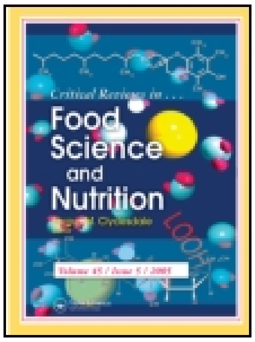

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Potato Production, Usage, and Nutrition—A Review

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Potato is an economically important staple crop prevailing all across the world with successful large-scale production, consumption, and affordability with easy availability in the open market. Potatoes provide basic nutrients such as—carbohydrates, dietary fiber (skin), several vitamins, and minerals (e.g., potassium, magnesium, iron). On occasion exposures to raw and cooked potatoes impart allergic reactions. Dietary intake of potatoes, especially colored potatoes, play an important role in the production of antioxidant defense system by providing essential nutrient antioxidants, such as vitamins, β-carotene, polyphenols, and minerals. This may help lower the incidence of wide range of chronic and acute disease processes (like hypertension, heart diseases, cancer, neurodegenerative, and other diseases). However, retention of nutrients in potatoes is affected by various cooking and processing methods. Cooking at elevated temperature also produces acrylamide—a suspected carcinogen. Independent and/or collaborative studies have been conducted and reported on the various pathways leading to the formation of acrylamide in heat processed foods. This article reviews the latest research on potato production, consumption, nature of phytochemicals and their health benefits, and allergic reactions to children. Also included is the discovery of acrylamide in processed starch-rich foods including potatoes, mechanism of formation, detection methodologies, and mitigation steps to reduce acrylamide content in food.

Keywords Potato, allergic reaction, antioxidant, phytochemicals, nutrient, acrylamide, diseases, potato products

INTRODUCTION

Potatoes (*Solanum tuberosum* L) belong to family Solanaceae originated in the Andean mountain region of South America. There are about 5000 potato varieties worldwide. Three thousand of them are found in the Andes alone, mainly in Peru, Bolivia, Ecuador, Chile, and Colombia (Hijmans and Spooner, 2001). There are two major subspecies of *Solanum tuberosum: andigena* or Andean; and *tuberosum* or Chilean.

Potatoes range in size, shape, color, starch content, and flavor. Some of the popular varieties of mature potatoes (large size) include the Russet Burbank, the White Rose, and the Katahdin, while the Red LeSoda and Red Pontiac are two types of new potatoes (harvested before maturity and are of a much smaller size). There are also other varieties available that feature purple-grey skin and a beautiful deep violet flesh. However popularity of potato cultivars varies with geographical region (Anonymous, 2008). The International Potato Center (CIP), based in Lima, Peru, holds an ISO-accredited collection of potato germplasm (CIP, 2008).

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Potato is now the fourth most important world food crop after wheat, rice, and maize (corn) because of its great yield production and high nutritive value (Geohive, 2013). This diverse and adaptable tuber has spread from its origin in South American heartland in the high Andes to all elevation zones in temperate regions of all the continents, and its production has been increased most rapidly in the warm, humid, tropical Asian lowlands during the dry season. Further advances in breeding and production of pigmented varieties have made potato an increasingly important and diverse crop in terms of production and eventually consumption. Serious evaluations on the use of potatoes continue not only as staple food for a source of energy, but also for managing health and wellness including prevention of the onset of chronic diseases.

The total world production of potatoes in 2010 was 324 million metric tonnes. China is now the world's largest potato-producing country, followed by India, Russia, USA, and Ukraine. China and India together now account for about one-third of global potato production and expected to continue higher production in coming years. It is interesting to note that while global potato production has decreased slightly between 2000 and 2010 from 327 to 324 million metric tonnes, it continues to increase in the developing countries, which now amounts to about 55% of total potato production. Some developing countries have dramatically increased potato production in last 10 years. For example, potato production in Bangladesh increased from about 3 million metric tonnes in 2000 to almost 8 million tonnes in 2010, but decreased considerably in major developed countries like US, Poland, Russia during the same period (Geohive, 2013). The consumption of potato has also seen dramatic increase in developing countries from 10 kg to 22 kg per capita during 1960–2008 (Avendano, 2012). Potatoes are processed in a variety of forms—chips, French fries, baked, mashed, and others as per local and regional delicacies prior to consumption. In addition, potato has industrial applications. Recently, European Commission approved *Amflora,* BASF's genetically modified potato for industrial starch production (BASF, 2010).

As per Food and Agriculture Organization Statistical Databases of United Nation (FAOSTAT) potatoes account for only about 2% of the world's dietary energy supply (FAO, 2009). Potatoes are rich in several essential nutrients that include carbohydrates, protein, vitamin C, vitamin B6, magnesium, potassium, fiber. For example, a 100 g skin-on-baked white potato provides 390 kJ (93 kcal) energy mainly from carbohydrates, and very little of which is from fat and proteins. Potatoes also provide a substantial portion of daily requirement values (DRV) of essential nutrients, e.g., potassium (plays role in acid–base equilibrium, also promotes Na elimination; 26% of DRV), vitamin C (needed for the growth and repair of tissues in all parts of body—antioxidant; 28% of DRV), vitamin B6 (needed for almost every enzymatic functions in the body; 27% of DRV) and dietary fiber (essential for body weight management (BMI); 15% of DRV), magnesium (constituent for several metalloenzymes with role in cellular functions; 12% of DRV) and iron (cofactor with several enzyme metabolism, 10% of DRV), and others (Table 1; USDA, 2011). The mineral compositions and DRVs differ significantly among varieties and countries. Regardless, in all cases, potassium and ascorbic acid after carbohydrates were the highest nutrients. For example, average potassium content in OD Idaho (USA) potatoes was considerably lower than Kennebee variety from Australia (209 mg 100 g^{-1} versus 417 mg 100 g^{-1}). Also there were significant differences between several varieties grown in various regions of Canary Islands (Spain). The potassium content ranged between 373 mg 100^{-1} g and 602 mg 100 g^{-1} (Luis et al., 2011). Also reporting of DVRs is reflected on the serving size. In the US, various potato boards list nutrient contents based on potato size and serving sizes. A recent study found that consumption of white potato, oven-baked fries, and French fries could be a source of important nutrients—fiber, potassium, magnesium, calcium, and vitamin E to children and adolescence. This group consumes, on the average, less fruits and vegetable, but considerably more fried potato products. The authors used the National Health and Nutrition Examination Survey (NHANES) data for 2003–2006 for their conclusion (Freedman and Keast, 2011).

Table 1 Nutritional Profiles of Potatoes (USDA, 2011)

Vegetable	Amount	Vitamins	Minerals
Potatoes	One medium baked potato without salt contains 4.33 g of protein 161 calories and 3.8 g of fiber	Vitamin C 16.6 mg	Potassium 926 mg
		Niacin 2.439 mg	Phosphorus 121 mg
		Vitamin B1	Magnesium 48 mg
		Thiamine 0.111 mg	Calcium 26 mg
		Vitamin B2	Iron 1.87 mg
		Riboflavin 0.083 mg	Sodium 17 mg
			Zinc 0.62 mg

The United Nations declared 2008 as the International Year of the Potato (IYP) to increase awareness of the relationship that exists between poverty, food security, malnutrition, and the potential contribution of the potato to defeating hunger (United Nation General Assembly Resolution, 2005). World price of wheat, rice, nearly doubled between 2005 and 2008, and continues to rise. The factors that most influenced the high prices were the high cost of bio, and fossil fuels (Avendano, 2012). Fuel used in the production of potato is almost half that of wheat (Carlsson-Kanyama and Faist, 2010). Any increase in food price affects mostly the poor people and population in low income countries. This may be one of the reasons that potato productions and consumption over the years have risen sharply in poor developing countries as dietary source of energy (Geohive, 2013).

Given the global importance of potato as predominant staple having recognized nutritional significance, health beneficial effects of phytochemicals, mass production, and consumption patterns (fried, baked, mashed) are the clear reflection of ongoing positive and beneficial outcomes availed by the consumers. Fried potato products are widely consumed as popular snacks by all ages, children to old age, all across the world. Recently, a review has appeared in print that examined the nutrient and bioactive in potatoes and their impact on human health (Camire et al., 2009). The present review provides a single comprehensive source on potato production, consumption, and latest data on clinical trials showing the importance of potatoes in global nutritional village for human health, and managing hunger and poverty. The importance of potato as a staple food is unquestionable, but processing techniques and consumption rate of some of the heat processed foods are of serious concerns and need to be monitored. This review also highlights recent discoveries of the production of acrylamide during processing using heat, and actions/recommendations for its reduction and quantification, and reported incidences of allergic reactions of cooked potatoes to children.

DIETARY AND NUTRITIONAL ASPECTS FOR HUMAN HEALTH

Potato tuber consists of about 77% water, 20% indigestible carbohydrates, and other health beneficial ingredients such as protein, fiber, vitamin (ascorbic acid), potassium, magnesium, etc., (Table 1: reproduced from United States Department of Agriculture (USDA), Food and Nutrition Centre; USDA, 2011). Consumption of potatoes is a good source of energy and other nutrients (positive value), but on occasion potato also may cause some undesirable health issues such as indigestion and allergic reactions (negative value).

(i) *Positive health benefits*. Raw potato must be processed prior to human consumption to make starch and other nutrients bioavailable. The nutritional value of potatoes along with its taste and ease of cooking has made it the most popular vegetable and snack in the world. Potatoes are affordable, nutritious, a good source of vitamin C (ascorbic acid), protein, and rich source of carbohydrate energy. People in under developed countries, who are unable to afford high-energy diets such as meat and milk products, use potatoes as their prime source of nutrient energy. In the seventeenth century potato became famous across Europe as a crop that could save people during famines. Also at times when and where other crops failed, due to severe winter conditions, potatoes typically relied upon to contribute toward food supplies (Woolfe, 2009).

In addition to ascorbic acid (vitamin C), the new pigmented varieties contain several phytochemicals that are antioxidants. Antioxidants are compounds that hinder the oxidative processes and thereby delay or prevent oxidative stress (Wilcox et al., 2004). Oxidative stress is associated with a wide range of chronic and acute disease processes like heart diseases, cancer, neurodegenerative, and other diseases. When free radicals are generated in vivo, many antioxidants act in defending from oxidative stress (Halliwell and Gutteridge, 2007). Excessive free radicals and reactive oxygen species (ROS), such as the superoxide anion ($O^{2-}\bullet$), hydroxyl radical ($OH\bullet$), and the peroxy radical ($ROO\bullet$), react with vital biomolecules (like lipids, proteins).

Traditionally potatoes (white) have been perceived as staple food similar to rice, etc.—a source of sustenance energy. However, the introduction and availability of colored potatoes have attracted consumers' and researchers' interests alike for reasons other than purely a source of energy (Lachman et al., 2005). A cellular antioxidant activity assay could provide biologically relevant information on bioactive compounds in raw as well as processed food products. Comprehensive analysis of phytochemical profiles of potato, their strong antioxidant activity was reviewed and discussed (Tsao, 2008). Measuring antioxidant activity using a biologically relevant assay adds important evidence in understanding the role of phytochemicals in vivo (Nayak et al., 2011a).

Raw potatoes consist of large amounts of resistant starch (RS), which must be processed (boiled in water 100°C; cooked in conventional oven often at considerably higher temperature around 200°C and has more RS; floured; microwaved; fried) for conversion into digestible starch (DS) for human consumption. Amount of conversion of RS greatly depends on the process employed. For example, boiled potato has less than 2% RS compared to 10% in retrograded flour (Garcia-Alonso and Goti, 2000). The effect of boiling and microwave baking on the amount of phenolic acids in peeled and unpeeled potatoes were studied. Greater loss was recorded in peeled potatoes irrespective of heating method. Loss of phenolics may be minimized by reducing low power microwave baking followed by shorter cooking time (Barba et al., 2008).

(ii) *Allergic reactions (Negative reactions)*. Potatoes are not commonly associated with toxicity. As part of the maturing processes, potato tubers accumulate small quantities of alkaloids but are bitter at high concentrations, which may cause some discomfort when consumed. The two major alkaloids (up to 95% of the total) in potato tubers are α-solanine and α-choconine, which are present in approximately 2 to 3 ratio. They are generally detected and quantitated using time-consuming and less efficient gas chromatography-mass spectrometry/liquid chromatography-ultra violet (GC-MS/LC-UV) techniques. However, very recently, the use of matrix-assisted laser desorption/ionization mass spectrometric imaging (MALDI-MSI) technique has been reported for the spatial distribution of glycoalkaloids in potato tubers. The method is rapid because it reduces complex time-consuming preparative steps for analysis (Ha et al., 2012). The concentrations of glycoalkaloids are affected by the environmental and genetic (varietal) factors. Total glycoalkaloid levels below 100 mg kg^{-1} are deemed safe for human consumption. However, the concentrations around 200 mg kg^{-1} could cause serious health issues. Research has shown that peeling of the skin prior to processing removes a good portion of alkaloids—to a non-effect level (Friedman, 2006; Friedman and Levin, 2009). Marketing and eating French fries and potato crisp with skin as snack are current trend among the younger generation, probably skin as a source of dietary fiber. This has raised concerns of safety of potato products (Rytel et al., 2011). A recent study reported the glycoalkaloid contents in seven colored potatoes that ranged between 127 mg kg^{-1} and 272 mg kg^{-1} dry weights. This study also reported that thermal processing either by baking or frying of potatoes with skin reduced the glycoalkaloids by up to 93% (Tajner-Czopek et al., 2012). In addition to natural toxicants, over the years many case studies have been reported showing sensitivity to raw potatoes in adults (mainly oral due to exposure of heat-labile allergen) and cooked potatoes in children. Major potato allergic symptoms include contact dermatitis, asthma, rhinoconjuctivities, wheezing, or even anaphylaxis. As early as 1966, but in 1989 it was confirmed that housewives exposed to aerosolized potato particles while peeling developed bronchial asthma (Quirce et al., 1989). Immediate contact allergy reaction (contact urticarial) is more common as occupational hazard, but recently a non-occupational allergic reaction to a 41-year old woman was reported (De Lagran et al., 2009). In children, allergic reactions are mainly due to cooked potatoes when they are exposed as part of their initiation of solid food (De Swert et al., 2007; Monti et al., 2011). Allergic reactions have been attributed to proteins, and to date four allergenic proteins have been identified in potatoes, the main being the soluble glycoprotein patatin, also referred to as Slot 1. A recent study reported substantial difference of patatin activity between cultivars and individual isoforms (Barda et al., 2012). Protein in potato is higher than other dietary tubers and cereal, and up to 40% of which could be patatin, responsible for allergic reactions in children (Barda et al., 2012).

EFFECT OF PROCESSING ON POTATOES INTO EDIBLE FOOD PRODUCTS

Potatoes have been known to mankind for centuries. It contains mostly water and 60% to 80% of the solid is indigestible substances, which is of no nutritional value to human. It is therefore potato is processed prior to eating. The main process involves heat (boiling, baking, microwaving, frying) to breakdown the starch. Most often skin of mature potato is not eaten. Thus, some of vitamin C is lost. By nature, a potato does not add much fat to diet, but is flat (less tasty). Taste is the king for food. Hence, potato edible products require addition of fat, salt to make them tasty and highly desirable, but are cause of serious health concerns- especially for the onset of obesity and other related health issues. While use of heat in the preparation of potato dish is almost essential, this also initiates several chemical reactions between the endogenous chemicals such as reducing sugars, amino acids. The most common and highly desirable reaction for aromatic and tasty product is the Maillard reaction—a reaction between sugar and amino acid. But, a chemical reaction and the end product are highly dependent on the nature and abundance of constituents during the process. This could lead to the production of highly undesirable toxic substance—acrylamide in high temperature baked products derived from high starch and proteinous raw material. Potato is one such raw material, and has been shown to produce acrylamide in large quantities when processed at elevated temperature. The most common potato products that are consumed globally are: baked, boiled, mashed, French fries, potato chips. In addition, potato flour is used in cake, pancakes. Researchers have also provided an excellent account of the processing effect on nutrient content of potatoes (Camire et al., 2009).

STARCHY NATURE OF POTATOES TO HEALTHY COMPONENTS

Globally potato is the most commonly consumed non-cereal staple food by general public, nutritionally well-known predominantly for its starchy carbohydrate. However, potato is also a good source of vitamins and other healthy phytonutrients of great importance (Hejtmankova et al., 2009). Generally the skin and/or fleshes of potatoes varieties are white, yellow, or saffron yellow but potato cultivars in which skin and/or fleshes are red, purple, blue, or orange are also prevalent, and are referred to as colored or pigmented potatoes. Several researchers (Rodringuez-Saona et al., 1998; Stelljes, 2001; Fossen et al., 2003; Brown et al., 2004; Brown, 2005, 2006; Eichhorn and Winterhalter, 2005; Lachman and Hamouz, 2005; Reyes et al., 2005; Jansen and Flamme, 2006; Zhang et al., 2009) have identified many phytochemicals in pigmented potatoes with antioxidative properties. These phytochemicals are polyphenols, anthocyanins, carotenoids, ascorbic acid, flavanoids, tocophenols, and alpha-linoleic acid. Several studies have indicated that highly pigmented, e.g., purple cultivars have more antioxidants-anthocyanins, carotenoids than other varieties (Lewis et al., 1998; Brown et al., 2005). Recently, researchers (Nayak et al., 2011b) reported total antioxidant capacity (TAC), total phenolics (TP), and total anthocyanins (TA) were in the descending order: purple, red, yellow, and white cultivars. They observed that the purple cultivar had almost four times more TAC (9.605 Trolox g^{-1} dry weight versus 2.403 Trolox g^{-1} dry weight) than the other three cultivars. Researchers have viewed colored potatoes as a potential inexpensive richest source of antioxidants in the human diets to prevent many chronic diseases. This view is supported by a comparison of total phenolic contents in colored potatoes (90–412 mg GAE 100 g^{-1} fw: mg gallic acid equivalent g^{-1} fresh weight (fw)) (Lachman et al., 2005; Sushnoff et al., 2008) with those in common berries (expensive) such as strawberries, blueberries, and cranberries (100–412 mg GAE 100 g^{-1} fw) (Zhang and Wang, 2003). Values of colored potatoes in managing human health and wellness are being investigated scientifically. Like other colored fruits and vegetables, potato extracts were assayed for their antioxidative properties in vitro. A recent study observed that potato extracts inhibited the proliferation of colon and liver cancer cells, which was significantly co-related to antioxidant activities of the cultivars (Wang et al., 2011). However, supporting in vivo studies (clinical trials) are very limited. The only clinical study reported to date supports the health value of colored potatoes, and explores the potential view with observation that consumption of pigmented potatoes alters oxidative stress and inflammatory damage in men. A randomized collaborated study was conducted between the Washington State University and USDA-Agricultural Research Services that employed 12 healthy men ranging between 18 and 40 years of age. Men consumed 150 g of cooked white (wp), yellow (yp), or purple flesh potatoes (pp) once per week for six weeks. Analysis of blood before and at the end of six weeks feeding experiment observed that plasma IL-6 (interleukin-6, a protein encoded with IL gene 6) was lower in subjects consuming yp and pp compared with wp (Kasper et al., 2011). Data presented at the 2nd Annual Scientific Meeting of the Canadian Nutrition Society in 2011 reported that the glycemic index of potatoes is related to polyphenol content, and which may be mediated in part by inhibition of α-glucosidase (Ramdath et al., 2014).

Potato is an excellent source of vitamin A in the form of β-carotene and a very good source of vitamin C. Both β-carotene and vitamin C are very powerful antioxidants that work in the body to eliminate free radicals. Compared with white potatoes, the yellows have higher concentration of carotenoids, whereas the purples have higher concentration of anthocyanins. Yellow potatoes are rich in lutein and can provide up to 10 times more carotenoids than their white-flesh counterparts. Today wide varieties of colored potatoes, including commercial ones, are available such as Cranberry Red, Shetland Black, Blaue St. Galler, Valfi, Zhaunxinwu (Brown et al., 2003, 2005; Groza et al., 2004; Zhao et al., 2007; Lachman et al., 2009). The impact of cultivar, storage, cooking, baking on the total anthocyanins content (TAC) was investigated in one red (Highland Burgundy Red) and several purple varieties (Blaue St-Galler, Blue Congo, Salad Blue, Shetland Black, Valfi, Violette, Vitelotte). TAC ranged from 248.5 mg kg^{-1} DM to 2257.8 mg kg^{-1} DM, which followed the order Viteolette> Violette> Highland Burgundy Red >Valfi and exhibited antioxidant activity in the same order. Purple varieties Blaue St-Galler, Blue Congo, and salad Blue had "marbled" texture, low TAC and low antioxidant activity. On baking the TAC increased 3.34 times, whereas it increased 4.42 times when cooked in boiled water. The impact on TAC on cold storage (4°C) was significant but dependent on variety (Lachman et al., 2011). The coloration pattern of the skin and fleshes of colored potatoes is variable, i.e., the skin alone may be pigmented, or the flesh may be partially or entirely pigmented (Groza et al., 2004).

In short, these highly colored potato varieties are rich in antioxidants (like anthocyanins and carotenoids) and consumption of such foods, if cooked properly, i.e., a process that does not destroy antioxidants, may help lower the incidence of chronic diseases such as cardiovascular disease, atherosclerosis, rheumatoid arthritis, and cancer. Potatoes contain carotenoids lutein and zexanthin, regarded as constituents of the human retina. These compounds are thought to protect photoreceptor cells from light-generated oxygen radicals, playing a key role in preventing advanced macular degeneration (Hymen and Neborsky, 2002; Li et al., 2012). High levels of lutein in the serum are also correlated with reduced lung cancer (Khachik et al., 1995). Carotenoids have been found to stimulate processes involved in the immune system of animal models (Lee et al., 1999) and lutein has been found to inhibit breast cancer development in mice (Park et al., 1998). Potatoes contain phenolic compounds and the predominant one is chlorogenic acid, which constitutes about 80% of the total phenolic acids. Flavonoids regarded as strong antioxidants are present in the flesh of white-fleshed potatoes with roughly twice the amount present in red- and purple-fleshed potatoes (Brown, 2005). The predominant flavonoids are catechin and epicatechin. Consumption of both yellow and purple potatoes can decrease oxidative damage and inflammation compared with those who consumed white potatoes, and as such recently at International Potato Processing and Storage Convention (IPPSC), researchers proposed to explore the potential physiological health benefits of consuming pigmented potatoes (IPPSC, 2011).

A recent crossover study reported results from 18 hypertensive individuals with an average BMI of 29, who were fed microwaved purple potatoes and no potatoes for four week and then changing the feed for next four weeks. At the end of the experiment, there was no significant effect on body weight, but there were significant decreases in blood pressures— diastolic 4.3% (4 mm), and systolic by 3.5% (5 mm) (Vinson et al., 2012). The data support the health benefits of purple potatoes. The idea behind microwave cooking is to preserve beneficial phytochemical that can help lower blood pressure in overweight and obese people. This study supported the already held views that potato chips and French fries lose their nutritive value because of high temperature frying/cooking.

POTENTIAL NEGATIVE HEALTH EFFECTS OF PROCESSED POTATO PRODUCTS

There is a serious public concern globally of cancer risk from consuming potato products processed at high temperature, which may contain acrylamide. The same concern also extends to several processed foods produced from high starch-containing ingredients and cooked at high temperatures. Published data clearly establish potato chips, French fries, as one of the major dietary sources of acrylamide for adults and children/adolescent, which is alarming particularly in western countries where French fries and chips are consumed regularly as part of meal or snack (Pedreschi and Zuniga, 2009). In Canada, it is estimated that almost 70% of acrylamide intake is from French fries and potato chips (Health Canada, 2008). The same may be true for the USA and developing countries. Thus, the reduction of acrylamide in French fries and potato chip would go a long way in reducing its overall human exposure.

The discovery of acrylamide in deep-fried potato and other baked-food products in 2002 was an eye-opener for both the regulatory bodies and food processing industries (Tareke et al., 2002). Acrylamide is classified by the International Agency for Research on Cancer (IARC) as a probable carcinogen (IARC, 1994). The carcinogenic nature of acrylamide opened a flood gate of enormous individual and collaborative research worldwide. Many national and international regulatory agencies took proactive leadership roles to understand the mechanism of formation of acrylamide in fried and baked products with a view to develop processing protocols for reduction and emanation in foods destined for human consumption. One such cumulative effort was an initiative by The European Commission on Food Quality and Safety, which involved 24 groups and 14 countries and produced the FINAL HEATOX report (HEATOX, 2007). The two recent articles have thoroughly reviewed the published literature on the formation of acrylamide in potato products and other baked products (Akhtar, 2012; Vinci et al., 2012). The Acrylamide Toolbox 2011 (FDE, 2013) and a recent review article (Lineback et al., 2012) are very important sources of information that trace the scientific activities with future considerations and needs for the processing industries. In following pages only the salient features and the most recent advances would be highlighted.

One of the major achievements of thorough studies has been the establishment of pathways leading to the production of acrylamide during food processing. The two major ingredients that are needed for the production of acrylamide are amino acid(s)—mainly asparagine and reducing sugar (fructose, glucose) in addition to the elevated temperatures (>120°C) and the duration of reaction. Both asparagine and sugars are normal constituents in potatoes. The reaction paths were conclusively established by a team of researchers at the Proctor & Gamble Laboratories in Ohio (Zyzak et al., 2003). These workers used labelled U-13C4U-15N2-asparagine [1] with glucose [2] and followed the reaction using LC-MS (Fig. 1; Akhtar, 2012). They detected the formation of the Schiff base [3] with labelled carbon and nitrogen atoms (MW 300 versus 294 for non-labelled product), which then proceeded via azomethine ylide [4], following different pathways to yield acrylamide [6] in which all carbon and nitrogen atoms were labelled with 13C and 15N [MW 75 versus 71 for non-labelled compound]. In summary acrylamide levels appear to increase in foods that are prepared with ingredients high in asparagine and reducing sugar, and at elevated temperature (>120° C) for longer duration.

Analytical Methodologies

Published data clearly establish potato products (French fries, chips) as the major dietary source of acrylamide for adults, children in the developed countries where these products are consumed routinely in meals and/or as snack. Acrylamide is a low molecular weight compound that is more soluble in water than in most commonly used extracting organic solvents. In order to protect citizens, the national regulatory agencies need to monitor the content often. This requires access and availability of accurate methods and instrumentations for its detection and quantitation. Since 2002, there have been some serious efforts that led to the development of methods that could detect and quantify acrylamide in food products derived from starch-rich ingredients. Researchers (Vinci et al., 2011, 2012) have extensively reviewed the literature till 2010 and the following descriptions should be read in conjunction with the above articles.

Like any other sample preparation for analysis, potato products also follow the steps that involve sample collection, homogenization, extraction with water or organic solvent alone or in a mixture, clean up, and finally detection and quantification.

GC-MS and LC-MS/MS have been the method of choice for the detection and quantifications of acrylamide in foods (Health Canada, 2003; Granby and Fagt, 2004; Castle and Eriksson, 2005; Zhang et al., 2005; Soares et al., 2006; HEATOX, 2007; Bagdonaite et al., 2008; El-Ziney et al., 2009). According to one survey report, amounts of acrylamide in various food matrices were highest in potato chips (700–3700 ng g^{-1}) followed by French fries (200–1900 ng g^{-1}), cereal (100–170 ng g^{-1}), bread (<100 ng g^{-1}, except toasted French bread 260 ng g^{-1}) (Becalski et al., 2003).

Efforts continue to identify other simple and robust detection and quantification methods that are less expensive and could be easily adopted by researchers, regulatory agencies in developing countries. For example, USDA Agricultural Research Service is investigating the use of Near-Infrared (NIR) Spectroscopy for efficient and cost effective method for rapidly analyzing acrylamide in chips and French fries. The method will be concurrently developed with routinely used GC-MS and LC-MS/MS. The goal of the NIR method is to detect and quantify acrylamide in the range of 0–500 ppm with an accuracy of ± 20% (USDA-Research, 2012). Recently, a report appeared in print (Yamazaki et al., 2012) regarding the use of GC-MS after derivatization of extracted acrylamide with xanthydrol instead of the commonly used bromination step. This method for potato snack has good linearity, excellent recovery (89.8% for 0.33 ppm, and 95.4% for 33 ppm fortification level), limit of detection (0.0045 ppm), and limit of quantification (0.012 ppm). Another interesting approach is the use of nitrogen–phosphorus detector in GC analysis (Kim et al., 2011). The detection has a linear response for 0.5–100 ppm with a limit of quantification 0.5 ppm, and a recovery of 106 ± 8%. This new approach when validated with GC-MS and LC-MS/MS should contribute to the screening of acrylamide in potato processed foods originating in developing countries.

Mitigation Strategies for the Reduction of Acrylamide Formation

Many sophisticated analytical methods that can detect the presence of acrylamide in processed foods including those derived from potatoes do exist to monitor the amounts of acrylamide in foods destined for human consumption. But they cannot eliminate and/or reduce the level to the "As low as reasonably achievable (ALARA)" level (FDE, 2013). There are needs for strategies for reduction leading to ALARA. It is well established that acrylamide is formed, via the Maillard reaction between reducing sugars and asparagines, in potatoes during deep frying for chips and French fries at high temperature for a long period (Mottram et al., 2002). Thus, elimination and/or considerable reduction in acrylamide content is possible by changing one or more of these parameters. The Acrylamide Tool Book (FDE, 2013) summarizes all the steps necessary to minimize production of acrylamide in the edible products. The Tool Book lists the efforts in two categories, namely, agronomics (reduction of asparagine and reducing sugar in potato tubers), and processing including recipes. Efforts have been made or underway to produce varieties of potatoes with less asparagine and sugars (Rothamsted Research, 2009; USDA-NIFA, 2011). The aim of these studies are to identify or produce new potato cultivars with low levels of asparagine and sugars with the added qualities of retaining the desirable attributes such as color, flavor, and “low acrylamide” content in the finished products. During the cold storage potatoes accumulate reducing sugar. Thus, one of the steps for keeping the levels of reducing sugar low is to not store potatoes below 8°C (De Wilde et al., 2005). Recently, researchers at UW-Madison reported creating a potato cultivar that prevents accumulation of reducing sugar during cold storage (Wu et al., 2011). These researchers demonstrated that silencing of the potato vacuolar invertase gene (Vlnv) reduced the reducing sugar by 93% during cold storage. Temperature, duration, and recipes (addition of ingredients/additives) are the processing parameters employed to meet organoleptic characteristics and easily controlled. Taste is the king and it must be maintained for marketable products. It is highly likely that changing several parameters in the same production line may not yield products that would meet consumers’ choices for taste, color, and appetite. Based on the available information, it would almost be unlikely to remove all reducing sugar and asparagine through breeding program because both these ingredients are essential for plants growth and maturity. Thus, there is a need to a new and workable approach to develop processes that produce foods that display consumers’ preferences, but has ALARA characteristics. Most commonly used food-processing techniques are rinsing, washing, treatment with acid or base solution, blanching in addition to heating at elevated temperature that includes roasting, boiling, pan frying. A single or a combination of these processes could reduce sugars as well as some asparagine. Asparagine can be reduced effectively by treatment with asparaginases, a naturally occurring enzyme (Spivey, 2010). The use of asparaginase in food has been approved in the US, Australia, New Zealand, and Denmark with the support from the Joint Food and Agriculture Organization/World Health Organization Expert Committee on Food Additives (Health Canada, 2009b).

Recently, researchers reported (Pedreschi et al., 2011) the effect of (i) rinsing in distilled water, (ii) rinsing in distilled water and blanching in hot water 85°C, (iii) rinsing in distilled water and immersion in with asparaginase solution at 50°C, (iv) rinsing in distilled water, blanching in hot water at 85°C, and immersion in asparaginase solution at 50°C, and (v) rinsing in distilled water, blanching in hot water at 85°C, and immersion in distilled water at 50°C on the amount of acrylamide formed. The amounts of acrylamide were highest for (i) 2047 μg kg^{-1} and lowest at 158 μg kg^{-1}, a 93% reduction for (iv) a process that combines rinsing, blanching followed by treatment with asparaginase. This reduction was attributed to effective removal of asparagine from blanched potato slices, which allowed access to asparaginase to diffuse through softened cellular walls. A very small reduction in acrylamide production was observed for (iii) mostly due to leaching of surface asparagine (Pedreschi et al., 2004). This certainly indicates serious consideration of multi-step processes for the reduction of acrylamide in final products. Several studies have shown that additives such as dietary plant materials, antioxidants, organic acids, mono- and divalent cations, e.g., calcium and magnesium ions combined, caused a reduction in pH of the food matrix and lowering the amounts of acrylamide (Pedreschi et al., 2004, 2007; Mestdagh et al., 2008; Levine and Ryan, 2009; Ou et al., 2010; Zhu et al., 2011). Most of these studies were performed on lab scale/model systems, and have not been validated under industrial production conditions. There are stronger needs for the validation of such studies in industrial production. Recently, a group of researchers at the University of Ghent, Belgium have reported the effect of various additives on the industrial production of French fries (Vinci et al., 2011). These workers investigated the use of acetic acid, citric acid, calcium lactate, and asparaginase in the production of industrial scale frozen par-fried French fries and their effect on the amounts of acrylamide produced. These workers observed no significant reduction in the amount of acrylamide in cooked par-fried (partially fried) French fries produced using acetic acid, citric acid, and calcium lactate compared to the untreated fries. On the other hand, chilled French fries treated with asparaginase only, and fried after cold storage for four days had negligible amounts, below limit of detection, of acrylamide.

SUMMARY AND FUTURE PERSPECTIVES

Potatoes are now grown globally. The developed countries has seen continuous decline in potato production from 190 million tonnes in 1990 to 155 million tonnes in 2006. During the same period, the production in developing countries has leaped from 89 million tonnes to 159 million tonnes (Geohive, 2013). The consumption of potatoes also dramatically increased in both the food deficit and low income areas. This is not surprising because prices for other staple foods, e.g., rice, wheat, and corn have been increasing at much higher rates than potatoes (Anderson, 2010) due to high cost of fuels and energy, and becoming expensive to afford. In the poor and developing countries, potatoes are used as sustenance—a source of energy and meeting other basic needs (higher carbohydrates, proteins, minerals, etc., compared to other grains) for living. Potatoes in North America and other developed countries are now most often used as “convenience” foods snacks (French fries, chips). Snacks are produced at higher temperatures to initiate Maillard reaction that is responsible for aroma and taste of the food (organoleptic factors). The same reaction under certain conditions (presence of large amounts of reducing sugars and asparagine) also produces carcinogenic acrylamide. Considerable collaborative research have been done globally with the

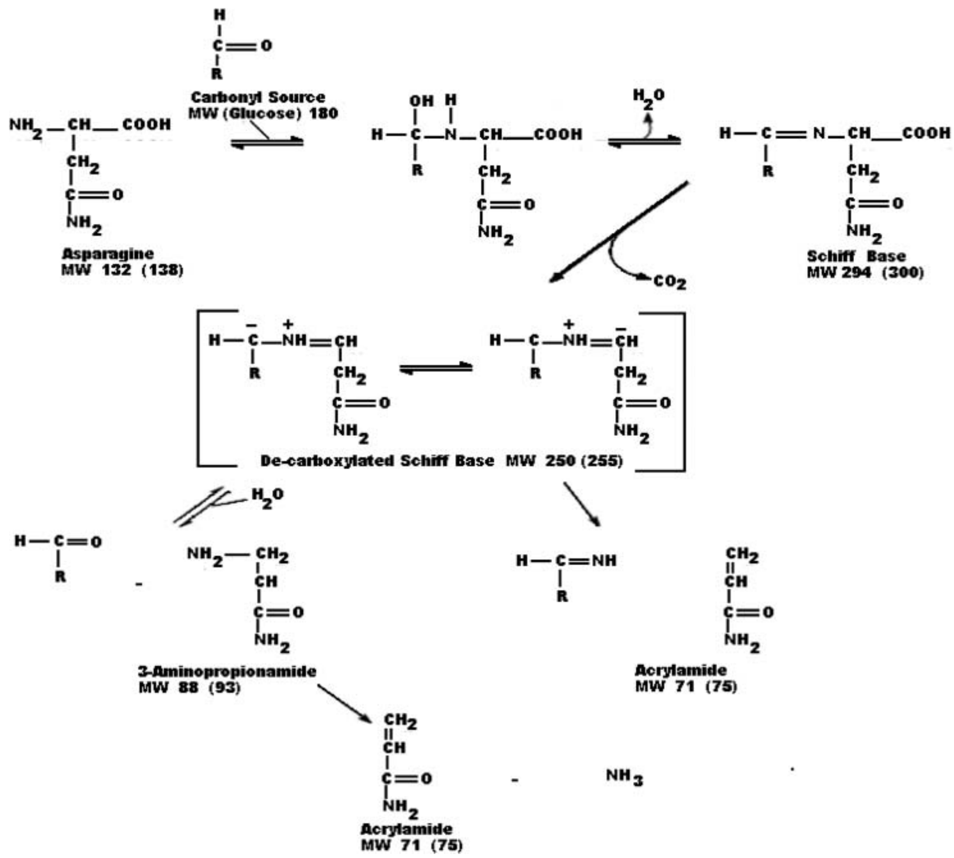

Figure 1 Mechanism of Acrylamide Formation in Heated Foods. Number in Parentheses are the Molecular Weights Observed when Uniformly Isotope-Substituted Asparagine was used (Reproduced with the Permission of Zyzak et al., 2003).

main goal to identify methods/processes that would eliminate or and/or reduce substantially acrylamide in the edible portions. However, to date no single process has been identified that removes acrylamide totally, but a combination of processes could reduce acrylamide content to non-detectable level or ALRA (i.e., a level that is not expected to induce toxicological symptoms). In addition, considerable research has shown health benefits of colored potatoes. Moderation in the consumption of snacks would go a long way to reducing the negative impact of consuming acrylamide in foods. The use of natural antioxidants as additive/ingredients also reduces acrylamide in the edible portion. In the developing countries, potatoes are processed in flour or boiled or baked. To date there is no report of acrylamide in baked or boiled potatoes.

Global warming is expected to reduce the size of arable land for the production of crops resulting in serious food shortage. It is estimated that globally more than 1 billion hectares of land has been rendered useless due to salinity alone and more to come. It is expected that over 125,000 hectares of farm land will become salinized shortly in the Netherland (Xinhua News, 2011). Recently, two Dutch potato varieties have been identified that thrive in saline soils. This discovery, when validated, could be of greater value to many coastal countries that are facing salinity of arable lands. Continued clinical trials with pigmented varieties would provide added information to consumers for nutritional choices for health and wellness through potato consumption, even though potato has large amounts of starch.

Due to the perceived and/or real presence of toxic chemicals (pesticides, veterinary drugs, etc.) in conventionally grown foodstuff (fruits, vegetables, grains, animal products, etc.) including potatoes and their negative impact on human health, there is a growing demand for produce that have not been farmed using synthetic chemicals directly or indirectly. Organic produce is filling that demands. Since potato is often used as part of regular diets in many developed countries, organic potatoes are available only at a premium cost. Recently, a comparative study was published on the minerals content and nutritional implications of organic and conventional potatoes. The study found that potatoes marketed as organic had statistically significant ($P < 0.0001$) more copper and magnesium, less iron and sodium, but similar amounts of other minerals such as calcium, potassium, and zinc compared to conventional potatoes (Griffiths et al., 2012). Although authors did not report on the cost-health benefit, they mentioned that it would not be able to distinguish between the two groups using the readily available techniques. Thus, it could be concluded that currently it would be difficult to justify the extra cost for organic potatoes.

Potatoes produce more energy per unit land and time (216 MJ ha^{-1} day^{-1} versus 159 and 121 for corn and rice, respectively) (Anderson, 2010). It is thus prudent to make concerted efforts to promote potatoes as source for dietary energy in poor and poverty stricken countries. Currently about 2% of the world's dietary energy is achieved from potatoes. Future advances in processing technologies for snacks will be dictated by consumers' demands for healthy, tasty, aromatic, appetizing, and nutritious products. Reducing acrylamide contents while maintaining finish fried product quality such as flavor, color, texture, crispness in fried potato production will remain a challenge for the food industry. Recent literature and regulatory actions in Canada, US, European Union provides ample examples of future direct actions and trends (Health Canada, 2009a).

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