Chapter 3

Breeding Potato for Quality Improvement

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Additional information is available at the end of the chapter

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Abstract

Potato is the most important non-cereal food crop in the world, that in general represent a non-fattening, nutritious and wholesome food, which supply important nutrients to the human diet. The potato tubers contain considerable amounts of carbohydrates, vitamin C, essential amino acids and minerals. The potato quality includes biological traits (e.g. proteins, carbohydrates and minerals); sensorial traits (e.g. flavor, texture); and industrial traits (e.g. tuber shape, cold sweetening and starch quality). These traits are deemed very important for fresh consumption, where they are most likely to influence consumer's choice worldwide. Since most quality traits are genetically controlled, breeding work can successfully meet the quality of potato tubers and fulfills the needs of a changing and demanding world. Breeding potato for quality traits requires a continuous flow of new genes and allelic diversity into the *Solanum tuberosum* gene pool. However, recent advances in conventional and non-conventional breeding methods have significantly improved the possibilities of producing novel genetic variability for selection of new genotypes, especially when biotechnologists and plant breeders pool the existing resources. The genetics, biochemical and physiology of several quality traits is to be given equal importance that ultimately makes breeding efforts less empirical and more predictable.

Keywords: *Solanum tuberosum*, quality traits, genotypes, gene, inheritance, conventional breeding, non-conventional breeding

1. Introduction

Potato (*Solanum tuberosum*) is one of the most important tuber crops, is used worldwide for human and animal consumption, and as raw material for starch and alcohol production. It is also one of the world's major staple crops, which produces more dry matter and protein per hectare than the major cereal crops [1]. Potato is mainly grown in Uttar Pradesh, West

Bengal, Punjab, Bihar, Haryana, Madhya Pradesh, Gujarat and Maharashtra. Total potato production is about 320 million tonnes (Mt) globally, of which about 66% is used as food, 12% as feed and 10% as seed [2]. At the highlands of Ethiopia, the potato holds great promise for improving the livelihoods of millions of smallholder farmers. The potential for high yield, early maturity and excellent food value give the potato great potential for improving food security, increasing household income and reducing poverty [3]. Potato is grown in India in almost all the states except Kerala. It is possible to see the crop in field round the year in one part of the country or the other. About 82% of the area under potato crop lies in the plains where the crop is grown during short-days of winters from October to March. About 10% lies in the hills where the crop is grown during long-days of summer from April to September in tropical and sub-tropical parts of the world.

Cultivated potato and its wild relatives belong to the genus *Solanum*, the largest genus with 1500–2000 species [4]. Within the genus *Solanum*, over a 1000 of species have been recognized [5]. The genus *Solanum* comprises 8 cultivated species and 2000 wild relatives out of which 235 *Solanum* species tuberize.

The tuber-bearing *Solanum* species are grouped in the *Petota* section. This section is divided into two sub-sections, *Potatoe* and *Estolonifera* [6]. The sub-section *Potatoe* contains all tuber-bearing potato species, including common potato (*S. tuberosum*, belonging to series *Tuberosa*). Two non-tuber bearing series (*Etuberosa* and *Juglandifolia*) are placed in sub-section *Estolonifera*. However, a number of molecular studies suggest that the series *Etuberosa* and *Juglandifolia* do not belongs to the *Petota* section [7, 8].

The cultivated potato (*S. tuberosum*) is divided into two sub-species: *tuberosum* and *andigena*. The sub-species *tuberosum* (**Table 1**) is the cultivated potato originated from Peru and widely in use as a crop plant in, for example, Asia, North America and Europe. The sub-species *andigena* is also a cultivated species, originated from Andean mountain (South America) and cultivation is restricted to Central and South America [6, 9]. The subsp. *andigena* forms tubers under short day conditions at high altitudes (>2000 msl.) while in the subsp. *tubersoum,* tuber formation is under long days in temperature climate and short days in the tropics at lower altitudes (500–2000). The cultivated potato (*S. tuberosum* subsp. *tuberosum*) is crossable with other cultivated species

Taxonomic rank	**Latin name**
Family	Solanaceae
Genus	*Solanum*
Section	*Petota*
Subsection	*Potatoe*
Series	*Tuberosa*
Species	*Solanum tuberosum*
Sub-species	*tuberosum*

Table 1. Taxonomic position of *S. tuberosum* subsp. *tuberosum*.

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(*S. tuberosum* subsp. *andigena*, *Solanum phureja* and *Solanum stenotomum*) and wild diploid species (*Solanum sparsipilum*, *Solanum berthaultii*, *Solanum spegazzinii* and others). For transgression of genes for improvement of quality traits as well as resistance to pathogens and insect pests in potato cultivars, wild species have been found useful. Potato tubers develop from the stolons formed from the lower basal nodes below the soil surface. The potato tuber is a modified stem with a few 'eyes' that are leaf scars with a subtended lateral bud.

Potato production is important due to many reasons but one of the most important aspects of potato production is tuber quality, that includes biological (e.g. proteins, carbohydrates and minerals) and sensorial traits (e.g. flavor, texture) and industrial traits (e.g. tuber shape, cold sweetening and starch quality). The potato is rich source of carbohydrate and has considerable amounts of protein, with a good quality of amino acid balance, vitamins C, vitamin B (B_1 & B_6), folate, minerals (potassium, phosphorus, calcium and magnesium) and in micronutrients (iron and zinc). Dietary fiber found high in the tubers, and potato skin contained higher amount of dietary fibers than flesh. Potato tubers are also rich in antioxidants comprising polyphenols, vitamin C, carotenoids and tocopherols. Freshly harvested potatoes are virtually free of fat and cholesterol as compared to stored potatoes [1, 10]. The nutrient-rich potato can contribute to improved diets, thus reducing mortality rates caused by malnutrition. It can improve food security and health, especially among women and children. To improve the livelihoods and food security of poor farmers, it is very essential to increases in potato yields.

2. Origin of potato

Potato is an auto-tetraploid species ($2n = 4\times = 48$) which was first introduced into Europe, and spreads as a botanical novelty and as fodder crop for livestock. Initially people treated the potato as suspicion relative of the toxic nightshade (*S. nigrum*).Eventually potato was adopted as a human food source and gradually gained popularity and then it introduced to the rest of the world, from the Andes of South America in the late sixteenth century. By the end of the eighteenth century, it was found that it is well adopted under long-day photoperiod then further selection of early tuberization cultivars and high-yielding clones were done from the derived seedlings from naturally occurring berries, the consequence of uncontrolled, largely self-pollination. Potato is an Andean tuber crop that was originally domesticated in South America and started its worldwide dissemination after Columbus voyages brought to Europe in the late sixteenth century some years after the discovery and conquest of Peru. It is believed that cultivated potato originated from its wild ancestors near the lake *Tritica* basin in Peru Bolivian region in high mountains. This plant was selected as article of food by the oldest civilizations of Mayas and Incas. There are strong evidences that potato was widely distributed throughout the Andes, from Colombia to Peru and also in southern Chile. Potatoes are said to have been taken to India and to China by British missionaries in the late seventeenth century and were known in Japan and parts of Africa by about the same period.

Potato was originated from the wild species *Solanum leptophyes* some 10,000–7000 years ago, and the first domesticated species was *Solanum stenotomum*. The evolution of *Solanum stenotomum* was only the beginning of potato evolution. In addition to first wild species *S. leptophyes* which gave rise to domesticated diploid species, *Solanum stenotomum*, three otherswild species, namely *S. sparsipilum, Solanum acaule* and *Solanum megistacrolobum* were instrumental in evolution of present day cultivated potatoes. Some authors believed that *S. tuberosum* is a straight tetraploid of *S. stenotomum*but there are stronger evidences in support of the allotetraploid origin of *S. tuberosum* by hybridization between *S. stenotomum* and *S. sparsipilum* [11].

3. Nutritional content of potato

Potato tubers contain about 75% water, 21% carbohydrates (of which about 82% is starch), 2.5% protein and less than 1% fat. Often looked upon as primarily a starchy vegetable, potatoes are actually highly nutritious. It is a good source of vitamins C and B_6. About 48% daily values (DV) for vitamin C and 46% for vitamin B_6 are provided by a large (299 g) baked potato. They also have fair amount of fibers (26% DV), proteins and minerals. The DVs are varied with different types of cultivars, various authors have been reported DVs of 46% for potassium, 33% for manganese, 21% for magnesium and 21% for phosphorus in large baked potato. Potatoes are rich source of essential amino acids which required for proper growth and development, hence it is considered as balanced and complete diet for adults. The flesh color varies according to genotypes and climatic conditions of cultivated area. The most common flesh color is white but other than this variety of flesh color cultivars evident in different countries. The carotenoids (yellow and orange colors) and anthocyanins (red and purple colors) are the two most valuable coloring pigments in potato. White-fleshed potatoes are low in carotenoids (<100 μg/100 g fresh weight) whereas, the carotenoid content of yellow-fleshed varieties are higher (about 560 μg/100 g FW) [12]. Intense yellow to near orange flesh color, associated with carotenoid concentrations >2000 μg/100 g FW, have been reported in diploid *Solanum* germplasm [13]. The primary tuber carotenoids in potato tubers are lutein, zeaxanthin and violanxanthin, although some studies have also reported finding neoxanthin and antheraxanthin [13]. In the macula of the human eye, lutein and zeaxanthin are found and it also plays a role in reducing the risk of age-related macular degeneration. In addition, increased intake of zeaxanthin may improve mental acuity in the elderly. The anthocyanin concentration in tubers is 100-fold greater than carotenoids. The red fleshed of tubers is mainly due to the anthocyanin pigment pelogonidin-3-(p-coumaroyltutinoside)-5-glucoside (200–2000 μg/ g FW) and peonidin-3-(pcoumaroyl-rutinoside)-5-glucoside (20–400 μg/g FW) while, petunidin3-(p-coumaroyl-rutinoside)-5-glucoside (1000–2000 μg/g FW) and malvidin-3-(p-coumaroyl-rutinoside)-5-glucoside (2000–5000 μg/g FW) compounds of anthocyanin pigments are responsible for dark purple-fleshed potatoes [14]. There is increasing interest in anthocyanins in potato tubers because of their perceived higher antioxidant content, and ability to combat both prostate cancer and breast cancers. The potatoes with high glycemic index play important role in the diet of persons suffering from diabetes. During digestion, quick breakdown of food with high glycemic index leads to rapid rise of blood sugar level. The two major components of potato starch are amylose (20–25%) and amylopectin (75–80%). While cooking recrystallization of some portion of amylose leads to formation of resistance starch. Resistant starch acts as a dietary fiber. It passes through the small intestines and once in the large intestines microbial fermentation results in the production of small chain fatty acids, which enhance colon health and lower the risk of colorectal cancer and diverticulosis. The diploid potato species adapted to long-day growing conditions, the concentration of amylose in starch ranged from 25 to 36%. Greater variations for amylose content were present in wild potato species, which ranged from 22 to 43%. There is considerable interest in the potential of potato to lessen micronutrient malnutrition, particularly for iron and zinc. About 40% of the world's population is iron deficient, however, no reliable estimate is available for the number of people with zinc deficiency. The iron content of potato ranges from 15 to 20 μg/g DW. However, iron concentrations ranging from 9 to 158 μg/g DW in Andean potato cultivars and 18–65 μg/g DW in recent American potato cultivars.

4. Genetics and chromosomal variations of potato

Breeding of potato is a cumbersome task due to inherent genetic and biological factors. To understand the genetics, we will first outline some important genetic and reproductive aspects of the potato. Potato has basic chromosome number as 12 and right from diploid to hexaploid species. Majority (about 73%) of the species are diploid followed by tetraploids (about 15%), hexaploids (about 6%), triploids (about 4%) and pentaploids (about 2%). The tuber-bearing *Solanum* species include several diploids (2n = 24), triploids (2n = 36) and a few tetraploids (2n = 48), and hexaploids (2n = 72). Many wild species of the series *Tuberosa* are diploid (*S. berthaultii, Solanum canasense, S. sparsipilum, S. vernei*, etc.) and the cultivated diploid (2n = 2× = 24) species, *S. stenotomum*, *S. phureja and S*. *ajanhuri*, of which former two are sexually fertile and the later one is less fertile and does not breed true. Triploid potato species are *S. chaucha* and *S. xjuzepczukii* derived from spontaneous crosses between diploid and tetraploid species. There are 3 cultivated diploid species, *S. stenotonomum, S. phureja* and *S.ajanhuri*. The cultivated potato *S. tuberosum and S. demissum* are autotetraploid species with chromosome number, 2n = 4× = 48 are usually fertile except in a number of highly bred clones outside South America. There is only one pentaploid species (2n = 60), that is, *S. curtilobum* which is reasonably fertile in crosses with *S. tuberosum*, but not in selfings. Nearly all the diploid species are self-incompatible while all the tetraploids and hexaploids are self-compatible [11].

4.1. Genetic diversity for quality traits

Genetic diversity is a prerequisite for an effective plant breeding program. It is a useful and essential tool for parent's choice in hybridization to develop high yield potential cultivars and to meet the diversified goals of plant breeding [15]. The cultivated potato have narrow genetic base due to limited introduction of germplasm from their natural range in South America [16]. Most of the potato cultivars are auto-tetraploid (2n = 4× = 48), highly heterozygous and out breeding species, which suffer from inbreeding depression. Cultivated potato species have a base chromosome number of n = 12 and may be diploid (2n = 2× = 24), triploid (2n = 3× = 36), tetraploid (2n = 4× = 48) or pentaploid (2n = 5× = 60). There are 7 cultivated potato species [6], whereas only 9 species and 141 intra-specific taxa have been identified [17]. Recent studies suggested that, genotyping of 742 landraces of all cultivated and wild species have been completed with SSR and chloroplast markers [18]. Based on these studies,

Species	Quality traits
S. medians, S. okadae, S. pinnatisectum, S. raphanifolium, S. sogarandinum	Chip directly from cold storage
S. siparunoides, S. sisymbrifolium, S. stramonifolium, S. tuberosum	Used in medicine
S. phureja, S. stenotomum	High carotenoid content
S. phureja, S. vernei	High starch content
S. phureja, S. estoloniferum	High ascorbic acid content
S. phureja	High protein content, low temperature non-sweetening
S. vernei	High starch and protein content, low reducing sugar content

Table 2. Species for important quality traits.

they reclassified the all cultivated potatoes in following four species: (i) *S. tuberosum*, with two cultivar groups (the *Andigenum* group – diploids, triploids and tetraploids and the *Chilotanum* group – tetraploid); (ii) *S. ajanhuiri* (diploid); (iii) *S. juzepczukii* (triploid) and (iv) *S. curtilobum* (pentaploid) [18].

1. *Solanum ajanhuiri* (2n = 2× = 24): this diploid species was formed by natural hybridization between diploid cultivars of *S. tuberosum* L. *andigenum* group and the tetraploid wild species *S. bolivense* (*S. megistacrolobum*). This landrace possesses frost resistance and is distributed in the high Andean Altiplano between southern Peru and central to North Bolivia, at elevations between 3700 and 4100 m [19, 20].

2. *S. juzepczukii* (triploid) (2n = 3× = 36): formed by hybridization between a diploid cultivar of *S. tuberosum* L. *andigenum* group, and the tetraploid wild species *S. acaule* Bitter [21]. It can be found from central Peru to southern Bolivia and can grow at an altitude of 4000 m (Spooner et al. [19]). This species contains high levels of glycoalkaloids, and local people prepare detoxified processed potato "chuño" by freeze drying [22].

3. *S. curtilobum* (2n = 5× = 60): formed by hybridization between tetraploid forms of *S. tuberosum* L. *andigenum* group (synonym for *S. tuberosum* subsp. *andigenum*) and *S. juzepczukii* [21] is cultivated in the Andean Altiplano at an altitude range of approximately 4000 m [19]. Because the tubers are bitter, owing to high glycoalkaloid content, the species is also used to prepare "chuño" [22].

4. *S. tuberosum:* the most popular cultivated potato is *S. tuberosum*, which is also known as "common potato" in most parts of the world. It has originated from the coastal regions of South Central Chile.

5. *S. chaucha*: *S. chaucha* is a cultivated triploid species that supposedly originated from natural hybridization between *S. tuberosum* subsp. *andigena* and *S. stenotomum* [6] distributed from 2100 to 4100 msl throughout Peru, with lower frequency in Bolivia, and rarely found in Ecuador and Colombia.

6. *S. phureja*: this species was cultivated from central Peru to Ecuador, Colombia, and Venezuela since the pre-Spanish era and is believed to have originated from *S. stenotomum* [6].

7. *S. stenotomum*: the species is diploid and cultivated from Central Peru to Central Bolivia. Most primitive form of cultivated potato. *S. stenotomum* shows the diversity within species, suggesting it to be the first domesticated potato derived from diploid wild species (**Table 2**).

5. Quality traits of potato

In the field of nutrition, there are several topics such as food and nutritional security, dietary adequacy etc. which have been discussed most vigorously at global level. These all are well defined by the quality of the produce. Potato is the fourth most important food crop of the world. Quality of a potato tuber can be defined as the sum of favorable characteristics of the tuber, which is a subjective and dynamic concept that depends on consumer's tradition lifestyles, food habits and the industrial process used.

Potato considered as an important source of nutrition for human diet. Potato tubers are good source of vitamin C and also having significant amount of 12 various essential amino acids along with minerals. In general, different cultivars have different uses. Red-skinned cultivars with low dry matter content, for example, are used for fresh market, whereas long types are suitable for French fries.

There are two broad category groups of tuber quality:

- **External quality:** this is the first category group which comprising the aspects such as skin color, tuber size and shape, eye depth [23]. Besides, dormancy and greening are additional important quality traits [24]. These traits are deemed very important for fresh consumption where external traits are most likely to influence consumer's choice.
- **Internal quality:** this represents the aspects such as nutritional properties, culinary value, after-cooking properties or processing quality. The traits such as dry matter content, flavor, reducing sugar, protein content, starch quality, type and amount of glycoalkaloids, enzymatic discoloration and other nutritional quality, etc. comprising the internal quality of tuber [1].

5.1. Inheritance of quality traits

5.1.1. Fresh market

The traits which are crucial aspects for consumers are tuber shape, eye depth, skin and flesh color, as these are immediately obvious while making the purchase [24]. Tuber shape is a syndrome of many characters that considers the length/width ratio for describing the overall shape, it varies from compressed/round to long [24]. The round shape of tuber mainly governed by a single locus on chromosome X with a dominant allele *Ro* reported that and other reports mention quantitative trait loci (QTLs) on chromosome II, V and XI, II and XI and VII and XII. Other than this, there are several factors which controlling this trait, most probably it depending on the genetic background of the respective populations used on their researches [24].

Eye depth is an important trait of tuber quality because the appearance of tubers is affected by deep eye which leads to increased cost of peeling in processing factories. As for tuber shape, contradictory hypotheses were formulated to explain the inheritance of eye depth. A single locus *Eyd/eyd* controls the appearance of eye depth, this locus is closely linked with *Ro* locus at chromosome X at a distance of 4 centi Morgan (cM) [25], whereas, at least four QTLs on chromosomes III, V and X were identified.

Skin color is one of the most easily notable traits of potato tuber. Potato having lots of variability in skin color as it ranges from white-cream to blackish. The different genetic systems that control the presence and absence of red and blue pigments are responsible for tuber skin color. The potato *R* locus is required for the production of red anthocyanins, which have been shown to be derivatives of pelargonidin, while P is required for the synthesis of purple pigments, which are typically derived from petunidin [14]. Whereas, the synthesis of red or purple anthocyanins in tuber skin is mainly due to I locus. These three loci have been mapped in the potato genome [26, 27].

Several studies [28, 29] reported that three genes *R* (*dfr*), *P* (*f3´5´h*) and *D* (*f3h*) were expressed in the periderm of red and purple skinned clones, while *dfr* and *f3´5´h* were not expressed, and *f3h* was only weakly expressed, in white skinned clones. Moreover, R gene linked to dihydroflavonol 4-reductase (*dfr*), *P* responsible for flavonoid 3′,5′-hydroxylase (*f3′5′h*) and *D* corresponds with *R2R3MYB* transcription factor which is similar to Petunia *an2* [28].The response is similar to expression of flavanone 3-hydroxylase (*f3h*), dihydroflavonol 4-reductase (*dfr*) and flavonoid 3′,5′-hydroxylase (*f3′5′h*) [29].

In potato tuber flesh color also lots of diversity occur, it varies from white to purple. The variation in tuber flesh is mainly due to two naturally occurring pigments, that is, anthocyanin and carotenoids (Lewis et al., [14]). Red, blue and purple color flesh is due to accumulation of anthocyanin pigment [30]. Red and purple fleshed potatoes have acylated glucosides of pelargonidin while purple potatoes have, in addition, acylated glucosides of malvidin, petunidin, peonidin and delphinidin [31]. Natural anthocyanin pigments are the economic constituent of colored potato, since it is a low-cost crop [32], and also are a significant source of potato antioxidant micronutrients [33]. Hence, colored potatoes can serve as novel sources of natural colorants and antioxidants with added value for the food industry and human health. Antioxidant values also depend on color of flesh of tuber. Red fleshed potato genotypes have the high antioxidant value (300%) as compare to white fleshed, while purple fleshed tubers have antioxidant value of 250% than white fleshed [34].

The single dominant allele at the Y locus on potato chromosome III controls the white, yellow or orange flesh of tuber which determines by the carotenoid level. A combination of the dominant β-carotene hydroxilase 2 (*Chy2*) allele and homozygous recessive *Zep* allele controls the yellow flesh (accumulation of high levels of zeaxanthin) of potato tubers [35].

Greening and tuber dormancy also another two important quality parameters. Greening of tubers mainly due to transformation of amyloplasts in the outer layers of the tuber to chloroplasts [36]. Green tubers having high concentration of glycoalkaloids, which is an antinutritional factor (poisonous) for human and animals. Several studies reported that there is no direct metabolic link between chlorophyll biosynthesis and total glycoalkaloids content. There is no single reason which is responsible for greening. Several factors such as light, maturity of tubers, time and temperature of storage, production treatments or tuber size are responsible for greening of potato tubers. Although tuber greening is affected by environmental factors, variability among varieties has been reported by several workers and this character has polygenic inheritance [37].

Tuber dormancy defines as the physiological state of potato tuber after harvest, during which tuber do not sprout under favorable condition for sprouting. Two molecular mapping studies detected a number of QTLs for tuber dormancy and demonstrated the complex character of this trait. There are several categories of genes which involved in breaking dormancy and sprouting action [24]. Among these, the first group represents the genes coding for homeotic proteins and transcription factors [38]. The second class of genes regulates hormone metabolism and hormone response. The dormancy of potato tubers is induced by abscisic acid and ethylene. The abscisic acid maintains dormancy and whereas the cytokinins are involved in loss of dormancy. The third group of genes is involved in metabolism of reserve storage molecules [39]. Recently, it was reported that, in DNA replication fourth gene category were involved [40].

Glycoalkaloid content is another important quality attribute that affects the taste of tubers. These are naturally occurring secondary metabolites which may be toxic against bacteria, fungi, viruses, insects, animals and humans beyond the optimum level and produce in all parts of potato plant. The predominant glycoalkaloids in potato are α-solanine and α-chaconine [41], both trisaccharides of the common aglyconesolanidine. These two compounds comprise about 95% of the glycoalkaloids in potato tubers [42]. The chemical structure of α-solanine consists of branched β-solatriose (α-L-rhamnopyranosyl-β-D-glucopyranosyl-β-galactopyranose) along with the side also attached to the 3-OH group of the same aglycon, while a branched β-chacotriose (bis-α-Lrhamnopyranosyl-β-D-glucopyranose) carbohydrate side chain attached to the 3-OH group of the aglyconsolanidine in case of α-chaconine [43]. Various factors influence the quantity of glycoalkaloid, that is, it increases during storage and transportation and under the influence of light, heat, cutting, slicing, sprouting and exposure to phyto-pathogens. The quantity of these chemicals decides the quality of tubers, that is, when this compound is present in low concentration, it may attribute to flavor of processed potato, but when its level crosses 15 mg/ 100 g fresh weight it cause bitterness of tubers. The maximum amount of glycoalkaloids in the potato tubers occur within the first 1 mm from the outside surface and decrease toward the center of the tuber [43]. The consumption of large amounts of glycoalkaloids by humans could produce toxication symptoms ranging in severity from nausea to, in extreme cases, death [42].

The quality of potato tubers also depends on sugar content of the harvested crop. For the fresh market, sucrose levels above 1% fresh weight (FW) are reported to give an unacceptably sweet taste to the boiled potatoes [1].

5.1.2. Potato for processing

The basic criteria of selection for processing potatoes are tuber shape, eye depth, dry matter and starch content. Selection of varieties is done based on the product to be prepared. For example, French fries need varieties with long tuber whereas for chips varieties with round tubers are preferred [44]. Shallow eyed potato tubers are ideal for processing because these help to minimize waste during peeling. Moreover, dry matter content (DMC) is also a critical component for the processing industry, it represents the internal quality of the produce. Starch is the principal compound of tuber which is having polygenic inheritance and the effects are located on all chromosomes [45]. For French fries preparation, the DMC should not be below 19.5% while for chips it should not be less than 20% [44]. The amount of DMC more than 25% is also not acceptable for French fries preparation. The susceptibility of produce to bruising depends on DMC and its distribution during harvest has an impact on cooking type, for example, a waxy or mealy texture when boiled, organoleptic characteristics and in processed potatoes the final product texture [46]. Several environmental factors such as solar radiation, soil temperatures, soil moisture, fertilizers and haulm killing affect the dry matter content during the growth and development of crop [47]. In general, DMC have negative response to cold climate and short growing period, while positive response, that is, increased in DMC is occurred in warm climate with long growing seasons and an adequate water supply. The accumulation of more DMC is occurred during vegetative phase of the crop. When root system remains active in wet soil there will be sharp decline in tuber DMC after defoliation of the haulm [1]. The quality of potato tubers is also affected by the level of sugars, because at high temperature Maillard reaction occur which leads to interaction between reducing sugars (glucose and fructose) and free amino acid which ultimately affect the color, flavor and it has also been related to acrylamide formation in fried potato products [48]. Amount of sugar in potato tubers depends upon several factors which include genotype, environmental conditions, agronomical practices and several post-harvest factors including storage [48]. Potato has both monosaccharides and disaccharide sugars. Glucose (0.15–1.5%) and fructose (0.15–1.5%) are monosaccharide reducing sugars, while sucrose (0.4–6.6%), is a non-reducing disaccharide [1]. In processing of chips and French fries, the acceptable levels of glucose and fructose is 0.2–0.3% and 0.3–0.5%, respectively. The molecular studies suggested that these sugars are occurred between one and three putative QTL regions per chromosome [49]. There are 24 QTLs which are related to sugar accumulation in potato tubers and were present on all potato chromosome. Among these QTLs, most of the QTL were mapped in the same positions for both glucose and fructose content. Besides, several candidate genes involved in carbohydrate metabolism have been mapped [45].

Enzymatic discoloration (ED) is another important trait which is responsible for loss of quality. Peeling potato tubers and exposing them to air cause the flesh color to change from red to brown. Deterioration of quality is due to the oxidation of phenolics compound to quinones by the enzyme tyrosinase (polyphenol oxidase, PPO) where quinones is transformed to dark pigments [50]. These changes affected the nutritional quality, flavor and color resulting to loss in economic for food processing and marketing industry [51]. The diploid (C × E) population contributes three QTLs for ED, namely, cholorogenic acid and tyrosine levels QTL on C_2 and C_8 parental chromosome, respectively, while chromosome VIII carry a candidate gene

PPO for ED. The absence of genetic correlations between these components represents non-overlapping of QTLs [51]. During cooking, the phenol (mainly chlorogenic acid) and iron combined to formed iron diphenol resulting in post cooking discoloration which is a non-enzymatic reaction. The oxidation process occurs during cooling which results into blackening of potatoes [50]. The dark patches that occur beneath the skin intact were the result of mechanical damage during harvesting, transport, and storage, which are known as black spot bruising. These deteriorate the consumer and processing qualities of potatoes. The damaged cells are oxidized by phenols mediated *PPO* which then results into spot formation like as in post-peeling discoloration [50].

Tuber size has positive correlation with time required for peeling and trimming. Small tuber size possessed more number of tuber eyes and skin ratio per unit weight in comparison with large tubers. For example, the processing cultivar 'Sayaka' used especially for salads required less trimming time due to large tubers and shallow eyes as compared to Irish Cobbler', an old cultivar with deep eyes and relatively small tubers which is one-third of 'Sayaka' [52].

5.1.3. Nutritional quality

Potatoes have gained a special status in world due to cheap availability of nutrients, which play major role to feed the poor population of the world. These are the valuable source of dietary vitamins, minerals and phyto-nutrients because of their per capita consumption. Potato is considered as a good source of antioxidants, such as polyphenols, carotenoids and vitamin C [34] and major contributor of antioxidants in American diet because of the high consumption [53]. Diets rich in antioxidants have been associated with a lower incidence of atherosclerotic heart disease, certain cancers, macular degeneration and severity of cataracts. Furthermore, the considerable high diversity offered by native Andean potato germplasm to contribute to the dietary antioxidant intake and indicates that native potatoes offer a new opportunity to promote the nutritional quality of potato [54]. Polyphenols are most important secondary metabolites obtained from potato, which act as antioxidant. These compounds have wide range of physiological activities, which help to protect against UV radiation, pathogens and herbivores [55]. Phenylpropanoid pathway is responsible for production of polyphenol compounds and contains a wide range of chemical classes, including phenolic acids such as benzoic and hydroxycinnaic acids, flavonoids such as flavonols and anthocyanins, stilbenes and lignans [56].

Food polyphenols have protective role on human however, there is no direct protective role of polyphenol but it gives indirect protection by activating endogenous defense systems and by modulating cellular signaling processes. This compound is important in the human defense system against reactive oxygen species (ROS), which are known to be involved in the pathogenesis of aging and many degenerative diseases such as cardiovascular diseases and cancers [57].

The higher content of lutein, violaxanthin and total carotenoids occur in yellow-fleshed potatoes. Yellow-fleshed varieties obtain their color from xanthophyll carotenoids. Many carotenoids have been identified, including lutein, violaxanthin, neoxanthin, antheraxanthin and β-cryptoxanthin, with deep yellow pigmentation due to the presence of zeaxanthin [34]. The genetic and molecular biology of orange flesh color in potato was studied by several researchers [35]. In orange-fleshed potato, only genotypes combining presence of the dominant beta-carotene hydroxilase

2 (*Chy2*) allele with homozygositiy for the recessive zeaxanthin epoxidase (*Zep*) allele produced orange-fleshed tubers that accumulated large amounts of zeaxanthin [35]. Potatoes are one of the best plant sources of the amino acid lysine. Lysine is one of the amino acids that are a necessary component of complete proteins [58].

5.2. Different quality traits and breeding for quality traits of potato

Breeding for quality traits in potato is a difficult task due to inherent genetic and biological factors. In order to better understand the strategies for quality breeding, first we have to outline some important genetic and reproductive aspects of the potato which help in getting positive results.

First of all, the tetraploid (2n = 4× = 48) cultivated *S. tuberosum*is a polysomic polyploidy with four sets of similar alleles. The genetic components are the primary factor attributing to quality traits.

Groups of genetically controlled traits as follows: (i) biological traits like carbohydrates, proteins, vitamins, minerals and low level of toxic glycoalkaloids. (ii) Sensorial traits such as color, flavor and texture. (iii) Industrial traits, namely, shape and size of tuber, dry matter content, cold sweetening, oil absorption, starch quality and specific gravity.

Biological traits: these traits included under internal quality of tubers. Brief detailed of these traits given below:

- **Proteins:** in potato, several types of proteins were present. A globulin protein has been extracted from potato tubers by using salt extraction method, which is designated as 'tuberin'. The nutritional value of tuberin, is basically a globulin protein of potato as well as it is the true protein present in potato. They also categorized the potato tuber proteins into tuberin, globulin II, albumin, prolamine and glutelin.

- **Potato starch:** starch content in potato is about 11 and 45% of the tuber fresh weight. It varies according to geographical area, climate and cultivar. The tuber starch content of middle European varieties ranges from 10 to 17% for table potatoes, from 14 to 20% for processing potatoes (e.g. chips, French fries) and reaches up to 25% in industrial potatoes. The amylose content of starches ranged between 15.0 and 23.1% and differed significantly among different potato cultivars.

Starch yield (amount of starch obtained per unit of arable land) is one of the most important trait for industrial starch production. Hence, breeding of cultivars with high tuber starch yield (TSY) can be considered as one of the objective for industrial starch production. The total tuber weight per plant, per plot or per unit of arable land, is negatively correlated with tuber starch content [59].

- **Glycoalkaloid:** a bitter chemical compound with a combination of a glycoside and an alkaloid, which is present in potatoes and some other plants. The pasting temperature of starch separated from potato tubers depend on the duration of storage and glycoalkaloid content. Before storage, the pasting temperature ranges from 64.6 to 67.7°C, whereas 90 days after storage the temperature range of 66.9–69.4°C was more suitable. The effect of temperature was also observed in viscosity of paste. The lower storage temperature (8°C) having the less viscous paste while higher storage temperature (16°C) leads to more viscosity. Storage temperature and processing also influence the viscosity of paste. Processing at high temperature leads to lower viscosity which ultimately leads to breakdown viscosity and set back viscosity after storage while the cold paste viscosity is not affected by temperature variation. For instance, solanine, the storage of raw material leads to increase in pasting temperature but significant reduction in pasting time.

- **Carotenoids:** the carotenoid pattern in four yellow- and four white-fleshed potato cultivars (*S. tuberosum*) was dominated by violaxanthin, antheraxanthin, lutein and zeaxanthin, which were present in different ratios, whereas neoxanthin, β-cryptoxanthin and β-carotene generally were only minor constituents [60].

The genotypes with extremely high levels of total carotenoids had zeaxanthin, an isomer of lutein, also present in the human retina. Total anthocyanins ranged from 1.5 to 48 mg/100 g FW in a solidly pigmented purple skinned, purple-fleshed breeding line.

- **Phenolic compounds (phenolic acids, flavonoids and anthocyanins):** potato tubers are one of the richest sources of polyphenols. The amount of polyphenols is affected by different parameters such as variety, year of cultivation, stress factors (mechanical damage of tubers, attack of pathogens, action of light on tubers or irrigation), storage and cooking treatment. Other than these, upto some extent it is also affected by of geographical location, soil type, potassium fertilization and storage temperature. It is commonly observed that about 50% of the phenolic compounds are located in the potato peel and adjoining tissues, which are often wasted, while the remainder decreases in concentration from outside toward the center of the potato tubers. It is also reported the total phenolic acid content in potato peel was about 3.93 mg/g powder and the major phenolic acids present were predominantly gallic acid, caffeic acid, chlorogenic acid and protocatechuic acid [61].

A number of health-promoting phytonutrients such as phenolics, flavonoids, folates, ketoimines and carotenoids has been found in potato [62]. High concentration of phenolic acids was observed in pigmented potato as compared to white-fleshed potato. Potato pigments are also rich in natural colorants and antioxidants.

- **Sugars:** β-ᴅ-fructose; α-glucose, β-ᴅ-glucose, myo-inositol and sucrose were the commonly occurring sugars in cold stored Kennebec potato tubers with stearic acid as internal standard [63].

- **Organic acids:** citric acid and malic acid in potato tubers in the ratio of nearly 20:1 together and also having small amount of isocitric acid.

- **Fatty acid:** almost 17 fatty acids were reported in *Solanum phureja* and *S. tuberosum* genotypes [64]. The predominant fatty acid was linoleic followed by α-linolenic and palmitic acids whereas the 15-Methylhexadecanoate was present in minute amount in both species. The amounts of these fatty acids were varied according to storage condition and period. The contents of linoleic acid decreased whereas α-linolenic acid increased in tubers of both species over the whole storage period.

- **Phytohormones and endogenous tuber inducing compounds:** potato plant had been reported to contain phytohormones like jasmonic acid, auxins (IAA), gibberellins (GA), cytokinins, abscisic acid (ABA), ethylene and strigolactones. It was also reported that both ABA and ethylene were required for dormancy induction, but only ABA was needed to maintain bud dormancy [65].

- **Specific gravity:** high specific gravity was found in a South American species *S. commersonii* and this species also possesses tolerance to both frost and heat.

- **Texture:** the texture of the tuber is a direct visible trait and helps to attract the consumers. S. *cardiophyllum* possesses yielding ability and attractive smooth tubers which can be used for breeding purpose.

Cultivars with the table quality demanded by supermarkets: these cultivars should have the following properties.

- Tubers must be resistant to after-cooking-blackening.

- Attractive skin finish paramount.

- Flavor and texture as judged by taste panels.

- Low levels of glycoalkaloids.

- Special purpose cultivars, for example, salad and punnet types.

5.3. Breeding for quality traits

Farmer selection from naturally occurring variation was responsible for evolution of many Andean varieties [66]. The low toxicity of present day cultivated potato tubers is mainly due to selection of tubers with less bitterness during the course of domestication. Large numbers of genotypes with lots of variation in tuber shape and color of skin and flesh has been maintained by Andean farmers. In later stage of development, the selection was made for early maturity, dormancy and resistance to different abiotic and biotic stresses for adaptation in different agro-climatic conditions. During the middle age, the primary objective of plant breeding was to increase yield and resistance to late blight in order to feed the large population of world [66]; followed by quality breeding as second priority of plant breeder. [24].Two aspects of wild potato species utilization: development of breeding methods and incorporation of valuable traits.

Rapid progress in potato breeding requires the correct choice of parents and crosses, and efficient selection procedures. Quality traits improvement can be achieved through two prominent genetic approaches at present. These are: (1) utilization of direct selection, traditional breeding or QTL mapping and subsequent marker assisted selection to exploit natural genetic variation and (2) introduction of transgenic plants or modifying expression of already existing gene which is linked with quality traits by using transgenic approaches.

Conventional potato breeding refers to the development of new varieties from sexual crosses between pairs of parents with complementary features followed by clonal propagation and selection based on several traits. Before going to breeding, the breeder should know about the parents which are used for crossing. Selection of suitable parents and parental combination depends upon the breeder's experience which helps to get superior offspring [23]. Presence of genetic variation among the parents is the main prerequisite for any breeding program. The large number of variation for different quality traits were reported for Andean potatoes. These variations can play a major role in improvement of quality traits of present cultivated potato, by incorporating the gene linked with particular traits. The exploitation of existing variation into a cultivated species can be done after developing a population having trait of interest. This population can be developed by crossing two parents with contrast characters followed by phenotyping of population and then quantitative trait loci (QTLs) analysis which helps in identification of location for trait of interest [24]. In general, maximum breeding work for improvement of potato have been done by using the diploid populations but rarely by using tetraploid species [49, 51].

Association mapping is a new approach which was used for the first time in human genetics. In crop plants, genetic resources which exhibit the genetic and phenotypic diversity of the species can be utilize for developing the association mapping population. The phenotyping of these population done for quality traits and followed by genotyping. Candidate gene approach and genome wide distribution approach using DNA markers are two ways for genotyping. Then the testing of markers done for identification of trait association. After a large number of meiotic generations, if a specific trait is co-inherited with a specific trait allele due to identity between marker and trait locus or close physical linkage between them, it represents the markers-trait association. The population substructure (result from direct selection for specific trait complexes) is responsible for marker-trait association between unlinked loci.

In an association mapping experiment on potato by using 221 tetraploid genotypes to identify the specific gene associated with quality traits [67]. The DNA markers linked to QTL can be used to more rapidly incorporate the desirable regions into agronomically superior genotypes. Selection of genotype for improving some quality traits such as tuber shape or eye depth is quite easy whereas for some traits (glycoalkaloids and polyphenols), it requires long time and investment. Association mapping of starch and yield related traits also have been performed in potato [68, 69]. The most prominent hot spot comprises the distal segment of approximately five Mbp on the North arm of chromosome V, which harbors among other candidate genes [69], the *StCDF1* locus that controls photoperiod dependent tuberization [70].

Microarray technique helps to identify consistent differences in gene expression profiles between *S. phureja* and *S. tuberosum* cultivars, including genes likely to impact on flavor, texture, carotenoid content and tuber life-cycle. A sesquiterpene synthase gene was identified that consistently expressed at higher levels in *S. phureja* tubers, and also encodes an a-copaene synthase gene [71].

Plant breeding in combination with biotechnology can be proves as boon for breeders in generating the new varieties with superior quality traits such as high starch content, anthocyanin and carotenoid content. In Netherlands, a variety Karnico1 has been developed by genetic modification of starch which leads to production of amylose free potatoes. Amylose production was completely suppressed by antisense RNA-mediated inhibition of granule-bound starch synthase, an approach made possible by the identification of an amylose-free mutant produced by techniques associated with conventional breeding.

Transgenic approaches have also provided new ways of understanding and manipulating carbohydrate metabolism aimed at developing genetically in-built resistance to low temperature sweetening caused by an accumulation of glucose and fructose.

The introgression of desirable genes from wild species to cultivated species and breeding at diploid and tetraploid level can be possible by using molecular marker-assisted selection (MAS) strategies. These strategies help to overcome the problems which are associated with selection of many economically important quality traits which are influenced by the environmental factors or require a special test for detecting these traits. MAS do not require DNA manipulations but only resides in the analysis of natural DNA variations that occur after intercrossing different genotypes. The MAS has several advantages over conventional breeding. In MAS breeding, 99% of cultivated genome can be recovered with only three backcross generation instead of the six to seven generations required to recover the same percentage of genome without the use of molecular markers. At present many markers are available, but only few markers such as RFLP, RAPD, AFLP and SSR are most widely used for MAS.

More than 350 markers that are uniformly distributed on 12 chromosomes saturates the molecular map of potato. There are more than 25 single dominant genes present on potato map. Among these, most of them show resistance to pest and disease while some of genes related to yield and quality traits together. Interspecific hybridization between wild and cultivated genotype is a valuable approach used to transfer the useful genes and in this case the use of species-specific molecular markers would allow the wild genomic content to be reduced in few backcross generations (negative-assisted selection). Potato map is one of the most highly saturated maps with different molecular markers and there are more than 350 markers which covers approximately 90% of the potato genome which provides an extensive opportunity for optimal use of DNA analysis for MAS and making it valuable tool for fixing the genes that controls the expression of quality traits [72]. The important tuber traits such as skin color, flesh color, tuber shape and leptin content [73] are controlled by single loci. The most of tubers traits are polygenic in nature and a lot of mapping work has been carried out by various researchers to localize the related QTLs on the potato map, using different segregating progenies and marker systems. DNA markers helps in early identification of quality traits such as tuber starch content, yield and starch yield potential in potato breeding populations and helps to facilitate the combination of superior alleles for high starch yield in novel cultivars.

Potatoes are an important source of carbohydrates, ways of reducing the glycemic impact of potatoes is an important research area. Moreover, existing biodiversity of potato varieties and their nutritional composition need to be explored before engaging in transgenics. The nutrient content of tubers needs to be among the criteria in cultivar promotion. As well as the cultivar-specific nutrient analysis and data dissemination should be systematically undertaken.

5.4. Bottlenecks in potato breeding for quality traits

There are several problems which hinder the breeding for quality traits. Among these, one potential problem due to extensive utilization of exotic germplasm is introgression of undesirable traits. For instance, wild species having higher amount of glycoalkaloid which can be introgressed into cultivated species leads to increase its concentration in tubers and made it unfit for human consumption.

6. Conclusions

Tuber quality is one of the most important characteristics of potato, it is probably the most poorly defined and least researched at the genetic level. The potato needs a continued improvement of quality traits to meet the needs of a changing and demanding world. Moreover, breeding objectives related to quality for processed potatoes are normally different from those for fresh use. Exploitation of cultivated and wild species of potato as source of valuable quality traits/allelic diversity, the possibility to manipulate whole chromosome sets make sexual hybridization a powerful strategy to produce new and valuable genotypes with high quality. However, the genetic improvement of potato is hampered by several factors, namely, its tetrasomic inheritance, high level of heterozigosity and incompatibility barriers. Moreover, these days molecular breeding helps the breeders for rapid identification of desirable genes and to produce quality traits like starches with modified amylose to amylopectin ratio, and potatoes with a higher nutritional value. As well as, genetic engineering is an additional tool to produce new genetic variability and to study important metabolic pathways. Equally important is the fact that basic studies have contributed to elucidate our knowledge on the genetics, biochemistry and physiology of several quality traits, making breeding efforts less empirical and more predictable. Since most quality traits are genetically controlled, breeding work can successfully meet the quality of potato tubers and fulfills the needs of a changing and demanding world.

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