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# Recent Updates on Healthy Phytoconstituents in Potato: a Nutritional Depository

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## Abstract

Potato (*Solanum tuberosum* L.) is considered to be one of the most prominent nongrain food crops throughout the world that can be regarded as most affordable and most accessible food to provide numerous health benefits. Potential role in improving human health is attributed to presence of wide range of phytonutrients in potatoes viz., polyphenols, anthocyanins, carotenoids, ascorbic acid and proteins, vitamins as well as minerals. In India, more than 75% of the potato production is confined to Indo-Gangetic plains due to thermo-sensitivity of the crop. Several reports are available in recent years to develop new cultivars with improved nutritional value as well as nutrient evaluation of existing cultivars. Current status of research on potato phytonutrients particularly antioxidants, minerals and vitamins in relation to human health as well as research carried out on enhancement of these phytonutrients through genetic manipulations has been compiled in this review article.

**Keywords** Potato · Phytoconstituents · Processing · Metabolic engineering

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## Introduction

Potato (*Solanum tuberosum* L.) is an important food crop after wheat, rice and maize, grown worldwide accounting for about 330 million tons production. India is the second largest producer of potato after China (Scott and Suarez 2011) and produces around 45.34 million tons that account for around 12.34% of total world production (FAOSTAT 2015). Potato constituents mainly phenolics, carotenoids, anthocyanins, proteins, minerals and vitamins have revolutionized the research interests in recent decade (Freedman and Keast 2011; Paget et al. 2014; Galani et al. 2017; Escuredo et al. 2018; Asokan et al. 2018).

Potato contains numerous compounds of high nutritional value imparting many health benefits (Katan and De Roos 2004; Raigond et al. 2017). Potatoes are consumed in a variety of ways such as boiled, baked, fried and roasted and are not only excellent source of energy but also exhibit secondary metabolites that are useful for human health (Badenhorst 2014). Various phytonutrients (anthocyanins, carotenoids, phenolics, flavonoids), minerals (potassium, magnesium, sodium, iron, copper, zinc) and vitamins (vitamin B1, B6, B9, C, E) are present in potato contributing towards health benefits (Lewu et al. 2010; White et al. 2012; Ngobese et al. 2017). These phytonutrients are of great interest for human consumption due to their antioxidant behaviour. The antioxidant activity of potato has been reported to be higher than those of bell peppers, carrot and onion and that too was highest in potato peels (Al-Saikhan et al. 1995). Potatoes have been reported to be the most affordable source of vitamin C, potassium and fibre providing about 10% of its daily value (Drewnowski and Rehm 2013). Similarly, another report justifies that baked Russet potatoes (99.22 g) contribute to 5% Recommended Dietary Allowance (RDA) of protein, and 5–10% of vitamin B3, B9, fibre, iron, magnesium and carbohydrates, whereas 10–15% of vitamin B6, manganese and 15–25% RDA of potassium and vitamin C. Interestingly, potatoes can provide about one-fourth of RDA of vitamin C (Gibson and Kurilich 2013). Bibi et al. (2019) highlighted potato as a functional food to improve gastrointestinal health either through gut microbiota modulation or by strengthening the function of intestinal epithelial barrier. Gut microbiota have been found to be enshaped by good diet. As potato contains a diverse range of phytonutrients and bioactive food components, it plays an important role in improving gut microbiota and gut health. Bioactive components in potato contribute to gastrointestinal health either directly through epithelium interactions or indirectly by manipulating the gut microbiota, and microbial secondary metabolites (like short chain fatty acids produced by polyphenols and phytonutrient degradation) so as to increase their bioavailability. Phytochemicals in coloured potatoes have been studied both *in vitro* and *in vivo* (in animal models) and were observed to act as free radical scavengers, thereby not only showing anti-proliferative and antimicrobial activities but also alleviate incidence of breast cancer in rat models (Thompson et al. 2009; Bontempo et al. 2013). Research work has been carried out and published in recent years on nutritional quality of potatoes, and the effect of potato processing on various phytochemicals and genetic modifications is compiled in current review article.

## Antioxidants

Potato houses a myriad of bioactive compounds that have high antioxidant potential attributed to its ability of quenching reactive oxygen or nitrogen species, so as to combat oxidative stress in cells which may otherwise lead to serious complications (Wang et al. 2011; Guaadaoui et al. 2014). Major antioxidants, beneficial for human health, in potato are phenolics, anthocyanins, flavonoids and carotenoids. Ranges of different phytonutrients reported in literature are given in Table 1. Antioxidants play an important role in human diet as they decrease the NF-κB activation that inhibits the over synthesis of cytokines from oxidants. Natural plant-derived polyphenols (mainly flavonoids) help in alleviating oxidative stress through anti-inflammatory effect thereby leading to activation of oxidative stress response (Chirumbolo 2010). Along with this,

**Table 1** Major phytonutrients present in the potato (*Solanum tuberosum*) and concentrations reported in different cultivars throughout the world

| Name | Reported range | Reference |
|---|---|---|
| Phenolics | 76 to 181 mg /100 g FW | Reyes et al. (2005) |
| | > 5 mg/100 g | Mattila and Hellström 2007 |
| | 1.8 to 11 mg/100 g DW (22 - 473 mg/100 g DW chlorogenic acid) | Navarre et al. (2010) |
| | 22.53–85.85 mg/100 g FW | Dalamu Singh et al. (2015) |
| | Flesh 191 to 1864 mg/100 g DM | Ah-Hen et al. 2012 |
| | With peel 345 to 2852 mg/100 g DM | |
| Anthocyanins | 61.5 to 573.5 cyanidin mg/kg | Hamouz et al. (2011) |
| | 11 to 174 mg/100 g cyanidin-3-glucoside | Reyes et al. (2005) |
| | 80.9 to 269.67 mg/100 g FW | Dalamu et al. (2014) |
| | 9.5–38 mg/100 g FW | Brown et al. (2005) |
| | Peel 0.65 g/kg FW<br>Flesh 0.22 g/kg FW<br>Whole 0.31 g/kg FW | Jansen and Flamme (2006) |
| Carotenoids | 50 to 2000 μg per 100 g FW | Hejtmankova et al. (2013) |
| | 41−131 μg/100 g | Breithaupt and Bamedi (2002) |
| | Skin (28 mg/kg DW)<br>Flesh (9 mg/kg DW | Valcarcel et al. (2015) |
| | 35 to 795 μg/100 g FW | Brown et al. (2005) |
| Vitamin C | 13 to 31 mg/100 g FW<br>217.70 to 689.47 μg/g DW<br>798 mg/kg to 117 mg/kg<br>47.21 to 208.63 mg/150 g FM<br>0.0828 to 0.2416 mg/g FW | Dale et al. (2003)<br>Andre et al. (2007b)<br>Valcarcel et al. (2015)<br>Nassar et al. (2014)<br>Galani et al. (2017) |
| Proteins | 3.77 to 7.36% dry wt.<br>8% dry wt. basis | Abebe et al. (2012)<br>Bártová et al. (2018) |
| Minerals | 17.13 to 164.83 mg/kg DW iron<br>0.07 to 20.21 mg/kg DW zinc | Nassar et al. (2012) |

they also play important role in inhibition of tumour cell growth or malignancy (Kim et al. 2015).

## Phenolics

Phenolic compounds are one of the most widely studied and main class of the products from secondary metabolism in plants (Naczk and Shahidi 2004), which acts as antioxidant and scavenges free radicals formed thus reducing the aldehyde or ketones generation through volatile decomposition (Alamed et al. 2009). Polyphenols are considered the potent inhibitors of carcinogenesis, obesity and cardiovascular disorders (Khan et al. 2008; Kubow et al. 2014). In comparison to a variety of vegetables, potatoes are a rich source of total soluble phenolic acids calculated as aglycones (more than 5mg/100g) (Mattila and Hellström 2007). Potato peels are better source of phenolics (1.2-14 folds) compared to flesh (Acosta-Estrada et al. 2014). Predominant phenolic acids in potato peel are chlorogenic acid (present in high concentration), gallic acid, vanillic acid, p-coumaric acid, p-hydroxybenzoic acid, caffeic acid and protocatechuic acid (Onyeneho and Hettiarachchy 1993; Mattila and Hellström 2007). Phenolics were estimated in cooking water left out after potato boiling. The water contained high concentration of chlorogenic acid followed by vanillic acid (Rojas-Padilla et al. 2019). Stem end and bud end were found to be the main accumulation centre of total anthocyanin and total phenols. These observations differ from the widespread idea that phytonutrients are mostly accumulated in the peel of tubers. Around 15 amino acids were found in different potato cultivars of Lithuania analyzed at three stages of maturity (very early, early and late) with caffeic acids, chlorogenic acid, tyrosine and tryptophan observed in highest concentrations. Also, the amounts of tested compounds were observed to decrease with increase in level of maturity (Brazinskiene et al. 2017). Reyes et al. (2005) reported that total anthocyanin and total phenol concentration in purple and red fleshed potatoes were 0.9- to 1.6-fold higher, respectively, in peel than in flesh thereby accounting for about 20% of the total concentration. The total phenol concentration of different purple and red-fleshed potato cultivars were observed to be in a range from 76 to 181 mg/100 g fresh weight (FW) chlorogenic acid, and these concentrations were cultivar and location dependent (Reyes et al. 2005). Nara et al. (2006) have witnessed the higher antioxidative potential through DPPH radical scavenging activity in potato peel as compared to flesh and correlated higher concentrations of chlorogenic acid and caffeic acid in case of free-form phenolics, while that of ferulic acid in case of bound form with radical scavenging activity. Antioxidant profiling of 23 native Andean potato cultivars revealed that chlorogenic acid and its isomers were dominant in polyphenolic profile in each cultivar (Andre et al. 2007a). Andre et al. (2007b) evaluated various antioxidants in 74 native Andean cultivars and observed a positive correlation between total phenolics (1.12–12.37 mg of GAE/g dry wt.) and hydrophilic antioxidant capacity (28.25–250.67 μmol of Trolox equiv/g dry wt.). Navarre et al. (2010) studied around 50 different potato cultivars and observed that chlorogenic acid was the major phenolic in potato ranging between 22 and 473 mg/100 g dry weight (DW) while total phenolics were reported to be 1.8 to 11 mg/g DW and antioxidant capacity was in a range of 27–219 μmol trolox equivalent/g DW. Kita et al. (2013) evaluated seven coloured potato cultivars for total

polyphenols and observed a high range of 227–845 mg/100 g DW. Lemos et al. (2015) observed high amounts of phenolic compounds in coloured cultivar Purple Majesty of 209 mg GAE/100g FW. The total amount of phenolics in popular Indian potato cultivars ranged from 22.53 to 85.85 mg GAE per 100 g FW in whole tuber and a slightly lower range of 20.26–63.05 mg GAE per 100 g FW in flesh (Dalamu Singh et al. 2015). Recent reports established the positive correlation of total phenols in potatoes with the environmental factors such as field altitude as well as the average temperature during the growing season (Hamouz et al. 2006; Zarzecka et al. 2017). Addition of nitrogen and potassium fertilizers to the soil enhanced the amounts of polyphenols, anthocyanins and thus antioxidant properties in tubers of bluish-purple potato cultivar 'Blue Congo' (Michalska et al. 2016). Nitrogen was more effective for anthocyanin enhancement as it almost doubled the concentration of anthocyanins and also played a crucial role to increase phenolics, especially chlorogenic acid, at 120 kg/ha rate. Ji et al. (2012) developed granules rich in phenolics and with low glycoalkaloids concentration from 20 coloured potato clones. These granules showed neuroprotective activity due to presence of phenols. Nassar et al. (2014) reported that total phenolics in potato somaclones was in the range of 61–122 GAE/150 g fresh matter (FM). Ah-Hen et al. (2012) reported that peeled potatoes contained lower concentration of total polyphenols (191 to 1864 mg/100 g) compared to unpeeled samples (345 to 2852 mg/100 g) in 12 landrace clones from Chile. Giusti et al. (2014) have characterized and quantified composition of phenolics in 20 native Andean potato cultivars, exhibiting different flesh colour. Amounts of total phenolics were observed in the range of 162.19 to 510.20 mg GAE/100 g DW in purple-fleshed potatoes while 152.40 to 261.49 mg GAE/100 g DW in red-fleshed and 113.37 to 114.63 in yellow-fleshed cultivars. Similarly, Andean cultivars were found to have chlorogenic acid or its isomeric forms as predominant phenolic (contributing more than 40%). These studies have indicated that potatoes contain various ranges of phenols that varied based on tuber colour, field altitude and environment. This information can be utilized for selection of cultivars rich in phenols and for development of potato-based functional foods.

## Anthocyanins

Anthocyanins are water-soluble polyphenolic pigments of flavonoid group that correspond to the colourful plant parts due to characteristic chromophores present in them (Smeriglio et al. 2016). Anthocyanins have been reported to prevent various chronic disorders including colorectal cancer in mouse models (Lippert et al. 2017) and dementia by enhancing cognition (Kent et al. 2017). Charepalli et al. (2015) witnessed the role of anthocyanin in prevention of cancer by revealing the efficiency of purple fleshed potatoes (rich in anthocyanins) in Wnt/β-catenin signalling inhibition contributing towards increased apoptosis and reduced cancer stem cells. Jiang et al. (2016) revealed that anthocyanins from purple-fleshed potatoes are effective in curing liver injuries induced by alcohol in mouse models by attenuation of cytochrome P450 2E1 expression. Han et al. (2006) suggested that flakes of anthocyanin-rich (petanin being the predominant anthocyanin) purple-fleshed potatoes show better DPPH radical scavenging property, linoleic acid oxidation inhibitory activity and escalation of hepatic superoxide dismutase, and glutathione peroxidase mRNA expression, thus contributing

to higher antioxidant potential. Major compounds responsible for pigmentation in blue-coloured potato cultivars (Hermanns Blaue, Vitelotte, Shetland Black and Valfi) were reported to be 3-*p*-coumaroylrutinoside-5-glucosides of malvidin, petunidin and peonidin (Hillebrand et al. 2009). Moser et al. (2015) reported high concentration of anthocyanins and chlorogenic acids, and concentrations were reported in decreasing order in purple-, red- and white-coloured potato peel extracts. They observed these extracts to be the modulators in glycaemic response that reduce the intestinal glucose transport up to 83%, but not much effect on starch digestion was observed, as studied on Caco-2 human intestinal cell monolayers. Later, these studies were carried out in an animal model system, and it was concluded that chips prepared from purple potatoes were observed to reduce blood glucose in 30 min in contrast to those of white potatoes thereby confirming their role as glycaemic response modulators (Moser et al. 2018). The flesh colour is a clear indication of total anthocyanin concentration as purple- and red-fleshed potatoes possess higher concentrations (61.5 to 573.5 cyanidin mg/kg) as well as better antioxidant behaviour (4–5 times higher) in comparison to yellow- or white-fleshed tubers (Hamouz et al. 2011). Jansen and Flamme (2006) reported that anthocyanins are densely distributed in the outer skin (0.65 g/kg FW) when compared with flesh (0.22 g/kg FW) or whole potato tuber (0.31 g/kg FW), and few changes were observed in anthocyanin concentration during 135 days of storage. The total anthocyanin concentration of different purple- and red-fleshed potato cultivars ranged from 11 to 174 mg/100 g FW (Reyes et al. 2005). Eichhorn and Winterhalter (2005) isolated and characterized the major anthocyanins present in four pigmented potato cultivars, Hermanns Blaue, Highland Burgundy Red, Shetland Black and Vitelotte. Petunidin derivatives were found to be predominant in three cultivars, while pelargonidin was dominant in Highland Burgundy Red and malvidin (aglycon) in Vitelotte. Overall, coumaric acid derivatives, mainly petunidin and peonidin derivatives, were observed as major anthocyanins in these cultivars. Similarly, Andre et al. (2007a) observed dark-fleshed tubers to be rich in anthocyanins mainly petanin (petunidin-3-p-coumaroyl-rutinoside-5-glucoside). Anthocyanins ranged from 21 to 109 mg /100 g DW in purple- and red-fleshed potato cultivars (Kita et al. 2013). Lemos et al. (2015) observed that the coloured cultivar Purple Majesty is a rich source of anthocyanin containing about 219 mg/kg FW. Giusti et al. (2014) identified cyanidin, peonidin and pelargonidin as major anthocyanins in red-fleshed cultivars with total anthocyanins ranging from 8.2 to 90.9 pg-3-glu equivalents/100 g DW. Similarly, in purple fleshed cultivars, range was 16.8 to 152.7 mg of cy-3-glu equivalents/100 g DW and cyanidin, peonidin, pelargonidin, petunidin and malvidin were predominant anthocyanins. Dark-fleshed cultivars can be used for anthocyanin extraction and development of anthocyanin-rich food.

## Carotenoids

Carotenoids are lipophilic isoprenoid compounds responsible for bright pigmentation in all photosynthetic organisms that not only act as singlet oxygen scavengers and vitamin A precursors but also help cure many disorders including cancer and cardiovascular diseases (Fiedor and Burda 2014). Although around 600 different carotenoids have been identified and characterized; those known as dietary compounds like β-carotene, lutein and lycopene were focussed on by researchers (Young and Lowe 2018). Flesh colour is an important attribute with yellow potatoes corresponding to

higher carotenoid value as compared to that of white-coloured skin or flesh (Valcarcel et al. 2015). All potato cultivars contain carotenoids in their flesh, but the concentration may vary from one cultivar to another, ranging from 50 to 2000 μg per 100 g FW, depending upon flesh colour (Hejtmankova et al. 2013). Janave and Thomas (1979) have studied the role of storage conditions on concentration of carotenoids in potato cultivars. They selected nine Indian cultivars with different flesh colours to study this effect, and it was observed that storage at low temperature (4 °C or 15 °C) was less beneficial than storage at ambient or room temperature (25–30 °C) showing increase in total carotenoid level. Irradiation (10 krad) to inhibit sprouting reduces carotenoid concentration to half when stored at 15 °C for 6 months. Level of carotenoids could be increased (up to six times) in these conditions by increasing the temperature to 34–35 °C for 6 to 12 days. However, these storage temperatures are not suitable for storing potatoes for longer durations. Brown et al. (2005) reported carotenoid concentration in range of 35–795 μg/100 g FW and correlated (r = 0.77) it to lipophilic fraction ORAC (4.6 to 15.3 nmol α-tocopherol equivalents/100 g FW). As degree of yellowness is a clear indication of carotenoid level, this study highlights a significant 10-fold increase in level of carotenoid in dark yellow cultivars. Breithaupt and Bamedi (2002) quantified the carotenoids in eight common potato cultivars of Germany and reported that antheraxanthin, zeaxanthin, violaxanthin and lutein are four major carotenoids accounting for about 175 μg/100 g FW, and only antheraxanthin was found in the form of carotenoid epoxide. However, β-cryptoxanthin, β-carotene and neoxanthin were reported to be in low fractions. Column chromatography followed by enzymatic cleavage by lipase enables direct quantification of carotenoid esters (ranging from 41 to 131 μg/100 g) in potato tubers. Similarly, another report highlights xanthophylls (violaxanthin and lutein) to contribute majorly to the total carotenoid concentration in potatoes while β-carotene contributed the least in most of the lines (Nesterenko and Sink 2003). Likewise, 60 different potato cultivars cultivated in Spain were reported to have total carotenoids in the range of 50.0 to 1552.0 μg/100 g DW with three major pigments in their carotenoid profile, violaxanthin, lutein and neoxanthin, while β-cryptoxanthin, antheraxanthin and β-carotene were minor and zeaxanthin was absent. Moreover, abundance of esterified forms of xanthophylls in the majority of cultivars is indicative of carotenoid accumulation in plastids (Fernandez-Orozco et al. 2013). The major carotenoids like lutein and zeaxanthin were found in high levels (up to 17 μg/g dry wt.) in potatoes (Andre et al. 2007a). Andre et al. (2007b) detected concentrations of carotenoids in the range of 2.83–36.21 μg/g DW in 74 Andean potato cultivars. Cultivation of potato in the same location year after year plays an important role in total carotenoid concentration (Valcarcel et al. 2015). Carotenoids concentration was found to be 3-fold higher in skin (28 mg/kg DW) than in flesh (9 mg/kg DW) in 'Burren' cultivar of Ireland. Brown et al. (2005) concluded that potatoes with dark yellow flesh comprised about 10-fold higher carotenoid concentration compared to white-fleshed cultivars and fall in the range of 35 to 795 μg/100 g FW depending upon the extent of yellowness in the flesh. Furthermore, the total carotenoid concentration was enhanced with a rise in temperature during the growing season (Escuredo et al. 2018). Carotenoids being good for human health are desirable in the human diet so that high concentration of carotenoids in foods consumed regularly such as potatoes is of high importance.

## Proteins

Potato contains approximately 2–3% protein content on fresh weight basis. On dry weight basis, potato protein content is approximately 10% that is comparable to protein content in most cereals including wheat and rice. Potato tuber proteins are mainly grouped into three categories, i.e. patatins, protease inhibitors and other proteins. Patatin is a major storage protein. Protease inhibitors are low-molecular-weight proteins. Patatin and protease inhibitors together account for 40% of total potato tuber protein. Potato proteins are nutritionally comparable to whole egg protein and are a rich source of lysine (Makinen 2014). Potato protein is considered as most valuable non-animal protein due to its high essential amino acid concentration. Potato (100g fresh weight) can contribute 10–30% of recommended intake for a child of 1–3 years age and 3–8% for an adult of 19–55 years age (Anon 2007). An ultrafiltration method combined with diafiltration to extract proteins from potato recovers higher-quality protein with better nutritional functions compared to their counterparts already available in the market (Zwijnenberg et al. 2002). Kudo et al. (2009) isolated and purified three peptide fractions from potato: Phe-Asp-Arg-Arg, Phe-Gly-Glu-Arg and Phe-Gly-Glu-Arg-Arg. These fractions were characterized by marked antioxidant potential as indicated by *in vitro* reduction in lipid oxidation (14.7%, 24.2%, 26.4%) and inhibition of linoleic acid oxidation. These peptides were also examined for *in vivo* activity in male Wistar rats through oral route (dosage 100 mg/kg body wt.), followed by injecting ethanol after half an hour. These peptides effectively reduced the damage that ethanol caused to mucosa in the stomach by 57%, 67.9% and 60.3% respectively. Fischer et al. (2015) studied *in vitro* inhibitory diversity of potato proteins that act as protease inhibitors. Predominant inhibitors were potato protease inhibitors I/II, metallocarboxypeptidase inhibitors, Kunitz-type inhibitors, pectin methylesterase inhibitors and defensins. Potato protease inhibitors I/II and Kunitz-type inhibitors significantly inhibited pig pancreas elastase, cathepsin K, β-secretase, HIV-1 protease and potato 5-lipoxygenase. Abebe et al. (2012) observed protein concentration in the range of 3.77 to 7.36% (DW) in 21 potato cultivars of Ethiopia grown in two different regions. Ralla et al. (2012) proposed a methodology that efficiently isolates the high value protein fractions (protease inhibitors and patatins) from waste collected from potato processing industries retaining their full activity but also reduces the amount of unwanted glycoalkaloids in single step.

Mäkinen et al. (2016) studied the potent roles of proteins in inhibition of hypertension *in vivo* through the Goldblatt rat model. Their effect on blood pressure was evaluated *in vivo*. Results showed that potato peptides induced difference of about − 60 mmHg in mean arterial pressure when compared with vehicle treated rats. Bártová et al. (2018) isolated proteins from potato starch effluent at four temperature variants from 40 to 100 °C with 20 degrees intervals and evaluated their structure, composition, stability and antifungal as well as trypsin inhibitory activities. Various variants of cysteine, aspartic and serine protease inhibitors were reported at all the temperature points. Interestingly, Kunitz-type protease inhibitors were detected only at 40 and 60 °C, thereby highlighting the thermal lability of the former. In contrast, high temperature resulted in isolation of protease inhibitors I and II, proteins with low molecular weight (7–17 kDa) and highest inhibitory effect on five strains of *Fusarium* sp. with marked antifungal activity having 0.18 mg/ml $IC_{50.}$ Owing to their antifungal behaviour and functional stability at high temperature, potato protease inhibitors I and II could find a potential role in agricultural, food or pharma

industry. Similarly, potato proteins from processing industry waste have been utilized for emulsifying properties through selection of peptides. These peptides could efficiently unfold at interface, followed by testing in emulsion of 5% rapeseed oil, with regular monitoring for 7 days for their stability. This technique can prove a step towards emulsifier production using potato proteins (García-Moreno et al. 2018). Yao and Udenigwe (2018) studied the post-translational modifications in peptides produced upon hydrolysis of potato protein by digestive proteases that can eventually bring a big breakthrough in modifying potato peptides in order to manipulate chemical properties and implicated in bioavailability, bioactivities and biomolecular interactions of food peptides.

## Minerals

Various minerals such as potassium, magnesium, phosphorus, copper, iron, zinc and selenium are present in potato (Nassar et al. 2012). Potato contains high potassium concentrations and low sodium levels which makes it most suitable for patients with high blood pressure but due to high levels of potassium, it is not recommended for patients with renal disorders (McGill et al. 2013). Subramanian et al. (2011) evaluated freeze-dried potato for the presence of minerals important for human health (iron, zinc, calcium, copper, phosphorus, magnesium, manganese, potassium and sulphur). Navarre et al. (2019) reviewed the daily recommended values for potassium (4700 mg/day) and magnesium (310 to 420 mg/day) in different potato cultivars. Potato peel has higher mineral concentration than potato flesh probably due to direct absorption from soil through periderm. More than half of the concentration of iron, 34% calcium and 17% of zinc was observed in potato peel. In case of flesh, the bud end was far less concentrated with minerals (except potassium) as compared to stem end while levels of calcium, phosphorous and copper decreased from the end to the middle of the tuber. Laursen et al. (2011) studied the composition of different minerals in potato when exposed to different methods of cultivation (organic and conventional), at three varied locations. It was observed that although high crop yield was recorded in conventional system, chemometric analysis and semiquantitative ICP-MS revealed that crops grown organically had distinct multi-elemental fingerprinting showing about 25 elements. Andre et al. (2007b) studied the micronutrient profile of 74 potato cultivars and observed calcium in the range of 271.09–1092.93, iron in the range of 29.87–157.96 and zinc in the range of 12.6–28.83 μg/g DW. Abebe et al. (2012) reported that mineral concentration in the potato depends upon the genetic variation as well as the location site. As mineral nutritional deficiencies are a major health concern globally, their study postulated that by consuming only 200 g of potato fresh weight, a portion of recommended daily intake of iron (65% in children, 29% in men and 13.3% in women) can be achieved from tubers of cultivar Sisay. Similarly, in the case of cultivar Menagesha, 200 g potato intake fulfils recommended intake of zinc by 17% in children, 12% in men and 14.3% in women. Overall, on dry weight basis, potato cultivars were observed to contain iron in the range of 17.13 to 164.83 and zinc in the range of 7.07 to 20.21 mg/kg DW. Besides the cultivars, geographical conditions of the region where the crop is grown also plays an important role in deciding mineral composition of potato tubers (Nassar et al. 2012). Important minerals (iron, zinc, calcium and selenium) were evaluated in 16 potato cultivars with five different geographical locations. Three

cultivars, Freedom, Russet Burbank and Yukon Gold, were a most promising dietary source of potassium, copper, iron, zinc, selenium, magnesium and phosphorus. Similarly, Lombardo et al. (2014) concluded that not only cultivar selection but also method adopted for cultivation and atmospheric conditions play an important role in mineral accumulation in potato tubers. Organic and conventional method were compared, and it was reported that organically cultivated tubers were more efficient in terms of phosphorous concentration (1.2 times higher) but had equal copper and magnesium levels and lower calcium, iron, sodium, potassium and manganese levels. Paget et al. (2014) determined the concentration of iron and zinc in potato cultivars grown in Peru and observed positive correlation (r = 0.05 to 0.18) between mineral concentration and tuber dry matter was on fresh weight basis, while negative (− 0.14 to − 0.38) on dry weight basis. Wekesa et al. (2014) highlighted that type of soil also affects the mineral accumulation in potato tubers. Four cultivars, Kenya Mpya, Cangi, Tigoni and Dutch Robjin (both fresh seed and that stored in diffused light), were grown in eight types of soil at various sites and then evaluated for mineral concentrations. It was evident that composition of minerals in soil is directly proportional to minerals in the potato tubers. Along with this, they observed that the actual composition depends on seed cultivar and period of storage as well.

## Vitamins

Potato is an important source of vitamins in the human diet which provides a good proportion of daily requirement (around 26–27%) of vitamin C and vitamin B6 (FAO 2009). Vitamins that are generally found in potato are vitamin B1, B6, B9, C and vitamin E, out of which vitamin C has drawn maximum attention as potato can synthesize it and store it in different plant parts. Vitamin C (ascorbic acid) is an antioxidant and plays an important role in human health like enhanced mineral absorption, inhibition of carcinogenesis and as a neuroregulator. Dale et al. (2003) have reported that vitamin C concentration in potato ranged from 13 to 31 mg/100 g FW, whereas Nassar et al. (2014) have reported 47.21 to 208.63 mg/150 g FM vitamin C in potato somaclones. Love and Pavek (2008) evaluated 75 potato cultivars cultivated in North America for vitamin C concentration and observed a wide range of vitamin C (11.5–29.8 mg/100 g FW). Similarly, Han et al. (2004) reported a range of 24–69 mg/150 g FW, while Kwon et al. (2006) reported 0.74–45.3 mg/150 g FW in different potato cultivars. Andre et al. (2007b) reported ascorbic acid concentration ranging from 217.70 to 689.47 μg/g DW, whereas α-tocopherol ranged from 3 to 20 μg/g DW. Similarly, vitamin C ranged from 0.0828 to 0.2416 mg/g FW in 11 Indian potato cultivars (Galani et al. 2017). Cho et al. (2013) estimated the ascorbic acid concentration in the range of 48.45–58.35 mg/150 g FW in advanced potato breeding lines. Valcarcel et al. (2015) highlighted that levels of vitamin C ranged from 798 to 117 mg/kg in potato flesh which is directly proportional to expression of L-galactono-1,4-lactone dehydrogenase (GLDH). In contrast, Tudela et al. (2003) reported that initial GLDH expression is not related to vitamin C accumulation; rather, when freshly cut potatoes are stored, GLDH activity gets increased and thus vitamin C accumulates. So, it can be assumed that GLDH is not the only component responsible for vitamin C accumulation but is rather one of them. French fries and oven-baked fries act as a

source of vitamin E for children and adolescents besides providing other phytonutrients (Freedman and Keast 2011). Potato contains vitamin B9, popularly known as dietary folate, in the range of 12 to 41 μg/100 g FW and 0.5 to 1.4 μg/g DW in cultivars, while 115 μg/100 g FW occurs in wild species (Goyer and Sweek 2011). It has been reported that potato consumption reduced the folate deficiency in serum (Hatzis et al. 2006). Mooney et al. (2013) observed vitamin B6 in the range of 16 to 27 μg/g DW in potatoes at different levels of maturity while the amount of vitamin B1 was reported in the range of 0.06 to 0.23 μg/100 g FW (Goyer and Sweek 2011). The reports have shown large variations in vitamin concentration in potatoes.

## Effect of Cooking on Antioxidants and Minerals

As potato cannot be consumed raw, it becomes very important to know what amounts of phytonutrients are retained after cooking and do their levels increase or decrease. Brief outline of effect of cooking on major compounds present in potato reported in literature has been summarized in Table 2. Recent studies on effect of cooking on antioxidants revealed that level of some potato polyphenols are known to get lowered during cooking thereby reducing overall antioxidant potential (Laib and Barkat 2018). In addition to that, hydrolysable phenolics are less prone to reduction and survive both microwave and steam cooking as compared to soluble polyphenols (Faller and Fialho 2009). Carotenoid level in Rosara potatoes was observed to rise when subjected to

**Table 2** Effect of potato processing methods on major antioxidants as well as micronutrients

| Class of the compound | Effect of cooking | | | Reference |
|---|---|---|---|---|
| | Boiling | Microwaving | Frying | |
| Phenolics | Constant | Constant | | Faller and Fialho (2009) |
| | Minimum losses | | Reduce | Tudela et al. (2002) |
| | Enhance | Enhance | Enhance | Navarre et al. (2010) |
| | Minimum losses | | | Lachman et al. (2013) |
| | Increase | | | Burgos et al. (2013) |
| | | Reduce | Reduce | Silveira et al. (2017) |
| Anthocyanins | Reduce | Reduce | Reduce | Perla et al. (2012) |
| | Constant | Constant | Constant | Lachman et al. (2013) |
| | Constant | | | Burgos et al. (2013) |
| | | | Reduce | Kita et al. (2013) |
| | Increase | Constant | Increase | Lemos et al. (2015) |
| Carotenoids | Increase | Increase | Increase | Gehse et al. (2018) |
| Vitamin C | Minimum losses | | | Lachman et al. (2013) |
| | Increase | | | Burgos et al. (2013) |
| | | Reduce | Reduce | Silveira et al. (2017) |
| Minerals | Reduce | Reduce | Reduce | Bethke and Jansky (2008) |

cooking (Gehse et al. 2018). Tudela et al. (2002) elucidated that fresh-cutting of Monalisa potato tubers triggers flavanol production (mainly quercetin 3-rutinoside, quercetin 3-diglucoside and quercetin 3-glucosylrutinoside) upon 3 days of cold storage (under light) and reported a range of 6 to 14 mg/100 g FW when stored for 6 days under similar conditions. However, cooking reduced the amount of flavonols, whereas steam cooking was observed to result in minimum loss of flavanols as well as phenolics (chlorogenic acid, caffeic acid). Navarre et al. (2010) reported a contrasting post cooking behaviour in immature potatoes (those harvested at developing stage and containing ample phytonutrients) of three cultivars, Piccolo, Bintje and Purple Majesty. Five different methods, baking, steam, stir-fry, microwave and boiling, were employed, and none of these lowered the amount of antioxidants (total phenolics, flavonols and chlorogenic acid) but rather the concentrations increased considerably. Interestingly, with baking, antioxidant capacity was enhanced 1.2-fold in cultivar 'Bintje' while in 'Purple Majesty', chlorogenic acid increased 1.36 times and level of rutin was also 2-fold higher.

Perla et al. (2012) investigated effect of cooking on overall antioxidant potential as well as individually on major potato antioxidants, anthocyanins, phenolics, flavonols and lutein, in 14 potato cultivars with different skin/flesh colours. In agreement with other studies, levels of all the antioxidants were lowered corresponding to reduced DPPH radical scavenging activity in all cultivars except in red- or purple-fleshed ones that retained fair concentrations even after cooking. Lachman et al. (2013) observed that concentration of chlorogenic acid and total glycoalkaloids were lowered following cooking treatment (microwaving, boiling, baking) but not total anthocyanin concentration. However, boiling could be considered the best cooking method after peeling to minimize phenolic and vitamin C loss and to enhance degradation of glycoalkaloids. The pigmentation in the flesh showed positive correlation with antioxidant retention after cooking.

Burgos et al. (2013) examined the amount of phenolic acid, total phenolics, anthocyanins and thus antioxidant activity in raw as well as boiled freeze-dried purple-fleshed native Andean cultivars of *Solanum tuberosum* Gp *andigenum*. In agreement with other reports, chlorogenic acid was found to be in high concentration followed by caffeic acid that tends to decrease drastically with boiling. Maximum anthocyanin concentration was observed (418 mg/100 g fresh weight) in deep purple-fleshed sample (Guincho) which thus showed high antioxidant activity of 17,305 μg Trolox equivalent/g FW while three other accessions showed comparable concentration of anthocyanins and chlorogenic acid. Total phenolics and antioxidant activity was more in boiled than raw tubers in case of all the accessions. As per this study, boiled potatoes with deep purple flesh serve as good source of anthocyanins. Silveira et al. (2017) have reported that frying and microwaving reduces total polyphenols and ascorbic acid concentration in five potato cultivars of different flesh colour. In agreement with other reports in literature, concentration of total polyphenols in potatoes with dark flesh colour was much higher (2880.5–3241.6 mg GAE/kg DW) than those of light flesh coloured cultivars. Ascorbic acid (260.7–511.6 mg AA/kg DW) and thus total antioxidant capacity was also higher in coloured potatoes. But total antioxidant capacity was found to get doubled after microwaving while reduced to half after frying. So, microwaved coloured potatoes could retain active phytochemicals and be a healthy serving. Furrer et al. (2017) studied the effect of industrial processing on various potato

cultivars (with white, yellow or pigmented flesh). They reported that total chlorogenic acid level was 43–953 mg/100 g DW while total anthocyanins ranged from 18.6 to 22.9 mg/100 g DW before processing. These concentrations were directly proportional to the pigmentation pattern irrespective of the type of antioxidant studied. Post processing analyses revealed that although there is a considerable loss in the level of antioxidants, in pigmented ones, unlike white- or yellow-fleshed potatoes, around 49 to 85% phenols and 79–129% anthocyanins were retained in the potato products. Kita et al. (2013) highlighted that frying generally reduces anthocyanin components by around 38 to 70% in red- and purple-fleshed potatoes, and petunidin derivatives were most labile while malvidin and pelargonidin derivatives were comparatively stable during frying process. However, antioxidant capacity was retained in potato crisps despite polyphenols and anthocyanin degradation.

Mineral concentrations are also affected by cooking processes. Leaching, however, individually does not affect minerals but if paired with boiling reduces minerals. Boiling alone can reduce potassium and other minerals to half in case of chopped pieces of potato while up to 75% of loss is reported if potato shreds are used. Not only potassium; other minerals reported to have been lowered following boiling were iron, zinc, magnesium, phosphorous, sulphur and manganese. Freezing followed by sun drying in Bolivian potato cultivars to prepare the traditional food chuño also reduces the phenolic concentration and antioxidant capacity, but not completely, which makes chuño, a food of choice for antioxidant-rich diet (Peñarrieta et al. 2011). Burrowes and Ramer (2008) studied the effect of cooking on potassium concentration in six cultivars and found around 1.5-fold loss during cooking. Lemos et al. (2015) observed that in coloured potato cultivar, Purple Majesty, the amount of polyphenols lowered during cooking while that of anthocyanins increased in all cooking methods except baking. Jayanty et al. (2018) have summarized different research studies on methods to reduce some unwanted compounds (such as acrylamide accumulated during cooking), to restore bioactive components of potato (anthocyanins, minerals, flavonoids, phenolic acids, vitamins and umami compounds) and to enhance bioavailability. It was concluded that in opting for any way of cooking (boiling, frying, baking or microwaving), care must be taken to avoid longer cooking time and high temperature and encouraged vacuum cooking so as to attain minimal nutrient losses and increase palatability as well as bioavailability post-cooking.

## Metabolic Engineering to Enhance Antioxidative Capacity (Fig. 1)

Several reports in literature revealed that most potato cultivars have low carotenoid concentration and when it comes to provitamin A activity (β-β-carotene or β-carotene, α-carotene, β-cryptoxanthin etc.), they are in negligible concentrations (Breithaupt and Bamedi 2002; Diretto et al. 2006; Fernandez-Orozco et al. 2013). Ducreux et al. (2005) successfully enhanced total carotenoid concentration (5.60–35.0 mg/kg DW) as well as individually β-carotene (11-fold) and lutein (19-fold) by overexpression of phytoene synthase gene *CrtB*. Likewise, Diretto et al. (2006) have reported about 14-fold increase in β-β-carotenoid and 2.5-fold in total carotenoid concentration by manipulating the biosynthetic pathway of carotenoids using Agrobacterium-mediated transformation to silence *LCY-e* activity. Later, Diretto et al. (2007) exploited metabolic

engineering to produce golden potato with approximately 20-fold increase in total carotenoid and 3600-times increase in β-carotene (reaching up to 47 μg/g DW). Three genes (CrtB, CrtI and CrtY) from *Erwinia sp*. (a bacterium) and their cumulative expression under tuber-specific promoter control resulted in higher accumulation of yellow pigment. Römer et al. (2002) reported increase in zeaxanthin concentration (4–130 times), achieved through transformation using both sense and antisense constructs coding for zeaxanthin epoxidase (enzyme involved in zeaxanthin to violaxanthin conversion) thereby raising the zeaxanthin concentration by inhibition of conversion process. Further, total carotenoid concentration was also observed to about 5-fold higher, clearly indicating that transformation had impact on whole metabolic pathway of carotenoid synthesis. Likewise, DellaPenna and Pogson (2006) reported that transformed neoxanthin epoxidase upregulates transcript for protein fibrillin responsible for carotenoid storage.

Stobiecki et al. (2003) reported a 4-fold increase in anthocyanin concentration in potato tubers especially petunidin and pelargonidin derivatives by transformation using a sense construct of the flavanol biosynthesis gene DFR (dihydroflavonol 4-reductase). Overexpression of this construct resulted in

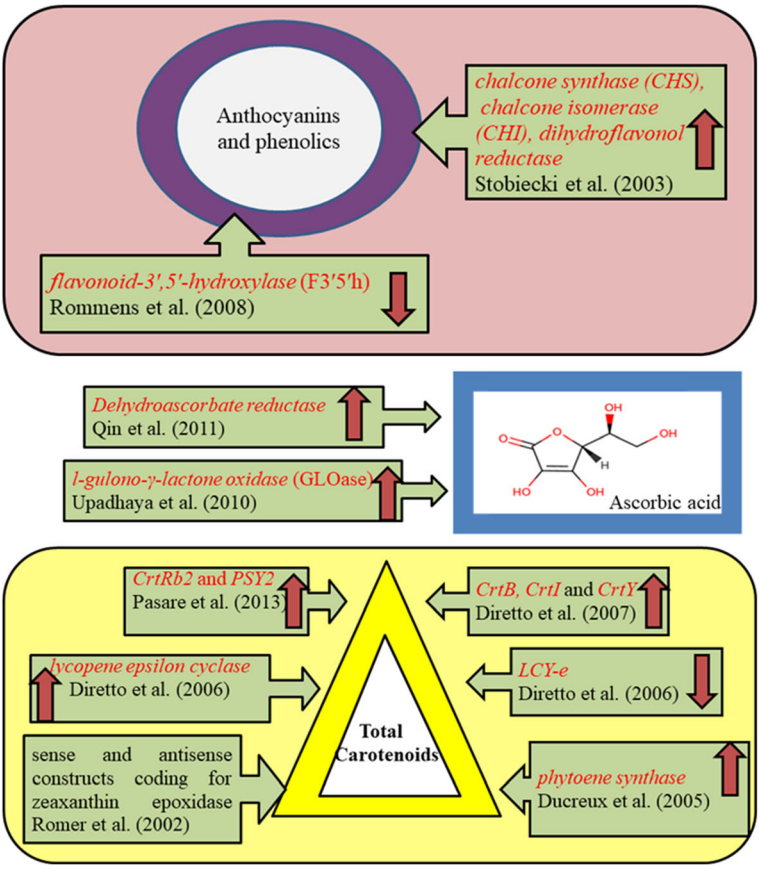


**Fig. 1** Metabolic engineering of antioxidant responsive genes of potato

steroid alkaloid glycosides, α-chaconine and α-solanine, α-solamargine and α-solasonine and triglycosides of solasonine, accumulation in addition to the above-mentioned effect. However, transformation using antisense orientation did not give similar results and anthocyanin levels were lowered. Rommens et al. (2008) produced transgenic potato tubers enriched not only in flavonols and anthocyanins but also with up to four times increased levels of caffeoyl quinates, including chlorogenic acid, while retaining the same taste and texture. Also, abundant accumulation of kaempferol-rut (around 100 times more than control) was achieved through flavonoid-3′,5′-hydroxylase (F3′5′H) gene silencing that impaired biosynthesis of anthocyanins. These changes were attributed to increased expression of chlorogenic acid biosynthetic gene hydroxycinnamoyl-CoA quinate hydroxycinnamoyl transferase (*Hqt*), prephenate dehydratase (*Pdh*) and chorismate mutase (*Cm*) genes. Overall, it was shown that phenylpropanoid biosynthetic pathway gets activated by tuber-specific expression of the MYB transcription factor gene $StMtf1^{M}$ and the majority of these phenylpropanoids were retained in processed products. Upadhyaya et al. (2010) used a transgenic approach to upregulate ascorbic acid production in potato through overexpression of gene encoding l-gulono-γ-lactone oxidase (GLOase gene). Transgenic potato cultivar Taedong Valley at 6–7 weeks not only showed 141% higher concentration of ascorbic acid but also resistance to abiotic stresses like salt stress, mannitol or methyl viologen-induced stress with better root and shoot length as compared to normal tubers. Qin et al. (2011) utilized overexpression of dehydroascorbate reductase from both cytosol and chloroplast to increase ascorbic acid level in potato. Jin et al. (2016) successfully came up with potato breeding clones KPG16 and KPG5 with enhanced levels of total anthocyanins, ascorbic acid and polyphenols that can be considered as a functional food.

## Future Directions

Potato has numerous beneficial compounds that are actually plant secondary metabolites effective against various ailments including cancers and cardiovascular diseases. The current need is to enhance nutritional and to reduce anti-nutritional compounds in potato. Although tracing genes responsible for expression of various phytonutrients have become easier with the sequencing of the potato genome, advanced analytical techniques that are rapid and accurate are needed. Anthocyanins and phenolics of potato are well documented for cytotoxicity in cancer cell lines, but further identification of individual components of the total anthocyanins that might correspond to cytotoxicity in prostate and other cancer cell lines is needed. Efforts can be made to manipulate genetic machinery of potato so as to upregulate the expression of genes responsible for these bioactives. Similarly, storage of these healthy components in tissue of potato can be targeted in the near future. Various proteins from potato waste have successfully been purified by many research groups in the past decade but use of these proteins as biofortificants needs attention that can bring about promising outcomes.

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