria-Hernandez, 2000; Bouchon et al., 2003). Oil that penetrates the surface is believed to be the main contributor to final lipid content (Pedreschi et al., 2008). Relative to raw potatoes, commercial frozen French fries typically have about 15% lipid after final frying (Aguilera and Gloria-Hernandez, 2000). Due to the tight control of frying operations and application of select technologies (described later), uptake and retention of lipid is often greater in-home compared to commercially fried products (Bradshaw and Ramsay, 2009). For example, home-fried chips have been reported to have higher fat compared to commercial counterparts (~45% relative to ~36%) (Burton, 1989).

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Vitamins & Minerals

Content in potatoes and potato products

Potatoes are a naturally good source of many vitamins and minerals. Based on USDA nutrient composition data, a serving of whole, baked potato provides an excellent source (>20% of DV) of vitamin C and vitamin B6 and a good source (10-19% of DV) of niacin and folate (USDA, 2014). A serving of potato equates to 1 cup of mashed/diced potato, or about one medium (2.5-3" diam.) boiled or baked potato (USDA, 2015). However, content of vitamin C and other vitamins and nutrients have been shown to vary widely depending on potato variety, growing year or environment, and storage length (Augustin, 1975; Love et al., 2004; Singh et al., 2009; Lee and Kader, 2000). Folate analyzed in >70 potato cultivars varied between ~0.5 and 1.4 ug/100 g dw (Navarre et al., 2009). In general, vitamin C is believed to degrade over potato storage, however reported results vary. Dale et al., (2003) reported a two-fold difference in the average vitamin C content in 33 varieties with significant losses (35-55%) through 4 months of refrigerated storage. Mazza (1983) and Linneman et al., (1985) report similar levels of sensitivity of vitamin C to storage. In contrast, Tudela et al., (2002) reported a small increase in vitamin C content in some varieties (Agria, Cara, Liseta, Monalisa) of potato strips stored at 4°C for 6 days. However, vitamin C in potatoes stored under frozen and modified atmosphere conditions decreased over the storage period.

Potatoes are also an important source of many minerals, including, copper (Cu), iodine (I), potassium (K), iron (Fe), phosphorous (P), manganese (Mn), magnesium (Mg), zinc (Zn), and calcium, (Ca) (Kärenlampi and White, 2009; USDA, 2014). Depending on soil and growing conditions, potatoes can also be a source of trace elements such as selenium (Se). Many minerals, including Ca, K, Mg, Fe, and Mn are concentrated in the peel, and can be lost through processing to finished products (Wszelaki et al., 2005). Mineral content can vary widely among cultivars, depending on genetics and the environment in which the potato was grown (True et al., 1979; Ereifej et al.,1998; White et al., 2009; Rusinovci et al., 2012). Illustrating this variation, Andre et al. (2007) reported Fe concentrations of 30-155 ug/g dw, Ca of 272-1093 ug/g dw, and Zn of 12.6-28.8 ug/g dw in 74 potato cultivars.

Concentrations of minerals inside the potato seem to depend on the availability of minerals in the soil. Thus, local soil composition as well as agronomic practices will affect mineral composition in potatoes. As overall productivity and yield increases, there is some concern that mineral content of commercial potatoes is decreasing through dilution or depletion, however, this relationship has not been firmly established (Kärenlampi and White, 2009). Applying mineral fertilizers can increase mineral content (White et al., 2009). Variation among cultivars also implies the potential for selective breeding to enhance mineral content of potatoes.

Effect of Processing on Vitamin and Mineral Stability & Recovery

Several studies have reported relatively high retention of vitamins in heat-processed potatoes. Augustin et al., (1978) measured retention of vitamin C, thiamin, riboflavin, niacin, folic acid, and vitamin B_6 in whole boiled, baked, and microwaved potatoes (R. Burbank, Katahdin, Norchip, and Pontiac). Discounting boiled peeled potatoes, retention of vitamin C ranged from 73-80%, thiamin 86-95%, riboflavin 77-87%, niacin 93-103%, folic acid 71-88%, and vitamin B_6 91-100%. Navarre et al., (2010) also reported 120-140%, 116-122%, and 118-155% retention of vitamin C in Bintje, Piccolo, and Purple Majesty varieties, respectively, after microwaving, steaming, boiling, or baking. In a study by Golaszewska and Zalewski (2001), cooking methods without water resulted in 73-92% retention of vitamin C. Other studies report lower retention of vitamin C and dependence on processing method (Keller et al., 1990). Han et al., (2004) reported retention as low as 12-23% in boiled potatoes and as high as 67-79% in microwaved potatoes (ranges for Sumi, Chaju, and Dejima varieties). Lachman et al., (2013) measured retention of vitamin C in Agria (yellow-fleshed), HB Red, Rote Emma (red-fleshed), Blaue St. Galler, Valfi, and Violette (purple-fleshed) potatoes. On average, boiled peeled potatoes retained 70% of vitamin C compared to fresh peeled, and microwaved and baked whole potatoes which retained 66% and 38%, respectively, compared to whole fresh potatoes. In this study, peeling did not significantly affect vitamin C content. In general, it appears that potatoes best retain vitamins after microwaving, which is a milder process that does not involve significant leaching compared to other methods.

Overall, processing does not appear to greatly effect mineral content, except by leaching. However, this effect may be variety dependent. True et al., (1979) reported minimal mineral loss from three varieties of white potatoes processed by: boiling with skin, without skin, oven baking, and microwaving. However, retention of minerals fell as low as 42% in the Norchip variety. In one variety of Irish potatoes, boiling did not affect Ca levels, decreased Mg levels, and actually increased Fe levels compared to the raw form (Dilworth et al., 2007), perhaps through surface or water contamination or other means.

Bioavailability of Vitamins and Minerals from Potatoes

Human studies on the bioavailability of vitamins and minerals from potatoes are limited. Vitamin C from mashed and chipped potatoes was reported to be similar to supplemental forms in water suggesting equivalency of potatoes to other dietary forms (Kondo et al., 2012). Insights into the bioaccessibility of key minerals including K, Mg, Ca and Fe has also been primarily limited to in vitro assays. Fe in vitro bioaccessibility was found to be generally lower than calcium and magnesium (Dilworth et al., 2007). Using in vitro assays, Gahlalwal and Segal (1998) demonstrated that roasting or baking could enhance the availability of potatoes' minerals. It is of interest to note that potatoes are high in compounds that improve absorption of minerals (such as Vitamin C), and low in phytate and oxalate, which limit absorption of minerals (Frossard et al., 2000; Brown et al., 2005). Phenolic compounds have also been shown to limit absorption of minerals, which should be taken into account when considering breeding high-phenolic varieties because this may reduce mineral bioavailability (Frossard et al., 2000). However, further human studies are needed to better understand the true contribution of potatoes to micronutrient status. This is particularly important for shortfall nutrients such as K, Ca and Fe.

Potato Bioactive Phytochemicals Content & Bioavailability

Potatoes are well known to be a source of several classes of dietary bioactive compounds as previously reviewed (Brown, 2005; Camire et al., 2009; Ezekiel et al., 2013) which are associated with several health benefits, including phenolics, polyphenolics, polyamines, tocochromanols, carotenoids and glycoalkaloids.

Potato Phenolics: Phenolic Acids and Flavonoids

Phenolics belong to a broad class of plant compounds structurally defined as containing one (phenolic acids) or more phenolic (polyphenols) functional groups (Manach et al., 2004; Crozier et al., 2009). While multiple phenolic species are present in potato tubers (Table 4). caffeoylquinic acids, commonly known as chlorogenic acids (CQAs), are most abundant accounting for up to 90% of the total phenolics in tubers (Payyavula et al., 2014). CQAs are synthesized in the potato through esterification of *trans*-cinnamic acids, primarily caffeic acid, with quinic acid (Stöckigt and Zenk, 1974). Common CGAs in potato include 5-*O*-caffeoylquinic (5-CQA, chlorogenic acid) and its isomers 3- and 4-CQA known as, neochlorogenic and cryptochlorogenic acid, respectively (del Mar Verde Méndez et al., 2004; Andre et al., 2007; Im et al., 2008; Zhu et al., 2010; Deusser et al., 2012). Free caffeic acid has also been reported in potatoes, however, hydrolysis of CQAs under acidic or alkaline conditions can release caffeic acid (Antolovich et al., 2000).

Flavonoids are a subgroup of polyphenols that include: anthocyanins, flavonols, flavan-3-ols (flavanols), flavanones, flavones and isoflavones (Beecher, 2003; Manach et al., 2004). In general, levels of flavonoids are lower than phenolic acids and chlorogenic acids in potatoes. However, appreciable levels (~0.6-21 mg total/100 g dw) of flavonols, including quercetin-3-rutinoside (rutin), quercetin, myricetin, and kaempferol-3-rutinoside have been reported in certain potato varieties (Lewis et al., 1998; Blessington et al., 2010; Navarre et al., 2011; Payyavula et al., 2013). Mendez et al., (2004) quantified levels of the flavan-3-ol catechin in four varieties of potatoes from the Canary Islands finding catechin levels (~48-66 mg/100g dw) comparable to those of chlorogenic acid. Brown et al., (2005) and Reddivari et al. (2007) have also reported similar catechin levels in select potato varieties. However, generally, flavan-3-ols have not been routinely reported, or if reported, only at low levels in common varieties (Navarre et al., 2011; Deusser et al., 2012).

In pigmented red and purple potatoes, anthocyanins are the primary flavonoid present providing red and purple pigmentation (Veitch and Grayer, 2008). Anthocyanins in potatoes are almost exclusively glycosides in both acylated and non-acylated forms (Eichhorn and Winterhalter, 2005). Varying by pigmentation common anthocyanidin derivatives in purple varieties include petunidin, malvidin, and peonidin forms, while cyanidin and pelargonidin derivatives predominate in red-fleshed potato varieties (Brown et al., 2003; Eichhorn and Winterhalter, 2005; Payyavula et al., 2013). Anthocyanin content has been report to be as high as 1600 mg/100 g dw in whole pigmented potatoes, but values range widely between varieties (Lewis et al., 1998; Jansen and Flamme, 2006; Andre et al., 2007) (Table 4).

Carotenoids and Tocochromanols

Carotenoids are lipid-soluble yellow to red plant pigments commonly in plant foods. Six carotenoid species are commonly found in the human diet including: lutein, zeaxanthin, lycopene, β- cryptoxanthin, α-carotene, and β-carotene, the latter three which contribute to provitamin A activity of many plant foods (Maiani et al., 2009). Typical, white- and yellow-fleshed as well as colored (purple, red) potatoes varieties do not typically accumulate high levels of carotenoids. However, orange-fleshed sweet potatoes (*Ipomoea batatas*) are well known for their high levels of β-carotene reported to range from 4.5 mg/100g fw to upwards of 16,000 mg/100g fw (Bovell-Benjamin, 2007; Donado-Pestana et al., 2012). In potatoes tuber (*S. tuberosum)*, xanthophyll carotenoids (lutein and zeaxanthin) predominate (Breithaupt and Bamedi, 2002; Payyavula et al., 2013). In native Andean potato varieties, lutein and zeaxanthin and related xanthophyll species such as neoxanthin, violaxanthin, and antheraxanthin were quantified, followed by beta-cryptoxanthin and beta-carotene at minor levels of <1 mg/100 g dw (Andre et al., 2007).

Tocochromanols are a class of eight related compounds including four tocopherols (α, γ, β, and δ) and four tocotrienols (α, γ, β, and δ) that collectively contribute to vitamin E content in foods (Dörmann, 2007). Potatoes are not considered to be a rich source of tocochromanols with content reported from 0.7-29 μg/100g fw (Chun et al., 2006; Spychalla and Desbourogh, 1990, Andre et al., 2007). However, it is important to note that while potatoes themselves are not considered a good source of vitamin E, potato products often have higher levels of tocochromanols by virtue of the oils in which they are prepared which can be rich in these phytochemicals (Falk and Munné-Bosch, 2010). During absorption of oil during frying, potatoes can accumulate tocochromanols (Fillion and Henry, 1998). Tocopherols from vegetable oils can provide some measure of oxidative stability to finished products (Ruiz et al., 1999), however, they can themselves deteriorate through frying operations (Gordon and Kourkimskå, 1995; Rossi et al., 2007). Interestingly, Andrikopoulos et al., (2002) reported a significant loss of tocopherols has been reported through up to eight frying uses, typical of household preparation.

Glycoalkaloids

As with other members of the nightshade family, potatoes produce glycoalkaloids that function as phytoalexins protecting tubers from infections but also possess potentially toxic effects in humans. In potatoes, α-solanine and α-chaconine predominate with minor forms including leptine, demissine and leptinine primarily accumulating the peels of potatoes (Friedman, 2006).

Historically viewed as potentially toxic compounds, potato glycoalkaloids, when consumed at high levels (>3-10 mg) have been documented to produce neurotoxic effects through inhibition of cholinesterase activity (Bushway et al., 1987) and proinflammatory effects in the GI and other tissues through disruption of cell membrane integrity, specifically cholesterol containing cell membranes (Keukens et al., 1992). However, at lower levels these compounds have also demonstrated the potential to promote anti-inflammatory responses (Kenny et al., 2013) and anti-cancer effects primarily through disruption of cellular membranes of cancer cells (Lee et al., 2004). The extent to which adverse health effects could be attributed to glycoalkaloid intake as part of a normal diet containing potatoes is not clear. Regardless, significant efforts have been made to mitigate levels of these compounds in potatoes. New commercial potato cultivars should have glycoalkaloid levels below 20mg/100g fw (~1 mg/g dw) to meet recommended safety guidelines (Friedman et al., 1997).

Factors Impacting Phytochemical Content in Potatoes and Potato Products

Natural Variation, Maturity and Environmental Influences

Phytochemical content can differ widely among potato varieties with much of the diversity between varieties resulting from centuries of breeding for specific traits including color, flavor and texture as well as differences in maturity and growing/storage conditions. Blessington et al., (2010) reported that genotype can influence up to 80% of phenolic acids content in potatoes. Overall, flavonoid rich purple and pink-fleshed potatoes have higher concentrations of total phenolics than yellow and white-fleshed varieties (Payyavula et al., 2013). Navarre et al., (2011) conducted a study on 50 varieties of potatoes, including colored-, yellow-, and white-fleshed potatoes, and found a 6-fold difference in content of total phenolics between the lowest

(~170 mg/100g R. Burbank) and highest (~950 mg/100g Magic Molly) varieties. Similar diversity can be observed with carotenoid and tocopherol content has been observed (Bovell-Benjamin, 2007; Ducreux et al., 2005; Crowell et al., 2007).

Immature potatoes, or “new potatoes” are often reported to have greater amounts phytochemicals including phenolics and glycoalkoloids and concentration of these phytochemcials decreases as the tubers mature. The change in phytochemical content varies widely and seems to be influenced by variety and growing conditions (Papathanasiou et al., 1998; Reyes et al., 2004; Navarre et al., 2011; Payyavula et al., 2013). Reyes et al., (2004) reported that for three varieties of purple-fleshed potatoes grown in both Texas and Colorado, the decrease in anthocyanins through maturation (ranged from 19-57%) was greater than the decrease in phenolic acids through maturation (ranged from 1-29%). However, total phenolics and anthocyanins were higher at later maturity stages as the size of each tuber was greater.

Research also indicates that location, wounding treatment, light, and temperature can affect all levels of phenolic content of potatoes at harvest and during storage. Reyes et al., (2004) reported that Colorado tubers had higher levels of anthocyanins compared to the same cultivars grown in Texas, in part due to cooler temperatures and higher solar radiation in Colorado. In regards to changes during storage, Tudela et al., (2002), demonstrated significant accumulation of flavonol and caffeic acid in fresh cut potatoes after 6 days of storage. Accumulation was greater in the light compared to dark conditions. Long-term storage may increase phytochemcial content of potatoes, though effects vary depending on phytochemical species and type of storage (Tudela et al., 2002; Blessington et al., 2010).

Effect of Processing

In recent decades, several studies have reported on the impact of processing on potato phytochemicals with wide variation in reported stability/recovery of individual phytochemicals (Table 5). In regards to the most abundant phenolic in potatoes, chlorogenic acid, Im et al., (2008) investigated the effect of in-home processing (oven baking, sautéing, microwaving, frying and steaming) of Superior potatoes reporting that chlorogenic acid was best retained via oven heating, and that most processing methods had ~60-80% retention of chlorogenic acid. Maeder et al., (2009) suggest that decreases in chlorogenic acid during processing could occur through isomerization to neochlorogenic acid, though cryptochlorogenic acid levels remained stable during processing.

More recently, evidence has emerged suggesting that extractable polyphenols levels may actually increase through processing. Deusser et al., (2012) demonstrated that boiling did not significantly affect chlorogenic and ferulic acid or rutin levels, but the levels of neochlorogenic and cryptochlorogenic acids, vanillin, and catechin were increased. Navarre et al., (2010) also reported increases in chlorogenic acids and flavonols after boiling, microwaving, steaming, or baking, which could not be attributed to enhanced extractability of these compounds post-processing potentially as a result of inactivation of degradative enzymes through processing. It is also apparent that potato processing may affect individual phenolic compounds differently. Blessington et al., (2010) found that average levels of phenolic acids, including 5-*O*-CQA and caffeic, vanillic, and p-coumaric acids, and epicatechin actually increased, while levels of quercetin decreased. While much research has been conducted on the stability of anthocyanins to food processing, studies specific to potato appear to remain limited to storage, rather than

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processing, conditions. In general highly acylated anthocyanin glycosides, common to potatoes are reported to have better thermal stability stability compared to simple glycosides (Giusti and Wrolstad, 1996; Rodriguez-Saona et al.,1998; Giusti and Wrolstad, 2003).

Overall, these studies support the notion that potatoes contain relatively stable phenolics that are well recovered through traditional or in-home processes and preparations. However, there remains a lack of well-controlled studies focused on the impact of industrial processing on key commercial varieties, including pigmented varieties. More research is also needed which controls for the high natural variation in potatoes as well as potential changes in extractability with processing to understand these disparate results.

Bioavailability of Phytochemicals in Potatoes

In addition to providing nutrients, potatoes may serve as a unique matrix to delivery bioactive phytochemicals. While the bioavailability of carotenoids and phenolics from plant foods has been the subject of intense investigation (reviews by Crozier et al., 2009; Del Rio et al., 2010; Manach et al., 2005b, 2004; McGhie and Walton, 2007) much less is known regarding availability of phytochemicals derived specifically from potato products. The unique combination of lipid, carbohydrate with phytochemicals within the potato matrix provides opportunities for interactions in the food matrix and the gut that may potentiate the delivery of bioactive phytochemicals and their associated health benefits.

Polyphenol Bioavailability

The bioavailability of chlorogenic acid and anthocyanins from foods can be categorized as modest to very poor, respectively. While approximately one third of ingested chlorogenic acid has been reported to be absorbed in the small intestine following a supplemental dose (Olthof et al., 2001), anthocyanin bioavailability is substantially lower- typically ranging below 2% in many animal and human studies (Faria et al.,2013). In addition, bioavailability of acylated anthocyanins, the primary forms found in pigmented potatoes, is thought to be lower than that of non-acylated anthocyanins (Kurilich et al., 2005). For chlorogenic acid, significant bioavailability research has been reported for other matrices such as coffee. Between 10-30% absorption has been observed when including both free and metabolized chlorogenic acid in circulation (Farah et al., 2008; Erk et al., 2012; Stalmach et al., 2014). While in vivo studies are limited with potatoes, evidence of phenolic absorption from sweet potato tubers (*Ipomoea batatas*) confirms absorption of both phenolics in animals and humans (Suda et al., 2002; Harada et al., 2004; Oki et al., 2006). Generally absorption of anthocyanins was observed to be rapid with Tmax values of 30min or less and modest Cmax values only in the nM range, consistent with other plant foods.

Similar findings were observed using an in vitro model to assess the bioaccessibility of phenolics from various potato varieties. Miranda et al., (2013) observed that polyphenols in potatoes and sweet potatoes are released during the gastric and small intestinal digestion phase, but only modestly absorbed (0.1-0.9%) by Caco-2 human intestinal cells. These results suggest that release from the food matrix may not be a limiting factor for potato phenolics, rather, intestinal transport is the rate limiting step.

One factor to consider regarding potato phenolics is the potential for direct and indirect interactions between potato starch and endogenous phenolics. The presence of carbohydrate in a food matrix either as simple sugars or digestible starch has demonstrated the ability to enhance phenolic absorption in both humans (Schramm et al., 2003; Cohen et al., 2011) and animal models (Neilson et al., 2010; Peters et al., 2010). This impact is believed to be due both to pre-absorptive increases in flavonoid solubility and by interaction with specific absorptive mechanisms at the intestinal level including competitive interactions with glucose transporters, notably SGLT1 and GLUT 2 (Farrell et al., 2013). The extent to which potato starch may serve to enhance bioavailability of chlorogenic acid, anthocyanins or other phenolics remains to be investigated in detail.

Carotenoid & Tocopherol Bioavailability

Absorption of lipid soluble carotenoids is highly aligned with and dependent on consumption of lipid in the form of triacylglycerides to potentiate carotenoid micellarization (Reboul et al., 2006) and intestinal secretion with chylomicron (Goltz and Ferruzzi, 2013). Considering the low natural level of lipid in potatoes, it becomes critical to consider inclusion of fat as a cooking medium (frying) or in the product formulation as a potentiator of absorption for endogenous potato fat soluble phyochemicals. Similar to the body of evidence available for potato phenolics, very little work has been done directly on absorption of carotenoids and tocopherols from potatoes (*S. tuberosum*). In one of the few reports on carotenoid bioaccessibility, Burgos et al., (2013) reported in vitro digestive recovery (70-95%) and relative bioaccessibility (33-71%) of lutein and zeanxanthin from yellow-fleshed potatoes. These values are similar to those reported for typical salad vegetables (Huo et al., 2007; Failla et al., 2014) and select thermally processed foods (Garrett et al., 2000; Reboul et al., 2006; Kean et al., 2008).

While modest compared to dark green vegetables (Vinha et al., 2015) this level of bioaccessibility can provide up to 600 ug/100g serving of boiled potatoes (Burgos et al., 2013).

Significantly more is known regarding orange flesh sweet potato (*Ipomoea batatas*) as a food vehicle for provitamin A carotenoids (Failla et al., 2009; Mills et al., 2009; Berni et al., 2015). While bioaccessibility of β-carotene from orange-fleshed sweet potato was reported to be low (0.6-3.0%) (Failla et al., 2009), this low level is consistent with low bioaccessibility for carotenes (Huo et al., 2007). Bengtsson et al., (2009) further reported that heat processing and lipid addition (2.5%) could enhance β-carotene in vitro bioaccessibility up to 22% from orange fleshed sweet potatoes. In humans, frying sweet potato was reported to provided a higher relative serum response of β-carotene compared to green leafy vegetables but significantly lower than supplemental doses (Huang et al., 2000). Considering the similarities between potato tubers and sweet potatoes, it is logical to assume similar effects from processing of sweet potatoes would be applicable to carotenoids from yellow and orange-fleshed potatoes. However, these effects must be assessed directly.

Leveraging Potential Health Benefits of Potatoes & Potato Products

While potatoes play a critical role in food security, they are simultaneously associated with many shortcomings of the Western diet by being associated with high fat, salt and glycemic index. These effects are often associated with the nature of potato processing and in-home preparation, as it impacts apparent nutritional quality, and to a broader extent, the nature of the foods potatoes are often consumed with. Reviews by Camire (2009) and King and Slavin (2013) have previously discussed potatoes and human health with a focus on the potatoes overall, and, to a more limited extent, commonly consumed products. Potatoes in contribution of bioactive nutrients and phytochemicals have been associated with several health benefits (Figure 1). The following sections review the potential nutritional impacts of potatoes and the potential for potato products and new technologies to leverage their intrinsic value.

Contribution of Potatoes to Dietary Nutrients of Concern and Bioactive Compounds

As previously described, potatoes of all forms and colors remain an important source of nutrients and bioactive phytochemicals in the diet. For US adults, white potato ranks in the top 15 contributors among 112 foods/food groups for 15 key nutrients (out of 30 total) (Table 6). This includes key shortfall nutrients including potassium and fiber. By more recent NHANES data (2009-10), potatoes provided 12.9-24.9% of daily potassium intake and 14.4-26.2% of daily fiber intake for US men and women. NHANES data reveals that average intake of white potatoes from 24-hour recall varied between age groups (highest for 19-30 year old women and 51-70 year old men), but was between 37.9-54.6 g/day for men and 30.0-40.8 g/day for women. When compared to other vegetables, potatoes comprised about 30% of total vegetable intake for men and 27% for women (Storey and Anderson, 2013).

In line with the previous discussion of potato phytochemicals, potato products are often overlooked as significant dietary sources of bioactives. White potatoes, while relatively low in polyphenols compared to fruit and green vegetables (Brat et al., 2006), contribute significantly to overall dietary polyphenols due to overall consumption. In France, potato polyphenols account for about 45% of total polyphenol intake- more than any other vegetable (Brat et al., 2006). In the United States, potatoes follow only oranges and apples in contribution to phenolic intake among commonly consumed fruits and vegetables (Chun et al., 2005). More recent estimates suggest that potatoes may account for ~25% of the phenolics in the American diet highlighting just how undervalued potato products may be in terms of contribution of dietary bioactive components (Liu, 2013).

Potatoes and Risk of Chronic Diseases

Potato consumption has often been associated with elevated risk of certain chronic diseases, most notably, type 2 diabetes (Halton et al., 2006; Khosravi-Boroujeni et al., 2012) and colon cancer (Miller et al., 2010). While in diabetes, the association is often attributed to the high starch content of potatoes and high glycemic response induced by many forms of cooked potatoes, other negative health outcomes are related to consumption with other “high risk foods” (e.g. high level of sodium and fat). This has made for a complex mixed message on the nutritional value of potato products (Shikany and White Jr., 2000).

Several potential health benefits of potato consumption have been previously reviewed. This includes prevention of cancer, cardiovascular disease, and obesity (Camire et al., 2009; McGill et al., 2013). Many of the potential benefits are believed to be due to the combination of macro and micronutrients as well actions promoted by potatoes bioactives including phenolic and carotenoids (Liu, 2013). As a key dietary source of potassium, vitamin C and dietary fiber potatoes contribute significantly to nutrients with defined roles in cardiovascular health (McGill et al., 2013). Reported health benefits derived phytochemical rich foods with similar phenolic profiles to those found in potatoes (anthocyanins and chlorogenic acids) include reduction of cardiovascular diseases, cancer and amelioration of diabetes (Van Dam and Hu, 2005; Manach et al., 2005a; Ghosh and Konishi, 2007; Zafra-Stone et al., 2007; He and Giusti, 2010; Akash et al., 2014). While the mechanism behind these effects and the extent to which these effects can be extended to potato products remain unclear, these observations combined with the contribution of potatoes to phenolic intake in the diet highlight the potential potato products may play in modifying risk factors. In these efforts it is important to consider the form of potato consumed as well as the potential for improvements in processed potato products in which the nutritional value of the potato can be leveraged.

More recent research also supports the potential of potato products to contribute to weight management through promotion of satiety when they compare to rice or pasta (Erdmann et al., 2007), despite the relatively high glycemic index of many potato forms (consumed alone). Generally, while associations have been made, both positive and negative, much remains to be studied, as consistency in reporting of potato forms and other potential confounding factors, including context of potato consumption in the overall diet, remains challenging.

Potatoes and Modulation of Oxidative Stress

While antioxidant micronutrients (vitamin C), minerals (selenium) and bioactive (phenolics, tocopherols and carotenoids) present in potato are commonly considered to contribute to overall antioxidant activity of potatoes (Brown (2005); Lachman and Hamouz,, 2005 Nov), it is the phenolic fraction that has been found to be directly proportional to in vitro antioxidant activity (Leo et al., 2008). As with other fruit and vegetable extracts, higher phenolic and flavonoid content of colored-flesh potatoes has been correlated to a higher antioxidant activity including reported ORAC values 250-300% than white potatoes (Brown et al., 2003; Navarre et al., 2011).

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Consumption of potatoes both with and without skins was found to positively influence lipid metabolism and antioxidant status in rats (Robert et al., 2006; Robert et al., 2008). Kaspar et al., (2011) demonstrated that consumption of colored potatoes reduced multiple markers of inflammation and oxidative stress in humans. However, in commonly consumed products from typical white potato varieties, such as baked and fried chips and fries, ascorbic acid may still remain a critical contributor to the ability of potato products to modulate markers of oxidative stress in vivo. Using a SMP30/GNL KO mice Kondo et al., (2014) demonstrated that feeding fried potato chips elevated ascorbic acid levels and in turn lowered levels of reactive oxygen species (ROS) in tissues compared with ascorbic acid-depleted mice. While promising, more detailed bioavailability assessments of potatoes bioactives in conjunction with long term human and animal trials is needed to leverage in vitro assessments of antioxidant content and ultimately develop strategic for specific health benefits.

Potatoes and Modulation of Inflammatory Stress

Inflammation is a complex physiological response to an adverse stimuli presented by cellular/tissue damage or infection (Ryan and Majno, 1977). Oxidative stress is one mechanism that can trigger an inflammatory response, thereby linking the two underlying mechanism in disease pathologies (Federico et al., 2007). Data on the anti-inflammatory activity of potatoes has generally been limited to in vitro and animal studies and a focus on GI inflammation in particular. A chloroform extract of the peel from a colored-flesh potato (Jayoung) demonstrated the ability to attenuate oxidative and inflammatory processes both in LPS stimulated RAW 264.7 macrophages and in a dextran sulfate sodium mouse model of colitis (Lee et al., 2014). Kaspar et al., (2011) found anti-inflammatory effects in healthy men consuming white and pigmented potatoes with greater effects from pigmented potatoes. As described previously, potato peels are a rich source of both phenolics and glycoalkaloids. While phenolic from potatoes and other foods have demonstrated similar anti-inflammatory effects (Bogani et al., 2007; Vitaglione et al., 2015) potato glycoalkaloids have also shown evidence of both pro- (Iablokov et al., 2010) and anti-inflammatory activities (Kenny et al., 2013) dependent on application of sub-cytotoxic dose paradigms in rodent and cell models respectively.

While interesting, few studies have focused on the impact of potato products as part of an overall meal/diet. Further, the contribution of resistant starch or fiber from select potato products may have direct impact on inflammatory stress in the GI. Indigestible carbohydrates including resistant starch and fiber have demonstrated the ability to modulate inflammatory markers in both animal models (Bassaganya-Riera et al., 2011; Fan et al., 2012; Vaziri et al., 2014) and human clinical trials (Jiao et al., 2015). Sweet potato resistant starch was also shown to ameliorate pro-inflammatory status in insulin resistant rats (Chen et al., 2013). Additionally, the potential for synergistic interactions between phenolics and prebiotic/anti-inflammatory effects of fiber resistant starch from potatoes remains to be investigated. Therefore, in a manner similar to oxidative stress, experimental evidence in humans and relevant animal models is still lacking. Furthermore, mechanistic studies investigating synergistic effects of potato micro, macro and phytonutrients are clearly required to better understand the extent to which the potato as a food contributes to positive modulation of inflammatory stress and related disorders.

Modifying the Glycemic Effect of Potato Products

Glycemic index (GI) has been used to classify starch-based foods and has been associated with the in vivo measured glycemic index or the in vitro digestion rate (Jenkins et al., 1981). As a starch-rich food, potatoes are often perceived as having a high GI and by extension potentially negative long-term health effects. However GI appears to be a good indicator of carbohydrate quality, it remains controversial to measure health effect of starch-based foods. Glycemic load (GL) is another value developed to describe the carbohydrate digestibility of a food in the context of the amount typically consumed. The GL is the GI of a food normalized by the carbohydrate content of a typical serving size, allowing for comparison between foods. GL of potato products often is lower than values of starchy foods including pasta and white rice, but higher than wheat breads and several kinds of fruits, vegetables, and legumes (Foster-Powell et al., 2002).

There are some other factors (e.g. variety and maturity of potato) which impact glycemic response in potato base foods. For instance Russet Burbank had a higher glycemic index than baked Prince Edward Island (PEI) or roasted California white potato (Fernandes et al., 2005). In regards to maturity, these authors found that “new” (or young, immature) potatoes had lower glycemic index compared to mature Desiree, which is attributed to lower starch digestibility in new potatoes. Glycemic response to potatoes is also affected by preparation method, including extent of processing and ingredient addition (Kanan et al., 1998). In data from Fernandes et al., (2005) with glucose as a reference food, cold boiled red potatoes had the lowest GI (56.2), and hot boiled red potatoes had the highest (89.4), which illustrates the potential impact of retrograded potato starch on glycemic response. As described previously, upon cooling of potato products, starch molecules from the disrupted granules form a gel and eventually retrograde into a semi-crystalline form producing both slowly digestible starch (SDS) and resistant starch type

RS3, which is resistant to digestive enzymes and may therefore slow glycemic response and contribute to dietary fiber (Raigond et al., 2014).

Interest in processing and formulation strategies to control starch digestion rate through formation of either SDS and RS has grown both for implications on glycemic control and to alter substrate availability for microbial populations throughout the gut. The extent of formation of SDS and RS3 in potato products is dependent on the type and extent of processing (Brand et al., 1985; Thed and Phillips, 1995) as well as the manner in which they are consumed (Englyst and Cummings, 1987). Specifically, the extent of initial gelatinization through thermal processing or cooking is a critical first step as raw potato starch is as rich source of RS2. Strategies to preserve a portion of the starch granule and RS2 structure could increase the relative levels of RS in finished potatoes. Some research suggests that cooking methods that provide sufficient water and heat for complete starch gelatinization may increase digestibility compared to dry heating methods, such as baking and frying (Lunetta et al., 1995; García-Alonso and Goñi, 2000). Others have found no effect of cooking method on glycemic index (Soh and Brand-Miller, 1999).

Cooling of gelatinized potatoes has been demonstrated to generate appreciable levels of SDS and RS3 and decrease glycemic index in vivo (Fernandes et al., 2005; Monro et al., 2009). Interestingly, the reduction in glycemic index is still observed upon reheating compared to products consumed immediately after processing (Tahvonen et al., 2006). RS content has also been increased by temperature cycling, or more than one heating and cooling sessions (Englyst and Cummings, 1987; Leeman et al., 2005). Freeze drying chips before frying has been reported to increase RS content to 32% compared to 1% in non-freeze dried chips (Goñi et al., 1997).

These authors also observed formation of 7% resistant starch in whole French fries. In addition, insoluble amylose-lipid complexes have been observed when amylose was heated with fatty acids (Mercier et al., 2013). These approaches may have application for select product categories including prepared dishes or snacks where such approaches can be integrated into the processing unit operations resulting in novel products with improved glycemic response and by extension nutritional profile.

Along with formulation factors, processing methods and meal complexity, potato phytochemical composition may directly play a role in modulation of potato glycemic response. In addition to antioxidant and anti-inflammatory activities of phenolic compounds, more recent evidence points to the abilities of these dietary polyphenols to influence carbohydrate digestion, absorption and metabolism. Interestingly, Thompson et al., (1984) reported that phenolic content of foods including potatoes was inversely proportional to glycemic index. This observation was initially attributed to potential for interaction between complex phenolics and starch making starch less digestible (Deshpande and Salunkhe, 1982; Barros et al., 2012). However, more recently smaller molecular weight phenolics from multiple dietary sources including tea, cocoa, fruits and cereals have demonstrated the ability to modulate carbohydrate digestion, intestinal glucose transport and metabolism leading to reduced glycemic response (Hanhineva et al., 2010).

A recent report from Ramdath et al., (2014) found a similar inverse correlation between polyphenol content of potatoes and glycemic index (GI) with colored anthocyanin and phenolic-rich potatoes tending to have lower GI. While promising, these studies are preliminary and, to date, rely on differences between potato varieties not as commonly leveraged in fresh market or commercial products. Further, it remains unclear if the observed effects are related to alteration of starch structure (to form more resistant starch), starch digestion rate (through inhibition of digestive enzymes) or through modulation of glucose transport. Further efforts to characterize impacts of processing and formulation on interactions between phenolics and potato starch are needed to better understand the potential of leveraging the native phenolics present in potatoes.

Potato Influences on the Microbiota

The recognition on the role of intestinal microbiota in general health and modulation of obesity and chronic disease has grown in recent years (DuPont and DuPont, 2011; Greiner and Bäckhed, 2011; Kootte et al., 2012). It is logical to consider potatoes, a key source of starch, fiber, and phenolics, as a potential modulator of gut microbiota communities and by extension selected benefits. Surprisingly, little is known regarding the impact of potato products on gut microbial diversity or metabolic activity. Raw potato starch has been shown to alter both purine base secretion and short chain fatty acid production in a growing pig model (Martinez-Puig et al., 2003). Raw potato starch fed at 9% of the diet was also shown to increase lactic acid bacteria in the caecum and proximal colon of rodents (Le Blay et al., 2003). While interesting, these results have little practical application to processed and cooked potato products. Further, they do not consider the role of potato phenolics, such as chlorogenic acid, which have demonstrated the ability to alter bacterial communities in vitro and in vivo (Gonthier et al., 2006; Jaquet et al., 2009; Mills et al., 2015). Considering the potential for interactions between starch and phenolics (reviewed by Bordenave et al., 2014) and the ability to alter starch substrate utilization by bacteria (Wang et al., 2013), research to clarify the impact of potatoes on gut microbial communities is needed.

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Improving Nutritional Value of Processed Potato Products

While breeding and selection of more nutrient dense potatoes for commercial products continues, application of technologies to reduce components of concern (salt, lipid, acrylamide and RDS) continues to evolve (Foot et al., 2007; Keijbets, 2008; Decker and Ferruzzi, 2013; Nayak et al., 2014). As the impact of processing and preparation improvement of slowly digestible and resistant starch content was discussed previously, it is important to consider the technology currently available to control lipid accumulation and acrylamide content of processed potato products.

5.7.1 Improving the Lipid Profile of Processed Potato Products

Improving the lipid profile of processed potato products either through improvement of fat and oil nutritional quality or by minimization of fat absorption during the frying process is a critical to improving the perception of potato nutritional quality. Improvement of the fatty acid profile of potato products has focused on improving the nutrition quality of frying oils by eliminating trans fat (Berger and Idris, 2005; Daniel et al., 2005; Katan, 2006) and minimizing saturated fat content to be more in line with recommendations of the Dietary Guidelines for Americans (Dietary Guidelines Advisory Committee, 2010). Technically, this has been achieved through application of high mono-unsaturated fatty acid rich oils and blending technologies that have generated products of higher nutritional quality with minimal impact to sensory properties of the final fried potato (taste, aroma and texture) (Man et al., 1999; Matthäus, 2006; Farhoosh et al., 2008).

A second approach to improve the nutritional profiles of fried potatoes has been to leverage coatings technology and novel frying methods to minimize the absorption of fat into the final fried product. In potatoes, lipid at absorption during traditional immersion frying is increased by larger surface area/volume ratio, lower frying temperature for chips, potato variety, maturity, and low dry matter (high moisture) content (O'Connor et al., 2001). Several pre-frying treatments can be applied to potato products to limit final lipid accumulation. Pedreschi et al., (2008) reported that pre-blanched potato chips absorbed more oil than control chips. However, others suggest that blanching gelatinizes starch on the surface of French fries and creates a moisture barrier (Miranda and Aguilera, 2006). Surface drying or par-drying (e.g. microwave or hot air) is currently used in the French fry industry to reduce oil absorption.

Technologies that can improve on traditional immersion frying include vacuum frying and centrifugal frying which reduce frying temperatures and drain more oil after cooking respectively. While these technologies have been shown to decrease fat content of fried potatoes up to 75%, capital investment and suitability for all product types has limited their broad application. Similarly, new frying technologies such controlled dynamic radiant frying (CDRF) can provide an alternative to immersion frying reducing oil content by up to 50% in potato products (Lloyd et al., 2004). Other pre-treatments treatments that have been shown to reduce oil absorption in fried products include cryogenic freezing, salt soaking, blanching with infrared radiation, and coating with film forming materials or hydrocolloid solutions (Mehta and Swinburn, 2001; Miranda and Aguilera, 2006). Hydrocolloid based coating systems composed of gums, cellulose and proteins applied to raw potato surface have been shown to minimize fat uptake during frying by forming a protective barrier that minimizes both water loss and fat absorption during cooking (García et al., 2002; reviewed by Mellema, 2003). While promising, the adoption of such novel processing and coating technologies is often limited by the nature of

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the application. While some success has been seen in limited use, the potential of these technologies across broad consumer potato product remains to be fully realized.

5.7.2 Management of Acrylamide Formation

Agronomic, genetic, and processing approaches to mitigation of acrylamide in processed potato products has been the subject of several reviews (Amrein et al., 2003; De Wilde et al., 2005; Foot et al., 2007; Zhang and Zhang, 2007; Muttucumaru et al., 2008). Briefly, methods to reduce acrylamide include reduction in reducing sugars and asparagine, reducing cooking time and/or temperature or exposure to high heat, addition of antioxidants, lowering pH, blanching or soaking to remove surface acrylamide precursors, and cutting with larger surface area to volume ratio. Additionally, Zhu et al., (2010) found a fairly strong negative correlation (r = -.6918) between phenolic acid content of potato varieties and acrylamide formation during processing, suggesting that selection of high phenolic varieties may mitigate acrylamide formation.

Research Needs & Future Directions

Potato products are an important dietary source of macronutrients, micronutrients and bioactive phytochemicals with associated nutritional and health implications. While potato consumption has been both positively and negatively associated with select health endpoints, inconsistencies in definitions of potato products, their role in a broader diet pattern and differences in study designs, have made interpretation of these associations difficult. However, these outcomes have resulted in increased interest in nutritional value of potatoes and potato products. Mostly recognized as a starch rich vegetable, potatoes are less recognized for their contribution to overall dietary fiber or micronutrients including Ca, K, Mg, Fe, and Mn as well as vitamin C. In regards to phytochemicals, potatoes remain a significant contributor to overall intake of phenolics, predominantly in the form of chlorogenic acids. While nutritional qualities of potato products are known, information on the bioavailability of potato nutrients and phytochemical remains limited mainly to preclinical models and limited clinical studies. In addition, many of the positive nutritional characteristics of potatoes are lost in consumer perception due, in part, to the suggestion that nutritional profile of potatoes can be altered by preparation and processing method which introduce limiters such as fat and sodium. Significant work has been done to capture the impact of in-home preparation on potato nutritional profiles, suggesting that finished products do in fact carry substantial amounts of nutrients and phytochemicals. However, much less is known regarding the impact of commercial processing on these endpoints. This information remains critical to establish considering the increased prevalence and interest in processed products by consumers and the potential for these products to be optimized.

As a starch rich food, the nutritional perception of potatoes still remains highly associated with the glycemic response from commonly consumed prepared or processed products. This has been the subject of intensive investigation yielding the general consensus that potato glycemic response will vary widely from low to high based on variety, starch structure, preparation and processing as it relates to generation of slowly digestible or resistant starch. More recently, phenolic profile of potatoes has shown promise as a modifier of starch digestion, intestinal glucose transport and ultimately may play a role in modifying glycemic response and associated health endpoints. To develop this notion, additional insights into phenolic-starch interactions and responses across product forms are needed. This includes the need to compare novel nutrient and

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phytochemical rich potato varieties (such as colored potatoes) to common white and yellow varieties currently used in potato products in functionality for known endpoints associated with health such as of glycemic response and ability to modulate oxidative and inflammatory stress. Consideration of the impact potato products have on microbial communities and activities in the gut is also lacking. The potential for microbial interactions to modify factors impacting disease risk (gut function, substrate utilization, oxidative and inflammatory stress), additional research is needed.

Despite these gaps in knowledge, clear opportunities exist to capitalize on the known nutritional profile of potatoes. The prevalence of processed potato products in the food supply and diets provides a unique opportunity to leverage new varieties or processing technologies to limit perceived negative nutritional attributes (fat and sodium) while optimizing positive attributes (phytochemical content, micronutrient retention, resistant starch). As our understanding of the nutritional attributes and quality of potato products grows, it is important to recognize that processing will be a key player in translation of nutrition enhancements to consumers.

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Table 1. Common US fresh market potato varieties and uses (United States Potato Board, 2007b).

Type	Description/Notes	Common Varieties
Russet	Most common variety, High in starch, floury, All purpose, good for baking, frying, roasting and mashing	Burbank, Norkotah, Ranger, Shepody
Round White	Medium starch, Thin skin, Creamy texture, All purpose, good for salads, scalloped dishes, steaming, frying, roasting	Atlantic, Katahdin, Norwis, Reba, Superior
Long White	Medium starch, Firm, creamy texture, All purpose, good for boiling, microwaving, and pan frying	Kennebec, White Rose, Cal-White
Red	Firm, smooth, waxy texture, Often found as "new potatoes", Good for salads, roasting, boiling, and steaming	Chieftain, Dakota Rose, La Rouge, Norland, Red La Soda
Yellow	Dense, creamy texture, Mild buttery flavor, Good for mashing, roasting, baking, boiling, and steaming	Yukon Gold, German Butterball, Sierra Gold
Blue and Purple	Mainly available in fall, Subtle nutty flavor, Good for microwaving, salads, steaming, grilling, and baking	Purple Peruvian, All Blue, Congo, Lion's Paw, Vitillete, Purple Viking, Purple Majesty
Fingerlings	Restaurant trend, Firm, waxy texture, Good for steaming, boiling, baking, and salads	Russian Blue, Red Thumb, French Russian Banana

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Petite, or New Potatoes	More concentrated flavor, Always starchier than their mature counterparts, Good for salads, roasting, frying	C-size and smaller of any potato variety

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Table 2. Common Commercial Potato Products Grouped By Processing Type (Kirkman, 2007; Bradshaw and Ramsay, 2009).

Product Category	Common Products Sold in USA
Snacks	Potato chips
	Sheeted or extruded products
Frozen Products	Baked, frozen whole potatoes and half shells
	Blanched, IQF slices or cubes
	Dehydro-frozen dices
	Hash Browns, patties, tots
	French fries, crinkle cut, waffles, wedges, curly
	Various child products
Dehydrated Potato Products	Standard flakes
	Standard flakes, ground
	Low peel flakes
	Flour
	Granules
	Slices, dices, and shreds

Table 3. Proximate composition and nutritive value of potatoes, potato products, and comparable carbohydrate sources per 100 g of product (US Department of Agriculture Agricultural Research Service, 2014).

Component	Unit	Potato w/ Skin, Raw[1]	Sweet Potato Raw[2]	Potato, Flesh, Boiled w/ Salt[3]	Potato, w/ Skin, Baked w/ Salt[4]	Macaroni, Unenriched, Cooked[5]	Brown Rice,Long grain, Cooked[6]	Potato Chips,Plain, Salted[7]	French FriesFrozen, Baked, w/ Salt[8]	DRV/RDI
Moisture	g	79	77	77	75	62	73	1.9	64	
Energy	kcal	77	86	86	93	158	111	532	158	2000
Protein	g	2.0	1.6	1.7	2.5	5.8	2.6	6.4	2.8	50
Fat	g	0.09	0.05	0.1	0.13	0.9	0.90	34	5.5	300
Carbohydrate	g	17	20	20	21	31	23	54	26	300
Total Sugars	g	0.78	4.2	0.85	1.1	0.56	0.35	0.33	0.37	
Fiber	g	2.2	3.0	2.0	2.2	1.8	1.8	3.1	2.0	25
Potassium	mg	421	337	328	535	44	43	1196	478	4700
Phosphorus	mg	57	47	40	70	58	83	153	87	1000
Magnesium	mg	23	25	20	28	18	43	63	24	400
Calcium	mg	12	30	8	15	7	10	21	12	1000

Sodium	mg	6	55	241	10	1	5	527	324	2300
Iron	mg	0.78	0.61	0.31	1.1	0.50	0.42	1.3	0.57	18
Zinc	mg	0.29	0.30	0.27	0.36	0.51	0.63	1.1	0.35	15
Thiamin	mg	0.08	0.08	0.10	0.06	0.02	0.10	0.21	0.13	1.5
Niacin	mg	1.1	0.56	1.3	1.4	0.40	1.5	4.8	2.1	20
Riboflavin	mg	0.03	0.06	0.02	0.05	0.02	0.03	0.09	0.03	1.7
Vitamin B6	mg	0.30	0.21	0.27	0.31	0.05	0.15	0.53	0.26	2
Folate	ug	16	11	9	28	7	4	29	23	400
Vitamin B12	ug	0	0	0	0	0	0	0	0	6
Vitamin C	mg	20	2.4	7.4	9.6	0	0	22	8.6	60
Vitamin A	IU	0	14187	0	10	0	0	0	5	900
Vitamin E	mg	0.01	0.26	0.01	0.04	0.06	0.17	10.5	0.39	30

[1]Report #11352. One medium potato (2.25-3.25”) is about 213 g. One cup is about 150 g.

[2]Report #11507. One 5” sweet potato is about 130 g. One cup is about 133 g.

[3]Report #11833. Flesh boiled without skin. One medium potato of 2.25” is about 167 g. One cup is about 156 g.

[4]Report #11828. One medium potato (2.25-3.25”) is about 173 g. One cup is about 122 g.

[5]Report #20400. One cup elbow macaroni is about 140 g.

[6]Report #20037. One cup of long-grain brown rice is about 195 g.

[7]Report #19411. Serving size is 28 g (1 oz). Values given equal about 3 servings.

[8]Report #11403. All types. 10 French fries weigh about 76 g.

Table 4. Potato phytochemicals: Range of content of main phytochemicals in key commercial and select specialty varieties, grouped by phytochemical and potato flesh color.

Name	Range[1]	Mean[1]	Potato Part	Potato Flesh (Skin) Color[3]	Number of Varieties	Source	
Chlorogenic Acid	2.6	23	7.2	Flesh[2]	W,Y (Y,R)	16	Deusser (2012)
(5-Caffeoylquinic acid)	24	170	68	Whole	W, Y	21	Navarre (2011)
mw 354	39	85	11	Whole	W (Bl,R,B)	4	Mendez (2004)
	17	146	31	Whole	W,Y (W,Y,P,R)	18	Andre (2007)
	3.3	203	54	Whole	W,Y (Y,B,R)	24	Im (2008)
	42	318	138	Whole	W,Y (Y,B,R)	8	Xu (2009)
	42	219	89	Whole	unk.	16	Zhu (2010)
	22	231	74	Whole	unk.	19	Navarre (2011)
	44	1275	404	Whole	R, P	5	Andre (2007)
	383	383	Whole	P	1	Deusser (2012)	
	80	330	230	Whole	R, P	9	Navarre (2011)

Cryptochlorogenic Acid	2.8	124	15	Whole	W, Y	21	Navarre (2011)
(4-Caffeoylquinic acid)	0.2	12	3.2	Flesh[2]	W,Y (Y,R)	16	Deusser (2012)
mw 354	1.4	46	9.8	Whole	W,Y (W,Y,P,R)	18	Andre (2007)
	1	145	17	Whole	unk.	19	Navarre (2011)
	9.1	77	32	Whole	R, P	5	Andre (2007)
	13	64	39	Whole	R, P	9	Navarre (2011)
	428	428	Whole	P	1	Deusser (2012)	
Neochlorogenic Acid	0.7	20	3.6	Whole	W, Y	21	Navarre (2011)
(3-Caffeoylquinic acid)	0.3	12	2.5	Flesh[2]	W,Y (Y,R)	16	Deusser (2012)
mw 354	0.6	9.6	3.4	Whole	W,Y (W,Y,P,R)	18	Andre (2007)
	16	83	29	Whole	unk.	16	Zhu (2010)
	0.1	19	4.0	Whole	unk.	19	Navarre (2011)
	94	94	Whole	P	1	Deusser (2012)	
	3.1	20	9.2	Whole	R, P	5	Andre

							(2007)
	2.9	44	24	Whole	R, P	9	Navarre (2011)
Caffeic Acid	0.02	0.07	0.04	Flesh[2]	W,Y (Y,R)	16	Deusser (2012)
mw 179	0.5	14	6	Whole	W, Y	21	Navarre (2011)
	3.5	5.5	4.5	Whole	W (Bl,R,B)	4	Mendez (2004)
	0.5	15	6.7	Whole	W,Y (Y,B,R)	24	Im (2008)
	0.9	3.1	1.6	Whole	unk.	16	Zhu (2010)
	2	48	20	Whole	unk.	19	Navarre (2011)
	0.9	6.2	2.8	Whole	W,Y (W,Y,P,R)	18	Andre (2007)
	2.4	2.4	Whole	P	1	Deusser (2012)	
	1.3	14	7.2	Whole	R, P	5	Andre (2007)
	5.2	15	10	Whole	R, P	9	Navarre (2011)
Ferulic Acid	0.02	0.06	0.03	Flesh[2]	W,Y (Y,R)	16	Deusser (2012)
mw 194	0.5	4	2	Whole	W (Bl,R,B)	4	Mendez (2004)
	1	1	Whole	P	1	Deusser (2012)	

p-Coumaric Acid	n.d.	n.d.	n.d.	Flesh[2]	W,Y (Y,R)	16	Deusser (2012)
mw 164	n.d.	0.6	0.4	Whole	W (Bl,R,B)	4	Mendez (2004)
	n.d.	n.d.	Whole	P	1	Deusser (2012)	
Rutin	n.d.	14	3.6	Whole	W, Y	21	Navarre (2011)
(Quercetin-3-rutinoside)	n.d.	1.6	0.36	Flesh[2]	W,Y (Y,R)	16	Deusser (2012)
mw 610	n.d.	19.1	4.6	Whole	V	18	Andre (2007)
	n.d.	1.7	0.8	Whole	unk.	19	Navarre (2011)
	n.d.	n.d.	Whole	P	1	Deusser (2012)	
	n.d.	16.6	4.9	Whole	R, P	5	Andre (2007)
	0.5	3.5	1.4	Whole	R, P	9	Navarre (2011)
Kaempferol-3-rutinoside	n.d.	4.5	0.9	Whole	W, Y	21	Navarre (2011)
mw 594	n.d.	0.3	0.03	Flesh[2]	W,Y (Y,R)	16	Deusser (2012)
	n.d.	22.4	2.8	Whole	W,Y (W,Y,P,R)	18	Andre (2007)

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	n.d.	2.5	0.9	Whole	unk.	19	Navarre (2011)
	n.d.	n.d.	Whole	P	1	Deusser (2012)	
	n.d.	22.7	6.1	Whole	R, P	5	Andre (2007)
	n.d.	10.6	3.5	Whole	R, P	9	Navarre (2011)
Catechin	n.d.	0.07	0.007	Flesh	W,Y (Y,R)	16	Deusser (2012)
mw 290	48.5	66	57	Whole	W (Bl,R,B)	4	Mendez (2004)
	n.d.	n.d.	Whole	P	1	Deusser (2012)	
Total Anthocyanins	n.d.	54	33	Flesh	W (P)	9	Lewis (1998)
	1.4	5.2	3.8	Whole	W,Y (W,Y,P,R)	5	Andre (2007)
	2	46	18	Whole	W,Y (P,R)	13	Jansen (2006)
	15	1160	640	Flesh	R, P	4	Lewis (1998)
	n.d.	1633	468.8	Whole	R, P	5	Andre (2007)
	42	785	238	Whole	R, P	17	Jansen (2006)

[1]All units given in mg/100 g dw. If originally on ww basis, converted to dw using 80% moisture.

[2]Values for inner flesh and outer flesh were averaged

[3]W= White, Y= Yellow, R= Red, P=Purple, B=Brown/Tan, Bl= Black

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Table 5. Effects of several processing methods on potato phytochemical content, grouped by processing type and author.

Processing Type	Processing Methods	Potato Part	Varieties	Polyphenol (s)/Nutrients	Effect of Processing[1]	Approx. Retention[2]	Source
Peeling	Whole potato steam peeled 9 sec @220°C	Flesh	Karlena	Sum of phenolics by HPLC		55% from raw whole	Maeder (2009)
Boiling	Whole potato boiled 18 min	Whole (New Potato)	Purple Majesty, Piccolo, Bintje	Total phenolics, CGA, NCGA, CCGA, Rutin, Kaempferol, Vit C.		100-300% from raw whole	Navarre (2010)
	Whole potato boiled, then flesh and peel separated	Flesh	Bintje	CGA, ferulic acid, rutin		100-110% from raw flesh	Deusser (2012)
				caffeic acid, NCGA, CCGA, catechin, vanillin		600-900% from raw flesh	
	Flesh boiled 15	Flesh	HB Red, Rote	chlorogenic		60-120% from raw	Lachman

	min		Emma, Blaue St. Galler, Valfi, Violette, Agria	acid		flesh	(2013)
	Potato dices (with peel) boiled 25 min	Whole	Atlantic, ATX85404-8W, Innovator, Krantz, NDTX4930-W, R. Burbank, Santana, Shepody	CGA, caffeic acid, vanillic acid, p-coumaric acid, epicatechin		106-300% from raw whole	Blessington (2010)
				quercetin dihydrate		40% from raw whole	
	Slices blanched 20 min @ 70°C	Flesh	Karlena	Sum of phenolics by HPLC		90% from raw flesh	Maeder (2009)
	Strips boiled for 1.5 min in pressure cooker	Flesh	Monalisa	Quercetin derivatives, caffeic acid derivatives		33-50% from raw flesh	Tudela (2002)
	Whole potato boiled 30 min	Whole	NDA 1725	CGA		40% from raw whole	Dao (1992)
	Whole potato boiled 15	Whole	Dakota Pearl, Goldrosh,	Total phenolics (Folin)		58-95% from raw whole	Xu (2009)

	min		Nordonna, Norkotah, Red Norland, Sangre, Viking, Dark Red Norland				
				CGA, CCGA, NCGA		30-360% from raw whole	
	Plugs boiled 10 min	Whole	Superior	CGA, CGA isomer (unidentified)		60-70% from raw whole	Im (2008)
	Whole potatoes boiled 18 min	Peel	Van Gogh, Rosamund, Nicola	caffeic, ferulic, sinapic, vanillic, p-coumaric, syringic		90-140% from raw peel	Mattila (2007)
Steam Cooking	Whole potato steamed 15 min	Whole (New Potato)	Purple Majesty, Piccolo, Bintje	Total phenolics, CGA, NCGA, CCGA, Rutin, Kaempferol, Vit C.		90-300% from raw whole	Navarre (2010)
	Slices steam cooked 30 min @ 100°C	Flesh	Karlena	Sum of phenolics by HPLC		80% from raw flesh	Maeder (2009)

	Strips steamed 2 min in pressure cooker	Flesh	Monalisa	Quercetin derivatives, caffeic acid derivatives		55% from raw flesh	Tudela (2002)
	Plugs cooked 10 min in steam cooker	Whole	Superior	CGA, CGA isomer (unidentified)		50-60% from raw whole	Im (2008)
Microwaving	Whole potato microwaved 2.5 min	Whole					
(New Potato)	Purple Majesty, Piccolo, Bintje	Total phenolics, CGA, NCGA, CCGA, Rutin, Kaempferol, Vit C.		90-130% from raw whole	Navarre (2010)		
	Whole potato cubes microwaved 10 min	Whole	HB Red, Rote Emma, Blaue St. Galler, Valfi, Violette, Agria	chlorogenic acid		15-50% from raw whole	Lachman (2013)
	Potato dices (with peel) microwave	Whole	Atlantic, ATX85404-8W, Innovator, Krantz,	CGA, caffeic acid, vanillic acid, p-		116-675% from raw whole	Blessington (2010)

d 2.5 min		NDTX4930-W, R. Burbank, Santana, Shepody	coumaric acid, epicatechin			
			quercetin dihydrate		30% from raw whole	
Plugs cooked for 1 min on high heat	Whole	Superior	CGA, CGA isomer (unidentified)		65-80% from raw whole	Im (2008)
Whole microwaved 30 min @ 218°C	Whole	NDA 1725	CGA		54% from raw whole	Dao (1992)
Strips microwavved 4 min	Flesh	Monalisa	Quercetin derivatives, caffeic acid derivatives		28-42% from raw flesh	Tudela (2002)
Whole potato microwaved 5 min	Whole	Dakota Pearl, Goldrosh, Nordonna, Norkotah, Red Norland, Sangre, Viking, Dark Red Norland	Total phenolics (Folin)		61-95% from raw whole	Xu (2009)
			CGA, CCGA, NCGA		5-147% from raw whole	

Baking	Whole potato baked 30 min @ 350°C	Whole (New Potato)	Purple Majesty, Piccolo, Bintje	Total phenolics, CGA, NCGA, CCGA, Rutin, Kaempferol, Vit C.		92-250% from raw whole	Navarre (2010)
	Baked, hot air oven, 45 min @ °C	Flesh	HB Red, Rote Emma, Blaue St. Galler, Valfi, Violette, Agria	chlorogenic acid		20-80% from raw whole	Lachman (2013)
	Potato dices (with peel) microwaved 15 min @ 204°C	Whole	Atlantic, ATX85404-8W, Innovator, Krantz, NDTX4930-W, R. Burbank, Santana, Shepody	CGA, caffeic acid, vanillic acid, p-coumaric acid, epicatechin		110-440% from raw whole	Blessington (2010)
				quercetin dihydrate		40% from raw whole	
	Whole baked 45 min @ 212°C	Whole	NDA 1725	CGA		0% from raw whole	Dao (1992)
	Plugs baked in foil 10 min	Whole	Superior	CGA, CGA isomer (unidentifie		80-95% from raw	Im (2008)

	@ 200°C			d)		whole	
	Whole tubers baked 40 min @ 178°C	Whole	Dakota Pearl, Goldrosh, Nordonna, Norkotah, Red Norland, Sangre, Viking, Dark Red Norland	Total phenolics (Folin)		70-99% from raw whole	Xu (2009)
				CGA, CCGA, NCGA		4-465% from raw whole	
Frying	Potato dices (with peel) fried in tea balls 1 min @ 191°C	Whole	Atlantic, ATX85404 -8W, Innovator, Krantz, NDTX493 0-W, R. Burbank, Santana, Shepody	CGA, caffeic acid, vanillic acid,			
p-coumaric acid, epicatechin		100-575% from raw whole	Blessington (2010)				
				quercetin dihydrate		20% from raw whole	
	Plugs boiled for 7 min, fried 30 sec	Whole	Superior	CGA, CGA isomer (unidentifie d)		75-85% from raw whole	Im (2008)

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	twice @ 170°C						
	Frozen French fries	Flesh	Unk.	CGA		0 mg/100 g dw	Dao (1992)
	Strips fried 4 min @ 190°C	Flesh	Monalisa	Quercetin derivatives, caffeic acid derivatives		28-45% from raw flesh	Tudela (2002)
Panfrying/ Sautéeing	Pieces sautéed in pan 3 min	Whole	Superior	CGA, CGA isomer (unidentified)		65-80% from raw whole	Im (2008)
Drying	Mashed slices drum dried @ 160°C	Flesh	Karlena	Sum of phenolics by HPLC		80% from raw flesh	Maeder (2009)

[1]Shapes represent general increase, decrease, or no change in potato phytochemical based on retention from flesh

[2]Retention reported or calculated by [amount remaining in processed sample/original amount in raw flesh or whole]

Table 6. Percent of dietary nutrient provided by potato for US adults (1994-96) and rank among 112 food/food groups (Cotton et al., 2004).

	White Potato[2]		Potato chips/corn chips/popcorn[2]		Sweet Potato[2]	
Nutrient[1]	%	Rank	%	Rank	%	Rank
Energy	2.8	10	2.5	15	--	--
Carbohydrate	5.3	5	2.3	14	--	--
Protein	1	15	--	--	--	--
Total Fat	--	--	3.9	10	--	--
Fiber	7.5	3	3.6	7	--	--
Vitamin C	5.8	5	--	--	--	--
Vitamin E	--	--	3.4	9	--	--
Vitamin A (IU)	--	--	--	--	4.6	5
Folate	2.9	7	1	<20	--	--
Thiamin	3.8	9	--	--	--	--
Riboflavin	--	--	1	<20	--	--
Niacin	3.9	5	1	<20	--	--
Vitamin B6	8.5	4	2.1	11	--	--
Phosphorus	2.8	8	1	16	--	--
Sodium	--	--	1	14	--	--
Potassium	8.9	2	2.3	11	--	--
Iron	2.6	9	1	19	--	--

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Zinc	1	13	1	19	--	--
Magnesium	4.7	5	11	2.8	--	--
Copper	8.5	1	1	<20	--	--

[1]30 nutrients were assessed. Nutrients that no potato product significantly contributes to (at least 1%) were not included. These are cholesterol, vitamin B12, calcium, and selenium.

[2]Blank spaces indicate that the potato provided <1% of the nutrient to the diet and had low ranking.

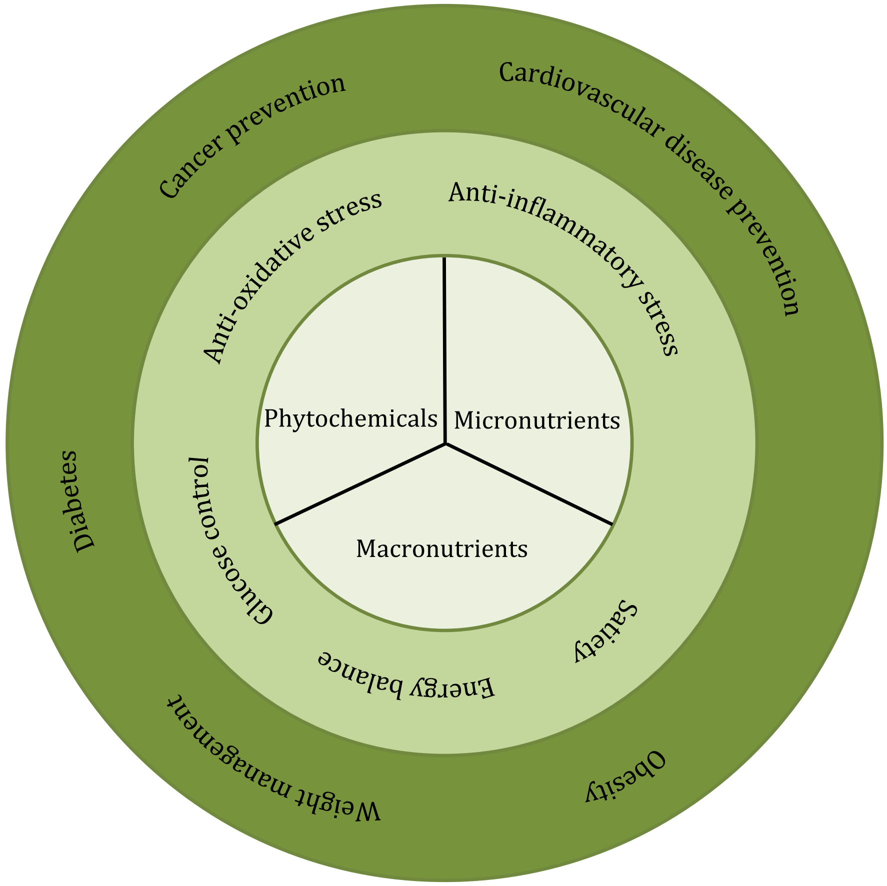

Figure 1. Schematic representation of the relationships between potato phytochemicals, micronutrients, macronutrients and human health effects. The composition of potatoes (center circle) including macronutrients, micronutrients and phytochemicals are believed are believed to impact several physiological mechanisms (middle circle) that ultimately can have positive impact on health outcomes or diseases (outer circle).