RTBfoods State of Knowledge Report On Boiled And Fried Potato (*Solanum tuberosum*) Product Profiles

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ABSTRACT

Potato has proved to be an important food security crop in SSA and has great potential for processing into various products. It is very important to understand the composition and structure of the tuber and how different processing methods affect the sensory quality of the resulting products. A lot of work has been done in other parts of the world, and as such, potato varieties have been developed for specific uses. Recent focus has been on improving cooking performance, flavour and texture. Dry matter, starch and related compounds have been reported to be more important than cell wall structure and composition, though other researchers have found cell wall components to be just as important. There is need to study the local cultivars and genotypes within breeding programs in SSA, in a bid to understand the quality determinants. There is also a need to develop instrumental techniques to measure quality attributes and ultimately, improve breeding progress towards improved quality and consumer preferred characteristics.

INTRODUCTION

Potato is the most important tuber crop, ranked 3rd in terms of total production, after wheat and rice (FAO, 2017). Throughout sub-Saharan Africa (SSA), potato is an important food and cash crop grown predominantly by smallholder farmers; for example, it is the second most important food crop after maize in Kenya and in Malawi it contributes to food security especially during the hunger months (November to February). Potato is a valuable, more nutritious alternative to reduce dependence on maize; it yields 2-4 fold more per hectare than cereals, can meet the daily human dietary requirement of protein, vitamin C, P, Zn and Fe, and is more water-use efficient. The crop has strategic value in decreasing hunger and malnutrition (Abong *et al*., 2010). Current annual production in Kenya is estimated at 2-3million MT from approximately 150,000 ha, by over 500,000 mostly small holder farmers (USAID KAVES, 2014). Potatoes are grown mainly for cash, with producers selling >60% of their produce. The industry has a strong multiplier effect, indirectly employing about 2.5 million people as marketing agents, transporters, processors, vendors, retailers, and exporters (USAID KAVES, 2014). National per capita consumption is expected to grow at 5.2% annually, with urban demand exceeding 7% for the next 10 years to >40kg per capita by 2022. Expanding fast-food and snack markets are also exerting additional demand for potato, especially good quality tubers free of pest damage. Thus potato has significant potential to contribute to food security and economic development in Kenya but current yields of approx. 20t/ha are far below the potential for several reasons, including lack of healthy planting material (96% of producers use uncertified seed), pests and disease, poor agronomic practices and the inefficient or broken production and value chains.

In Malawi, potato is at the forefront of the Government's crop diversification efforts (FAO and WFP, 2005) aiming to create wealth through sustainable economic growth and achieve poverty reduction. The market for potato is expanding rapidly because of urbanization. This growing domestic market presents a valuable livelihood opportunity for small holder farmers besides benefiting vulnerable low-income consumers. Supported by several funding initiatives, production for the period 2006 – 2015 increased by 102 % and potato yield increased by 33 %, from 13.0 MT/ha to 17.3 MT/ha. However national demand for potato remains higher than production, and considerable quantities of table potato are imported from South Africa. Despite the relatively acceptable yields and gradual improvements in tuber quality, potato varieties are still not reaching their full potential of32 – 41 MT/ha. Similar issues are faced in Rwanda, the third largest producer in SSA where per capita consumption is extremely high (125 kg per annum). Potato is grown in all 12 Rwandan agro-ecological zones mostly on small family farms that intercrop potato with beans and maize, and yields average ~10 t/ha. Shortage of healthy seed is a major limitation, and 97 % is supplied by an informal seed system. Farmers are encouraged to join cooperatives so that they can be taught best farming practices in order to increase the potato productivity.

1. COMPOSITION AND STRUCTURE OF RAW MATERIAL

1.1 Composition

Potato is highly nutritious and a good source of carbohydrates, vitamins, minerals and proteins (table 1). The tubers have a very high water content which principally contributes to low energy (calorie) content (per 100g tuber) of 66Kcal when boiled with the skin intact and about 77Kcal when boiled without the skin. The use of fat during cooking, such as in the preparation of French fries or oven baking, significantly increases this value to about 162 – 364Kcal (Stewart and Taylor, 2017). The energy is mainly due to dry matter. Potatoes have an average dry matter content of 22%, of which approximately 60 to 80% is starch and the rest is made up of small quantities of sugars (mainly glucose, fructose and sucrose), fibre, protein and ash. Dry matter content is genetically controlled and great variation exists between cultivars. Some varieties consistently produce high dry matter while others produce low values, however, there is no absolute for any cultivar, as it can be modified by cultural practices and environmental factors (Burke, 2017). Abong *et al*. (2010) reported average dry matter content of 19.50 – 24.20% amongst twenty four Kenyan cultivars.

Table 1. Chemical composition and nutritional value of raw potato tuber per 100g

Nutrient	Value per 100g
Water	77 – 79
Dry matter	17 – 25g
Energy	66 – 77Kcal
Carbohydrates	15.40 – 34g
Protein	1.40 – 4.5g
Total Fat	0.10 – 0.30g
Cholesterol	0mg
Dietary fibre	1.5 - 2.5g
Vitamins	
Folates	18mcg
Niacin (B3)	1.149mg
Pantothenic acid (B5)	0.279mg
Pyridoxine (B6)	0.239mg
Riboflavin (B2)	0.038mg
Thiamin (B1)	0.081mg
Vitamin A	7 IU
Vitamin C	10 – 30mg
Vitamin K	2.9mcg
Minerals	
Sodium	6mg
Potassium	320 – 455mg
Calcium	10 - 12mg
Iron	0.70 – 0.78mg
Manganese	0.141mg
Magnesium	22 – 23mg
Phosphorus	57 – 61mg
Zinc	0.29 – 0.33mg
Phytonutrients	
Carotene-β	4mcg
Lutein zeaxanthin	21mcg

(Sources; Eufic (2010), Furrer *et al*. (2016), Stewart and Taylor (2017) and USDA (2018)

Potatoes are one of the richest protein sources of any root or tuber crop, contributing 10 -30% of the recommended daily intake for children between 1 and 3 years old (Sewart and Taylor, 2017). Approximately 40% of the soluble protein is classified as patatin, a class of glycoprotein storage proteins. The most abundant amino acids are asparagine, glutamic acid, aspartic acid and lysine, while methionine, cysteine, and histidine are found albeit in low quantities (Furrer *et al*., 2016). Potato protein is high quality because it supplies the essential amino acids in concentrations higher than most cereals. Potatoes have no cholesterol and have very little natural lipid, with levels typically around 0.1% fresh weight across varieties (Storey, 2007). The large majority (90%) of fatty acids in potato are palmitic, linoleic, and linolenic acids (Furrer *et al*., 2016). When consumed with the skin, it is a good source of dietary fibre and antioxidants.

The tuber also has vitamins C, B6, thiamine (B1) and folate (folic acid, B9). Vitamin C is the most abundant and at 10 – 30mg, it provides about 11 – 30% of the recommended daily intake, though it varies greatly in cooked potatoes, depending on the method of cooking. Potassium is the most abundant mineral in the tuber and a 100g serving can contribute to 7-20% of the daily reference value of 3500mg/day (Stewart and Taylor, 2017). The other key minerals provided are calcium phosphorus, magnesium and the micronutrients (iron and zinc).

Potatoes contain glycoalkaloids, which are potentially toxic at high concentrations (safe limit is 150mg/kg fresh tuber weight). Two major glycoalkaloids found in the tuber are α-chaconine and α-solanine, with α-solanine ($C_{45}H_{73}NO_{15}$) being the more toxic of the two (Burke, 2017). These are detected as a bitter taste upon consumption, although at low concentrations they enhance flavour. Peeling the tubers decreases the concentration of glycoalkaloids.

1.2 Structure

Potato tubers are usually oval to round in shape with white flesh and a pale-brown skin, although numerous variations in size, shape, and flesh colour are frequently encountered. The tuber has a bud and stem end on opposite, longitudinal sides. The skin is made up of a layer of approximately ten dead cells, referred to as the corky periderm (figure 1). These cells do not contain starch or protein, and have thickened cell walls (Troncoso *et al*., 2009).The skin contributes about 4% total fresh weight and 3% total solids of the whole tuber. The cortex, underlying the periderm, makes up 35 – 50% of the total fresh weight and about 40 – 50% total solids of the whole tuber. It is made up of vascular storage parenchyma and is rich in starch. The pith (medulla) is located at the centre of the tuber and radiates narrow branches to each of the eyes. It contains much smaller cells and a lower starch content. In immature tubers, the cortex makes up a small volume but in mature tubers, it can exceed the volume of the pith.

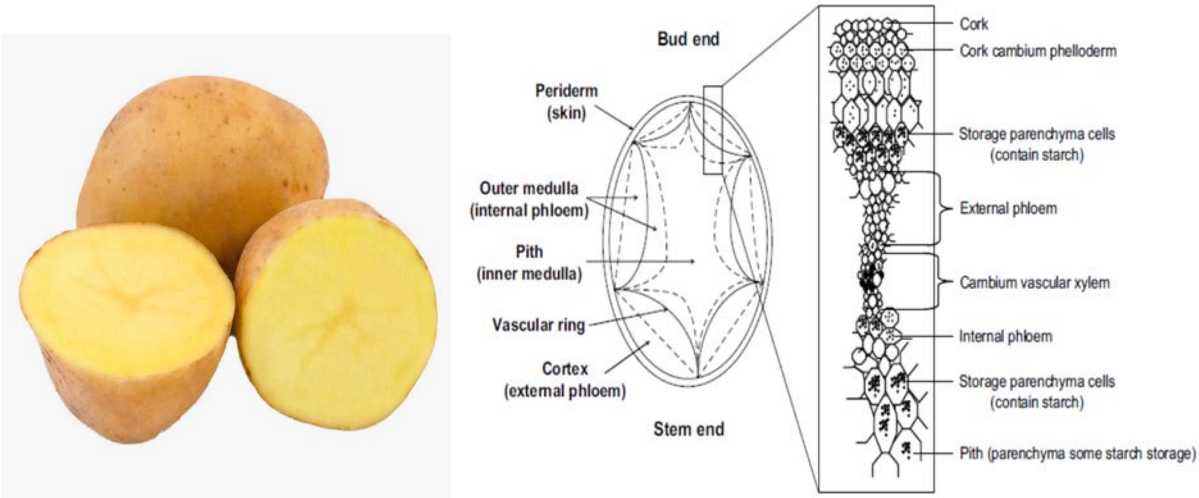

Figure 1. Image (A) and schematic (B) of cross section of the potato tuber. Adapted from fr.pngtree.com (A) and Troncoso *et al*. (2009) (B).

The parenchyma cells are usually polygonal in shape, although they vary amongst cultivars; some are roughly spherical while some are elongated. The cell structure can be determined through staining techniques and viewing under a light microscope (figure 2) or by advanced microscopic techniques, such as confocal scanning laser microscopy (CSLM) and scanning electron microscopy (SEM). Measurements of cell dimensions for potato tuber parenchyma indicate that the average cell diameter is 212 μm, the average edge length of a polyhedral cell face is 115 μm and the average cell wall thickness is 1 μm. Potatoes with a large cell size have been reported to also have larger starch granules (Bordoloi *et al*., 2012).

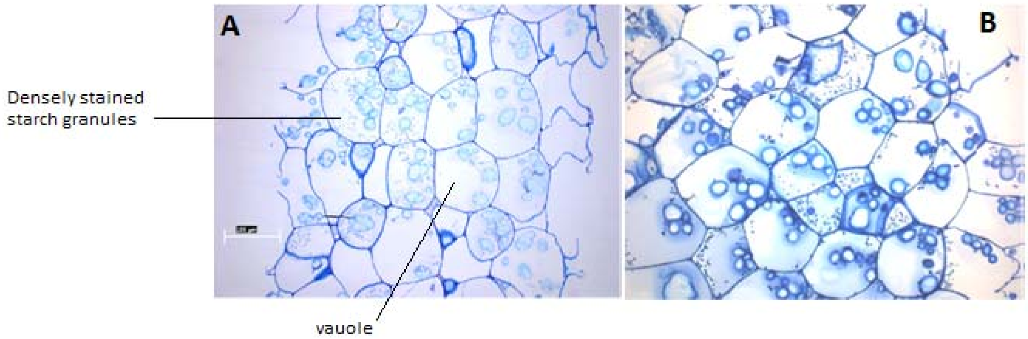

Figure 2. Light micrographs of raw tuber parenchyma from (A) Moonlight and (B) Red rascal potato cultivars from New Zealand. Adapted from Bordoloi *et al*., (2012).

The parenchyma cells have thin, non lignified primary cell walls and a middle lamella made up of cellulose, hemicellulose and pectic substances, which give the raw potato its rigid structure. The cell walls account for about 1 – 1.5% of potato tubers (Jarvis *et al*., 1981). Pectins are the main constituents of the middle lamella and play a major role in intercellular adhesion and also contribute to the mechanical strength of the cell wall (Abu-Ghannam and Crowley, 2006). The cell wall polysaccharides consist mainly of pectic polysaccharides (56%), xyloglucan (11%), cellulose (30%) and minor proportions of heteromannans (3%) and heteroxylans (<3%) (Vincken *et al*., 2000). Early work by Hoff and Castro, 1969, reported similar findings; 55% pectic substances, 7% hemicellulose, 28% cellulose, and 10% protein. The cellulose molecules are arranged into thin hair-like strands called microfibrils which, in turn, are arranged in a meshwork pattern along with hemicellulose, glycans and pectins (Bordoloi *et al*., 2012).

The pectin molecules consist of a backbone of α-(1-4)-D-galacturonic acid and contains some regions with alternating L-rhamnose (rhamnogalacturonan, RG-I and II), D-galacturonic acid (homogalacturonan, HGA I and II) (Ross *et al*., 2011a) and xylogalacturonan. Potato HG makes up approximately 20% of the cell wall polysaccharides (lower than most plant species) and is a linear polymer of α-(1→4)-linked galacturonosyl residues which can carry a methyl ester at C-6 and/or with acetyl groups at *O*-3 (figure 3). Acetylation is uncommon in other plant species. The RG-I component makes up to 75% total pectic polysaccharides (higher than most plants) and its backbone consists of α-(1→2)-L-rhamnose (Rha)-α-(1→4)-D-galacturonic acid (GalA) dimers in a long chain (figure 3). The galactan and arabinan side chains are composed of (1→4)-β-D-galactose (Gal) and/or (1→5)-L-arabinose (Ara) residues and are attached to the *O*-4 position of Rha of the RG-I backbone. In contrast to potato HG, the acetyl groups are attached to *O*-2 position of GalA residues in potato RG-I.

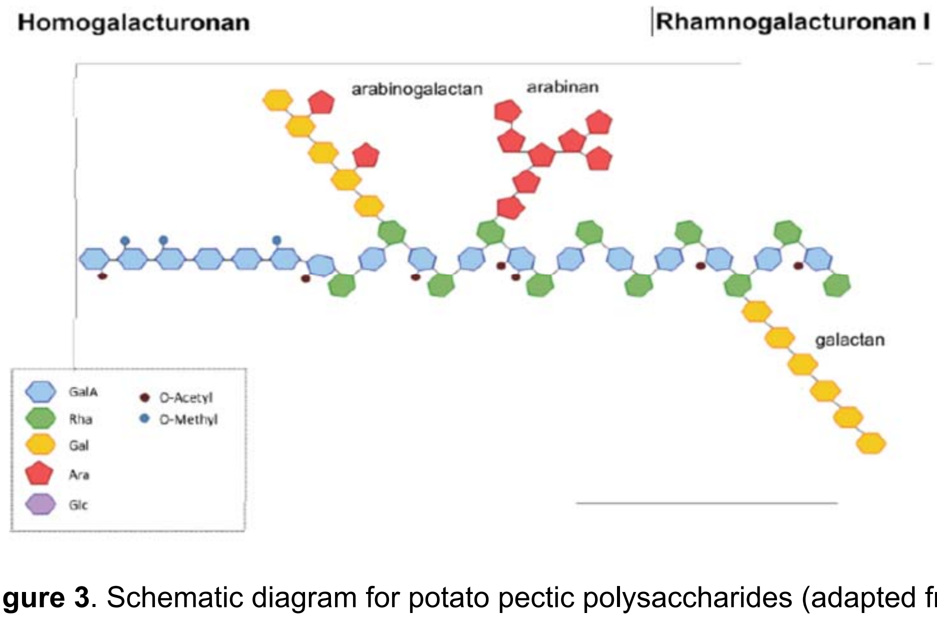

Figure 3. Schematic diagram for potato pectic polysaccharides (adapted from Cankar *et al*., 2014).

The precise composition of cell walls varies amongst cultivars and with different developmental stages. The structure and composition, particularly of the pectic substances greatly influences the texture of cooked potatoes (discussed later in section 5).

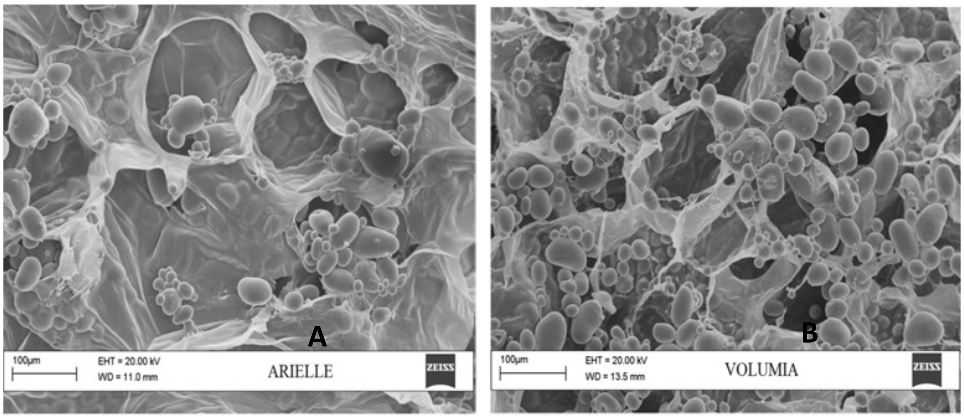

Figure 4. SEM micrographs of potato tuber parenchyma cells containing starch granules from (A) Arielle and (B) Volumia cultivars from Italy. Adapted from Romano *et al*., (2018).

The cells are filled with starch granules that are larger than most other root and tuber crops. They are lenticular, oval or spherical shaped, with a mean diameter of 23–30 µm, and a broad size range of 5–150 µm as determined through SEM (figure 4). The granule size and distribution is important for the nutritional and functional properties of the starches.

Potato starch has some unique physico-chemical characteristics; these include a high phosphate content, absence (or minimal concentrations) of internal lipids and proteins in granules (Romano *et al*., 2018). The amylose: amylopectin ratio is roughly 3:1; typically, starch from unmodified potatoes contain 17 – 22% amylose while genetically modified starches may contain up to 70% amylose or as low as 1% amylose in waxy potatoes. The amylopectin accounts for the crystallinity of potato starches (described as 'B' type X ray pattern) while amylose represents the armophous component.

2. PROCESSING CONDITIONS

Fresh potatoes undergo commercial processing into products such as: chips/crisps, frozen potato products (mostly French fries), dehydrated potato products (such as flakes, granules, flour, meal, and dried potatoes), chilled-peeled potatoes and canned potatoes. South Africa has the most advanced processing industry, utilizing 380 000tonnes of fresh potatoes (20% of total potato crop) to produce French fries, frozen and chilled products and crisps as well as mixed vegetables (canned and frozen), baby food and reconstructed potato products (Potatoes SA, 2013). In East Africa, Kenya has a more advanced processing industry compared to Rwanda, Ethiopia and Uganda. The major processed products are chips followed by fresh and frozen French fries. Tesfaye *et al*. (2010) reported that at that time, there were four major fresh French fry companies which processed an average of 117 tons annually, with two of them processing about 183 tons annually and Njoro Canning, a company for frozen French fries, processed about 144-216 tons annually.

The fresh market for potatoes includes home use, hotels, fast food outlets, schools amongst other institutions. The potatoes are processed through boiling/steaming, baking/roasting, frying and microwaving. For boiling, the potatoes are prepared by first washing the skin, peeling and cutting into the desired shape and size. The pieces are submerged or partially submerged in water at room temperature and brought to the boil (around 96°C). Cooking time varies with cultivar. The potatoes can be seasoned with salt or other spices. Frying is a dehydration method that employs high temperatures (160-180°C) and a short cooking time, product temperature does not exceed 100°C and results in minimal leaching of water soluble compounds (Troncoso *et al*., 2009). The major fried products are French fries and chips (also called chips and crisps, respectively in the UK). French fries are prepared by first washing and peeling potatoes by mechanical methods or by treatment with lye, followed by abrasion. The peeled potatoes are trimmed, sorted and cut along the longitudinal axis to produce strips of approximately 1 x 1cm^2 in cross section and about 6 – 7cm in length (Troncoso *et al*., 2009). The strips are blanched (optional) to; make the colour more uniform after frying, to form a layer of gelatinized starch that limits oil absorption, and to improve texture (Miranda and Aguilera, 2006). Blanching is followed by air drying to reduce excess surface moisture. The blanched potato strips can be par fried for 1 – 3 minutes, the oil drained and the fries frozen to be fried later. For immediate consumption, the strips are directly fried in hot oil at 180 – 195°C for up to 5 - 8 minutes. This results in a dry, crispy, oily outside crust and a well cooked, tender centre, with an oil content of 10 – 15% wet basis. Potato chips/crisps are very thin slices (1.27 – 1.78mm thick) fried in a continuous fryer at 177 – 190°C for up to 3 minutes, to a final oil content of 2% wet basis. The resulting product is crispy all the way.

3. SENSORY ANALYSIS AND CONSUMER PREFERENCE

Consumer preference for new crop varieties is an essential factor in adoption and traits desired by consumers are likely to be necessary for high nutrient potatoes to succeed commercially. The organoleptic drivers; appearance, texture and flavour, are increasingly recognised as important drivers of consumer purchase (McGregor, 2007), and can these can be evaluated by a sensory panel (table 2), or through instrumental means.

Motivated by an understanding of why fresh potato consumption is in decline in Europe and North America, several focus group and consumer attitude surveys have been published (Fernqvist, 2015; Dukeshire et al., 2016; Karadas *et al.,* 2017). Whilst these studies indicate that convenience is important, all cite taste and or texture as being factors in consumer choice. Further consumer research may add to an understanding of different potato markets and how much traits such as flavour and texture influence purchasing decisions. Interestingly in China where fresh potato consumption is increasing, preferred taste is cited as a factor in the success of a recently released variety, Cooperation 88 (Li *et al*., 2011). The texture or mouth-feel of the cooked product is also an important related sensory trait. Few researchers have documented consumer preferences in Africa. Kaguongo *et al*. (2007) reported that taste was a key determinant of adoption by farmers intending to sell their produce to home users in selected regions in Kenya and Uganda. The high marketability of the varieties Kerr's Pink and Ngure in Kenya was attributed to their high scores for taste. In Uganda, the variety Bumbamagara was rated high in taste and remained highly marketable despite its low yield and late blight susceptibility. Despite the importance of consumer preference profiling, there are significant gaps in publicly available data on this issue. Nevertheless, significant effort is undertaken by commercial potato producers to relate to consumer preferences. An interesting development is the Pommonde potato taste concept recently developed by the major Dutch potato company (HZPC) recognizing that flavour is the most crucial factor for consumption (http://www.pommonde.com/). In this concept, potato varieties are placed into one of four categories: creamy and refined, light and subtle, firm and tasteful, or dry and floury. The aim here is to describe the sensory characteristics of the products in terms that the consumer can understand and identify them by developing a clear vocabulary.

Table 2. Lexicon that can be used for sensory analysis of boiled potato. Adapted from Booysen *et al*. (2012).

Sensory attribute	Description
Aroma	
Cooked potato	The aroma and flavour that refers to the internal portion of a baked/cooked potato, which is absent in a raw potato
Potato/ earthy	Aromatic notes associated with damp soil, wet foliage or undercooked potatoes
Buttery	Aromatic notes associated with a potato that has butter added, less bland
Texture	
Compression with a fork	Ease with which a fork can be pushed into the potato
Fracturability	Point of first fracture, force with which the sample crumbles, cracks or shatters
First bite: hardness in mouth	Force required to divide the potato in two parts by the front teeth
First chew: firmness/compactness	Degree of compression between molar teeth before item falls apart. Expresses the work (amount of mastication) before the potato is ready to be swallowed
Mastication/Chewing	
Graininess	Expresses the content of grainy particles in the mouth after chewing
Adhesiveness	Force required to remove potato sticking to teeth and palate after chewing
Mealiness	Expresses how mealy/crumbly the potato is experienced in the mouth after chewing
Moistness	Expresses how moist the potato is experienced in the mouth and how much moisture it releases in the mouth after chewing
Dryness when swallowing	Evaluate the ease with which the sample is swallowed. Dryness in the throat
Flavour	
Cooked potato	The flavour that refers to the internal portion of a baked or cooked potato as opposed to a raw potato
Earthy/potato skin	Taste associated with earthy potato skin notes
Buttery	A taste associated with potato to which a small amount of butter has been added, a potato with more flavour, less bland
Blanched water/earthy	A flavour of recycled water used to cook potatoes, not fresh, slightly dirty, stale and earthy aroma
After-taste	A metallic-like taste that causes drying in the mouth
Metallic	

Processing/ cooking method has a great impact on the sensory quality of potatoes. Boiled potatoes are usually bland, compared to fried products. In fried potato products, the flavour is more complex than in boiled or mashed potatoes due to the higher cooking temperatures and the oil absorbed during the process. The flavour compounds are not only from the raw potato but also from the frying oil, Maillard reaction and from the interaction of Maillard reaction products with lipid oxidation products. Crispness is the most desirable textural attribute in chips, lack of crispness implies poor quality and is undesirable to consumers. The crispness/brittleness is due to moisture loss and structural changes to the potato cells. Fries are acceptable when crisp on the surface but moist in the centre. A golden yellow colour is desirable in both chips and fries, while a darker brown colouration is undesirable and associated with a burnt product and bitter taste (Burke, 2017), making it unacceptable to consumers.

4. PRODUCT CHARACTERIZATION AND RELATIONSHIP WITH SENSORY EVALUATION

4.1 Evolution of composition and structure with processing

Upon processing, there are several changes in the structure and chemical composition of potatoes. In boiled potatoes, softening is the most evident structural change and is mainly due to changes in the cell wall and starch composition. During processing, the pectic substances in the middle lamella and primary cell wall are brought more easily into solution and hydrolysed subsequently contributing to the degradation of the potato structure. Pectin methylesterases, which are activated at temperatures in the range of 50 – 65°C, hydrolyse pectins by removing methyl moieties from the pectic substances, replacing them with Ca^{2+} ions, resulting in a firm calcium pectice gel in the cell wall matrix. Cell wall softening is due to the disintegration of the calcium-pectic gel by thermal β-eliminative cleavage of the pectic chain. In cases where pre-processing blanching is undertaking, the potatoes are usually firmer due to absence of β-elimination reactions. Abu-Ghannam and Crowley, (2006), reported that a low temperature blanching at 65°C, in combination with a typical high processing temperature range such as 95–100°C, resulted in an increase in the force required to shear whole new potatoes as compared with processing treatments without a pre-blanching step.

Starch granules hydrate and swell in the initial boiling moments. The swollen starch within the cells exerts a strong pressure on the cell wall and middle lamella, the middle lamella disintegrates after about 20-30 minutes leading to cell separation (Troncoso *et al*., 2009). The cells continue swelling and after about 50 minutes the cells collapse and disintegrate (figure 4), accompanied by pasting of gelatinized starch to the surface of the samples. These structural changes are associated with the textural parameters (such as softness and dryness) of the cooked potatoes. Softness results from cell cleavage and cell separation, dryness results from the ration of cell separation to cell cleavage.

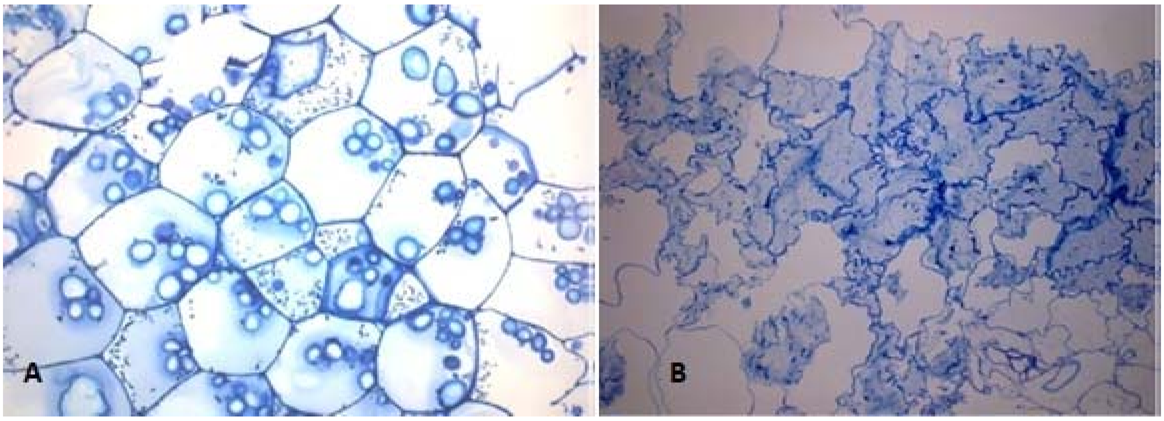

Figure 4. Light micrographs for (A) raw and (B) boiled Red Rascal tuber parenchyma from New Zealand. Adapted from Bordoloi *et al*., (2012).

Frying induces changes in starch and cells similar to those observed in boiling of potatoes. However, there is more rupture of cells in fried potatoes (figure 5), this can be a result of osmotic dehydration which disrupts the middle lamella and dissolves the cell wall (pectin) (Romano *et al*., 2018). The starch granules undergo gelatinization at around 60 - 70°C. At 60 - 80°C, the middle lamellae between cells disintegrates and cells separate giving the so-called mealy texture. Exposure to temperatures above 100°C causes starch granules and cells located in the forming crust to become dehydrated.

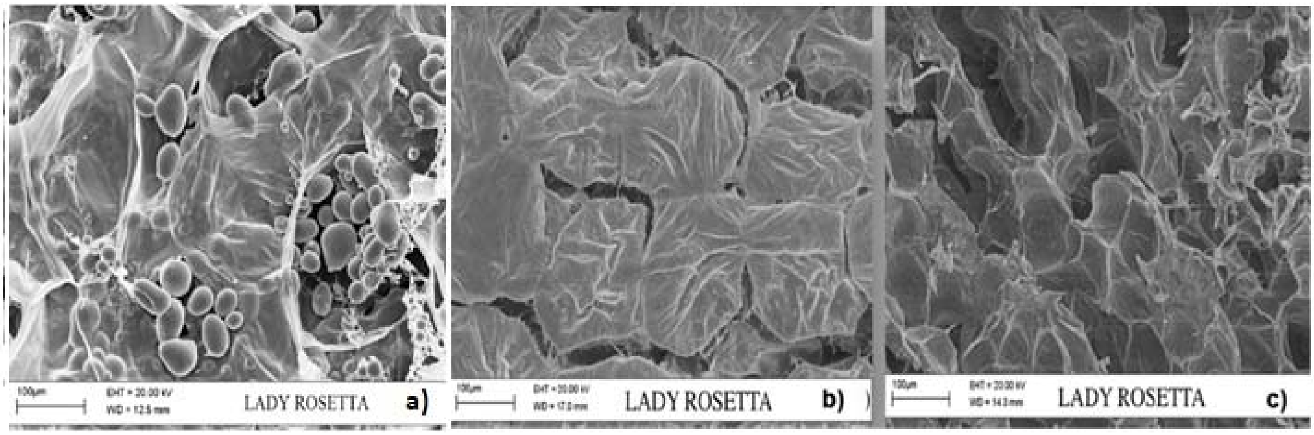

Figure 5. SEM micrographs of a) raw, b) boiled and c) fried tuber parenchyma from Lady Rosetta cultivar. Adapted from Romano *et al*., (2018).

The proximate composition of tubers does not significantly change during processing. In the boiled tubers, there is very little moisture absorption and loss of soluble solids. However, there is an appreciable loss of nutrients such as vitamin C. Jimenez *et al*. (2015) reported that vitamin C retention was higher when tubers were boiled with the skins on. In fries, vitamin C was completely destroyed by the high temperatures of the cooking process. The boiling process caused a vitamin C loss of between 27.41% and 64.18%, depending on the variety. According to Lachman *et al*. (2013), boiled peeled potatoes retained 70% of vitamin C compared to fresh peeled potatoes. In this study, peeling did not significantly affect vitamin C content.

The major compositional changes that occur during processing of potatoes into chips (crisps) are moisture reduction and an increase in oil content. The water content is reduced from about 80 % to between 1 and 2 % (Miranda and Aguilera, 2006). The final moisture content is critical as it influences stability from microbial spoilage and contributes to the final crisp texture (Miranda and Aguilera, 2006). The potatoes absorb the frying oil and this results in an oil content of 30% to 40% (wet basis), and this gives a unique texture-flavour combination that makes them desirable. Higher oil content results in greasy/oily chips while a very low oil content results in a hard texture and lack of flavour. There is development of brown colour during Maillard reactions between sugars (mostly fructose and glucose) and amides (mostly glutamine and asparagines) and it becomes rapid at temperatures above 150°C. In the frying process, excess asparagine often leads to acrylamide formation, which is a health concern in humans (Burke, 2017).

4.2 Relationship between composition, instrumental texture and sensory evaluation

The microstructure and composition of raw potato tubers play an important role in determining the sensory attributes of the processed potato (table 3). Flavour depends on the interaction of volatile aroma compounds with soluble cellular constituents. The soluble compounds define the basic taste parameters, bitter, sweet, sour, salty and umami. The volatiles produced by raw and cooked potatoes have been studied extensively and over 250 compounds have been identified in potato volatile fractions (some mentioned in table 3). Methods for capturing volatile components evolved from cooked potato have been described and include GCMS analysis of volatiles captured on solid phase micro-extraction fibres. Tuber matrix associated compounds can be analysed by LC-MS as well as GC-MS of polar and non-polar compounds. Since then, attempts have been made to discriminate which of these components are important for potato flavor, which are specific to the method of cooking, cultivar differences, the effects of agronomic conditions and effects of storage (Oruna-Concha *et al*., 2001; 2002; Duckham *et al*., 2001, 2002; Dobson *et al*., 2004).

Table 3. The relationship between composition and sensory attributes of potato tubers.

Composition	Sensory attribute	Relationship
Dry matter	Texture	Firmness High dry matter results in more firm, less mashable product (Van Dijk *et al*., 2002a)
Starch content	Texture	High starch potatoes (20-22% fresh weight) result in a floury texture Low starch potatoes (16–18% fresh weight) result in waxy texture (Furrer *et al*., 2017)
Starch granule size	Texture	Mealy potatoes have larger starch granules (>50μm) in comparison with waxy potatoes (Bordoloi *et al*., 2012)
Starch type (amylose/amylopectin)	Texture	High amylopectin content leads to waxy texture High amylose content leads to floury texture (Furrer et al., 2017)
Pectin structure	Texture	High degree of methylesterification correlates with increased firmness
Pectin methyl esterase expression	Texture and cooking time	PME is involved in cell wall modification through pectin demethylation Low PME activity results in less crosslinking of pectin with Ca^{2+} and correlates with fast cooking in Phureja tubers, increased sloughing (separation of skin from the flesh) and an extremely floury or crumbly texture (Ross *et al*., 2011a)
Total sugar	Taste Texture Colour	High sugar - increased sweetness High sugar - poor/soft texture after cooking High sugar - darker colour especially in French fries and crisps (Miranda and Aguilera, 2006)
Glycoalkaloids	Flavour	High levels of chaconine and solanine result in increased bitter taste, decreased flavour intensity, creaminess and savouriness in boiled potato (Morris *et al*., 2010)
Amino acids and volatile compounds	Flavour, Colour	α-copaene gives the typical potato aroma Glutamate contributes to umami taste Methional (from methionine) gives off baked potato flavour Most amino acids participate in Maillard's reactions resulting in production of coloured compounds Asparagine leads to acrylamide formation in fried products. (Ducreux *et al*., 2008) Earthy flavours are due to 2,3-pentanedione, 2-pentanal, 2,4-octadienal and 2,4-heptadienal. Metallic flavour and aftertaste are due to 2-methylbutanol, pentanal, dimethyl disulphide and dimethyl trisulphide

Dry matter and starch have been reported to be the major contributors to textural properties in cooked potato, however, other research findings suggest the composition, structure and modification of cell wall pectins during cooking might also have an important role. In a study by Ross et al. (2010), there was little correlation between starch content and textural properties. The textural properties of the low starch pith were similar to other regions of the tuber containing higher levels of starch. There was also no obvious correlations between cell size and shape and texture parameters. A striking difference in the texture of *S. tuberosum* group Tuberosum and *S. tuberosum* group Phureja has been reported by Ross *et al*. (2011a and 2011b). The Phureja group cooks in half the time taken by Tuberosum, exhibits an appreciable degree of sloughing (separation of skin from the flesh) after 10 minutes of boiling and results in an extremely floury or crumbly texture when boiled (Ross *et al*., 2011a). The group requires a lower peak force to initiate a fracture as observed in instrumental texture analysis (wedge fracture test, which measures the force required to cut through the sample). This has been attributed to the much lower pectin methyl esterase (PME) activity in Phureja tubers, which may underpin changes in pectin structure and contribute to the differences in textural properties compared with Tuberosum (Ross *et al*., 2010). More research is still required if we are to fully understand the relationship between cell wall properties and textural traits in potato.

The sensory-perceived texture of potatoes can be assessed either by laboratory studies using a panel of trained judges or by consumer tests. The instrumental assessment of the textural characteristics of potatoes has been performed by cutting, compression, puncture, tensile stress, and relaxation and extrusion measurements (Van Dijk *et al*., 2002). Most commonly applied is a uniaxial compression test in which the sample is compressed once and the force required to penetrate it is recorded. Texture profile analysis (TPA) has also been employed to measure texture. Here, the instrument simulates mastication by partially compressing the sample twice, to imitate the first two bites taken, while measuring the changes in force over time. Results of TPA have been reported to correlate with sensory texture better than uniaxial measurements. However, Thybo and Martens (1999) concluded that instrumental TPA parameters they investigated were not relevant to replace the sensory evaluation of cooked potatoes.

In addition, a wedge fracture test was first developed by *Vincent et al*. (1991) providing a method that more closely reflects the consumer's sensory experience of the medullar tissue. It involves using an acrylic blade to cut through a cooked potato, work done is the energy required to penetrate to 10 mm while peak force is the maximum force required for the wedge initially to cut and then force the tissue apart and propagate a crack in the cube ahead of the wedge (Ross *et al*., 2011a). Good correlations between the wedge fracture and panel sensory tests for a range of different food products have been demonstrated. Using this method, it was demonstrated that tubers from *Solanum tuberosum* Phureja Group have a greatly reduced cooking (by steaming or boiling) time than typically observed for those from *Solanum tuberosum* Tuberosum Group and hence represent an extreme variant in textural properties (Ross *et al*., 2010). The fast cooking attribute may address convenience issues for consumers and has the potential to be a marketing tool. Other methods of assessing different aspects of potato texture have also been developed, such as the measurement of cell 'sloughing', the extent of cell separation of the cortex from the medulla during cooking (Hejlovaet *et al*., 2006).

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