Potato – A basis for human nutrition and health benefits

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Executive Summary and Roadmap

The literature review identifies that, in opposition to general public opinion, that potato has a definite place in the diet and is associated with good nutrition and health.

Assessment of the current state of play for the potato and human nutrition and health identified several points and these are highlighted below;

- Due its nature as a food stable, potatoes are a significant source of Vit C, Vit B6 (pyroxidine), Vit B9 (folate) and a whole host of macro and microminerals. Together these are responsible for maintaining homeostasis and retarding the initiation and progression of a plethora of degenerative diseases.
- The micro/macro-minerals and, to a lesser extent, the vitamins can survive processing and cooking methods. In addition genetic studies have identified that there is significant variation in these components with the potential to be exploited by breeding for enhancement.
- Non-nutrient but health beneficial components such as carotenoids, polyphenols have been the target of many model and intervention studies and almost uniformly they were identified as beneficial to human health with respect to reducing markers of degenerative disease. These are emerging science health areas and need a watching brief.
- Toxic glycoalkaloids can accumulate in potato tubers in some varieties however recent developments will enable their levels to be manipulated via breeding.
- Dietary fibre (cell wall polysaccharides and resistant starch) has been the focus of many papers identifying health benefits either as potato in foods or as extracts added to other foods.
- The reported values of glycaemic index for potato show wide variation between different studies however it is clear that the glycaemic index values depend on cooking method and variety and are not necessarily higher than other starchy food sources. If eaten with oil and meat the GI reduces significantly.
- Potato has a very high satiety index compared to foods with an equivalent carbohydrate content and this represents a very positive aspect of potato nutrition.
- Recent reviews of clinical intervention and observational studies centred on potatoes came to the conclusion that the identified studies did not provide convincing evidence to suggest an association between intake of potatoes and risks of obesity, Type II diabetes (T2D), or CVD. The data for French fries were less equivocal and they may be associated with increased risks of obesity and T2D although confounding factors were reported to be present.
- Allied to the obesity studies, major population based studies targeting potato and CVD were also encouraging, identifying that "replacing meat in the diet with vegetables or potatoes is associated with a lower risk of MI (myocardial infarction – heart attack).
- Increasingly relevant is the impact of potato intake on the elderly. Although early days as regards intervention studies, of those undertaken it was shown that potato intake was strongly associated with enhanced cognitive function. This represents a fruitful market for potato to target with the lifespan increasing and birth rates forecast to plateau for the next 30-50 years.
- Potato should be reassessed as a source of nutrient and beneficial chemicals as well as a food and this could be a viable processing income stream for primary production as well

as processing waste. The production of potato-derived chemicals such as starch and cell wall polysaccharides (prebiotics,dextrins), protein(s), glycoalkaloids, polyphenols, carotenoids etc may well be a viable business in the post-Brexit economy.

- Behind all of the above is the implicit understanding that varieties need to evolve to deal with climate and environmental changes (including disease) but with that the market requirements will also change (increasing recognition of flavour and texture distinction for, and desirability by, the consumer). Breeding programmes to deliver this are, by their nature, long term and here the emergent approaches of genomic selection, F1 hybrid breeding, and gene editing technologies (and particularly the combination of the latter two) could well see a game- change in potato varietal generation in vastly reduced timeframes.

Roadmap

UK Potato is a dual game at the moment with fresh (table potato) in a straight line decline whilst the processed market is buoyant. The perception of potato as something to be dropped from the diet if one is to be healthy is simply not supported by the intervention studies. Indeed, it looks like potato consumption could well be a route to maintaining mental acuity as one gets old according to recent interventions.

- ***Potato needs a sustained campaign identify its health benefits across the age ranges.***

Increasing consumer sophistication and desire for the new suggests much can be made of the existing potato flavour and texture diversity for fresh market potato

- ***Promotion of fresh/table potatoes for distinct taste and texture***

More health related research is needed for potato but not in terms of obesity, GI, CVD etc. There exists a significant bank of such research but its collation into a coherent body of knowledge (beyond this review) is lacking. However the targeting of elderly (or post 60) health and nutrition is an increasing market and one requiring specific nutritional and health needs. This market (home buy and/or procurement) could be significant

- ***Explore the potential of potato as a source of health, nutrition and cognitive ability in the aging population.***

Potato is a vibrant feedstock for nutraceuticals that can be generated either from primary production potatoes or processing waste. However there needs to be a targeted assessment of the potential for this as a business opportunity, especially in post-Brexit UK.

- ***Explore the potential of primary production and (processing) waste potato as a feedstock for nutraceuticals to go into the expanding health food/ingredient market.***

The UK has a long history of potato breeding but the ability to significantly change one trait let alone several is neither facile nor fast. In fact, arguably there has been little genetic gain in potato in the last century. Subsequently the potential of the emergent breeding (F1 hybrid and genomic selection) and gene editing (CRISPR/CAS9) should be explored as they could separately, or more likely together, create step changes in potato variety generational timelines. This may then allow true potato nutritional enhancement to become a commercially viable option, e.g. starch structural manipulation, mutli-vitamin enhancement etc

- ***Align with initiatives established to exploit advances in new breeding and gene editing technologies allowing for potato enhancement (health, nutrition etc).***

Introduction

Potato is now the world's 3rd most important food crop, after rice and wheat (Anon, 2016), and in 2014 the global production total was ~376.4MT. This figure masks a shift in consumption figures globally with the decline in world consumption of traditional roots and tubers seeing a shift to potato in some areas with much of this trend driven by China, where millions of farmers and consumers have switched from sweet potato to potato (Anon, 2002). This increase has masked a decline in consumption in the developed world (Europe, EU etc). Nevertheless potato is still a major source of nutrition and health for many.

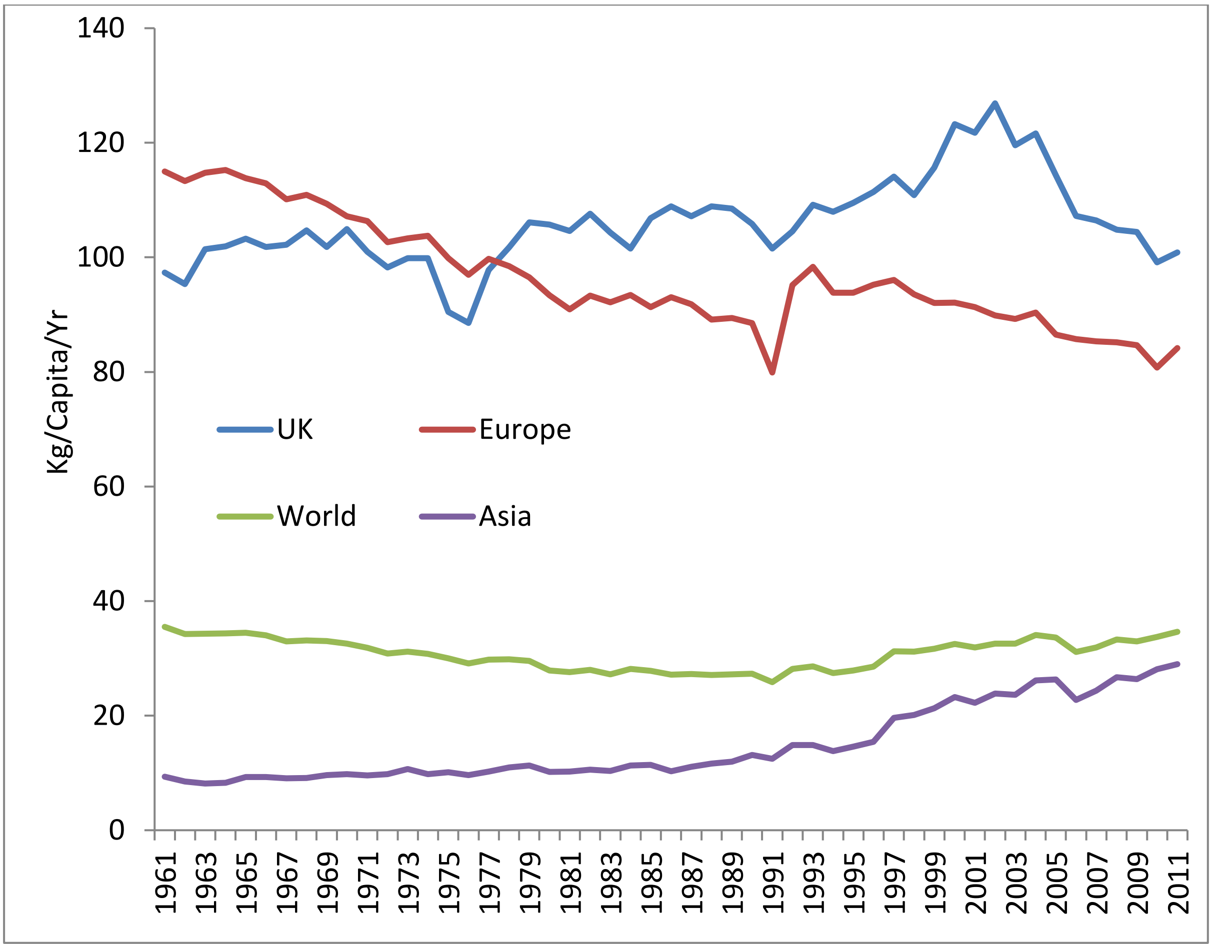

Figure 1. Global and selected country and region potato consumption (Ex FAOSTAT, 2017)

The basis of the beneficial health derived from potato has been as part of a balanced diet but more recently, indeed since the post war years and in the UK, table potato consumption has been in stark decline for many years whilst the processed sector continues to flourish. However, overall consumption, as assessed by FAO, continues to decline (Figure 1). This decline in the UK has laterally been mirrored in the EU also from ~2000.

Underpinning this decline are two factors: the availability of other food options and the perception, through marketing and some scientific studies, that potato per se is a comparatively poor health option.

Here we have looked at several factors at the scientific level with respect to health, concentrating on clinical trials and metadata analyses and, where these were lacking, model systems to tease out if there is a basis for these claims. These trials and interventions have been broken down into target conditions and pathologies. Overall the conclusion is extremely positive for potato as part of the diet and as a contributor to health.

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Nutrients, vitamins and Intake

Compared with other sources, such as fruit, meat and leafy vegetables, potatoes are often considered as lesser sources of vitamins and minerals. This is not correct and as a consequence of its significant *per capita* consumption the vitamin and phytonutrient content of potato can have greater dietary relevance and impact than foods eaten in lower quantities. The combined nutritional profile of potato distinguishes it from other carbohydrate sources such as pasta and rice and could be further emphasised in marketing campaigns.

The consumers' diet is ever evolving due to the increasing variety of products available but there are absolute requirements with regard the composition of these foods for good health. These nutrients are carbohydrates, fat, fibre, protein, minerals and vitamins and going forward these could well form viable targets for enhancement to make potato an even more attractive foodstuff.

The recent review of Weichselbaum (2010) outlined in some detail potato consumption in the UK and other countries and identified to what degree it contributed to the provision of nutrients. The review also identified potato as a naturally low energy food, due to the inherent water content, and that its use in the diet, perhaps as a side dish replacing other sources, is beneficial with the high starch content a ready source of carbohydrate.

The recent data from AHBD Potato (Anon, 2017) on the trends for potato consumption over 1974-2014 present an interesting scenario with fresh potato purchases declining but processed potato increasing over 1974-97 and generally stable from then on. The latest data for 2014 identifies that for fresh potato the purchase is just over 400g per person per week whilst for processed products such as chips, instant potato, crisp and potato snack, takeaway chips, canned potatoes and other potato products the current combined purchase level is ~240g per person per week. This highlights that fresh potato although in a decline is still seen as a valid food stuff and source of nutrition. For example, the most recent data from the National Diet and Nutrition survey (Anon, 2016) identified that potato, along with wholemeal and whole grain cereal & cereal products (especially bread and breakfast cereals) and are major sources of fibre in the UK.

With regard to the specific nutrients in potato it may surprise people that potato has a low energy (calorie) content at 0.7kcal (2.9Kj)/g due principally to the high water content. This energy is largely derived from starch. Of course the cooking of potato can alter the energy content significantly with the use of fat (for chips) increasing this value. Other factors such as chip size/cut and cooking duration impact fat absorption and hence energy content of the final foodstuff. This means that within the range of thick and fat cut chips and frying time duration and methods (oven bake, standard deep frying etc) the energy value can range from 364kcal (1523 kJ)/g to 162kcal (678kJ)/g.

Depending on the method of preparation potato can deliver an appreciable level of dietary fibre. The fibre largely resides in plant cell walls and is elevated in the peel. Weichselbaum's review (2010) identified that the fibre content for new potatoes with the skin is 1.5g/100g which compares favourably with boiled brown rice (1.5 g/100 g). If a large portion (220g) of boiled new potatoes with skin is consumed then this equates to 3.3g of fibre and ~20% of the dietary reference value for adults (Anon 2002)

With respect to fat content, the inherent content in potato is low (~0.3g/100g raw) and is largely modulated by the potato age (slight decline) and cooking processes with frying and roasting elevating this to 4.2-21.3 g/100g potato product (Anon 2002).

Protein is another key nutrient for health and, dependant on the variety, age and processing method, potato can deliver 1.4-4.5 g/100g fresh weight. At this portion size it contributes to 10-30% of the recommended intake for a child of 1-3 years and 3-8% for adults 19-55. (Anon, 2002, 2007).

Mineral deficiencies are prevalent in both developed and developing countries because of the relatively low content of bioavailable minerals in many staple crops (Welch and Graham, 2004). Globally, Ca, Fe, Se, I, and Zn deficiencies are the most widespread forms of mineral malnutrition. Billions of people are affected by these deficiencies that increase childhood disabilities, mortality, and elevate health care costs. Potato, as a major staple food crop, could play an important role to combat mineral deficiencies, in part because of its relatively high content of certain macro- and trace minerals (True et al., 1978; Anderson et al., 1999). Notable in potato are the prevalence of magnesium, potassium, iron and zinc. Of these potassium is the most abundant (320mg/100g raw) with a higher concentration in the skin and consequently lower in peeled potato products. Boiling also adds to potassium loss but other cooking routes such as baking, roasting etc give an apparent 2-2.5 fold increase through the commensurate loss of water. With a daily reference value of 3500mg/day 100g of cooked potato could contribute to this by 7-20%. Similar losses and gains are evident for the other identified micronutrients with 100g cooked potato potentially contributing 3-11%, 2-11% and 1-6% to the daily reference values for a 19-55 years adult for magnesium (310-420mg), iron (14.8mg) and zinc (9.5mg), respectively (Anon, 1997; Anon 2007).

Interestingly, studies have reported variation in potassium content in different potato genotypes (Rivero et al., 2003; Brown et al., 2013) that indicate that breeding approaches to elevate tuber potassium contents are feasible. Similarly, recent studies have reported significant variation in Fe content that could also become a target of breeding (Brown et al., 2010). Other approaches to enhance tuber mineral content include biofortification by application of mineral enriched foliar fertiliser. Such an approach was demonstrated to enhance tuber Zinc content by ca. 3-fold (Kromann et al., 2015; White et al., 2016).

Vitamins are also present in potato with thiamine (B1), folate (forms of which are known as folic acid and vitamin B9), Vit B6 and Vit C. Vit C is by far the most prevalent at 10-30mg/100g raw potato (Davey et al., 2000) followed by folate, Vit B6 and thiamine. Within Europe it has been estimated that potatoes contribute ca. 20% of the dietary intake of vitamin C however overall vitamin C intake is inadequate especially in some socio-economic groups (Love & Pavek, 2008).

Cooking the potato invariably reduces the absolute amount of Vit C with, for example, thick and/or thin cut and oven baked chips in general experiencing a 33% reduction in Vit C. Baking the potato gives a smaller reduction of 12% (Anon, 2002). Boiling generates the greatest loss through exposure to water and leaching leading to >40% loss. The detailed impact of processing on the Vit C contact is covered in significant detail by Weichselbaum (2010). In essence, a large portion of boiled potato (220g) provides ~33mg Vit C and this compares well with the daily reference value of 40mg/day for adults (Anon, 1991) and represents 82.5% of the requirement. It is worth noting that Vitamin C levels in potato tubers decrease rapidly during cold storage with losses of 20-60% occurring over 15-17 weeks (Keijbets et al., 1990; Dale et al., 2003). Significantly, considerable genetic variation in tuber vitamin C content has been identified but the effects of environment are also significant and could complicate breeding efforts (Love et al. 2004). We are unaware of any genetic study that has led to the development of gene markers for potato tuber vitamin C content although work at the James Hutton Institute as part of the Scottish Government Environment, Agriculture and Food Strategic Research Strategic Research Portfolio could possible deliver this (http://www.gov.scot/Topics/Research/About/EBAR/StrategicResearch).

Deficiencies of folate are implicated in a number of serious diseases including spina bifida, megaloblastic anaemia, cardiovascular diseases and some cancers (reviewed in Rebeille et al. 2006; Warzyszynska and Kim, 2014). Plants are the major source of folate in the diet, with potato providing ca. 10% of the folate requirement according to several European studies (Konings et al., 2001; Brevik et al., 2005). Although the range of potato tuber folate content (10-37 ug 100/g FW) is lower than in spinach (100-194 ug/100g FW; Navarre et al., 2009) the higher per capita consumption of potato does make potato an important source of folate. Again using a large portion of potato (220g) as the benchmark, boiled potatoes would provide 19% of the daily reference value of 200ug/day. Interestingly unlike folate in other vegetables, e.g. spinach and broccoli, prolonged boiling did not reduce the folate value significantly (McKillop et al., 2002).

Surveys of potato germplasm have demonstrated some variation in folate content. For example, a three-fold variation within 75 genotypes was reported by Goyer,and Navarre (2007) and a 10-fold range was observed in a survey of wild species (Robinson et al., 2015) suggesting that it may be possible to breed for enhanced folate levels.

Potatoes are an important source of dietary vitamin B6 (Kant and Block, 1990) with a medium baked potato (173 grams) providing about 26% of the RDA (USDA, 2017). Recent work reports considerable variation in tuber vitamin B6 content between different genotypes indicating that a breeding approach to enhance levels may be possible (Mooney et al., 2013). The same report also indicated significant (ca. 2-fold) increases in tuber vitamin B6 content during low temperature storage.

For the remaining vitamins, thiamine (Vit B1) and Vit B6 the recommended daily intake values are 0.8-1mg and 1.2-1.4mg, respectively. Vitamin B6 deficiency is associated with anaemia, impaired immune function, depression, confusion, and dermatitis (Spinneker et al., 2007). Deficiency is generally not a problem in the developed world, but there could be as yet poorly defined consequences of suboptimal intake particularly for the elderly. Vitamin B1 deficiency is common worldwide, but rare in the UK (Bates et al, 2010; Finch et al., 1998) and is known as Beriberi or Wernicke's Encephalopathy (Goyer, 2017) with accompanying symptoms/consequences of cardiac failure, neurological disorders, oxidative stress (lactic acidosis and sepsis) and refeeding syndrome (Collie et al 2017). Potatoes are an important source of vitamin B6 (Kant and Block, 1990) with a medium baked potato (173 grams) providing about 26% of the RDA (USDA, 2017). With respect to thiamine, (Vit B1), the content in potato is 3-13 ug per 100g fresh weight meaning that a large portion (220g) potato can contribute 0.3-1.3% of the daily reference value.

It is clear from the information outlined above that potato ***is*** an important part of the diet for good nutritional health and that it should be considered as a source of multiple nutritional benefits rather than on a nutrient by nutrient basis. These *in toto* see potato represented as a positive dietary route to nutrition and health. For example the view of potatoes solely as a simple carbohydrate source is clearly incorrect and indeed the inherent starch which underpins the potato energy content can, if allowed to cool before further cooking, can be made to retrograde to a degree and this resistant starch can behave like dietary fibre with the associated benefits for glycaemic control, good gut health and reducing the risk of cardiovascular disease (Lockyer and Nugent, 2017). Indeed, the European Food Safety Authority issued a statement identifying that resistant starch meets the EU definition of fibre specified by Commission Directive 2008/100/EC (European Commission, 2008).

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Starch and dietary fibre

Starch, the main component in potato is often viewed as the reason potato has been vilified as a food due to it being a ready source of glucose following consumption which if over indulged can lead to glucose overloading and the associated problems of oxidative stress, metabolic syndrome, CVD and type II diabetes. However, several studies have identified that there are routes to altering starch megastructure to render it less digestible and to deliver health benefits in a dietary context.

Resistant starch (RS) is a form of starch that resists digestion in the small intestine and, as such, is classified as a type of dietary fibre. The benefits of a fibre rich diet are well documented impacting on gut health, glycaemia and plasma lipid effects, satiety and bodyweight (reviewed in Lockyer and Nugent, 2017). RS can be categorized as one of five types (RS1–5), some of which occur naturally in foods such as bananas, potatoes, grains and legumes and some of which are produced or modified commercially, and incorporated into food products (reviewed in Lockyer and Nugent, 2017). The reduced glycaemic response consistently reported with RS consumption, when compared with digestible carbohydrate, has resulted in an approved European Union health claim.

Björck et al (1989) identified that potato starch that had been mildly modified (distarch phosphate (DSP), acetyl di-starch phosphate (ADSP) and hydroxypropyl di-starch phosphate (HPDSP)) led, in some cases (HPDSP) to a significantly reduced (~50%) degree of digestion and absorption compared to corresponding unmodified control. More recently Raigond et al (2015) reviewed the whole area of resistant (poorly digested) starches and concluded that for potato the various types of resistant starch can be enriched via processing and/or processing conditions leading to colonic health benefits. Additionally potato starch has been crosslinked to generate a nutraceutical product, Fibersym 80ST, that due to the reduced digestibility confers health benefits by reducing cholesterol, triglyceride and glucose levels in blood.

Non-modified potato starch does show considerable variation in RS content even in the small-scale trials that have been reported (Chung et al., 2014). The environmental and genetic drivers of this variation however are not yet clear.

Potato starch has also been used as a feedstock for the generation of resistant dextrins, low-molecular-weight hydrolysis derived carbohydrates (Barczyńska et al., 2015). These were shown to exhibit selective and beneficial prebiotic activities highlighting the potential of modified potato starch as a route to improved colonic health. Allied studies by Jochym et al (2012) studied potato starch thermolysis in the presence of inorganic (hydrochloric) and organic (citric and tartaric) acids under controlled conditions and found that the resultant dextrins exhibited definite soluble dietary fibre activities.

The other polysaccharides in potato have also been studies for nutraceutical impacts. Hashimoto et al (2006) fed de-starched potato peel to rats and reported an associated reduction in plasma total cholesterol and increased cecal ratios of Lactobacillus and Clostridia and decreased cecal ratios of Bacteroides and Gammaproteobacteria, respectively. They concluded that ingestion of the starch free potato peel (polysaccharides) for four weeks was likely to improve both cecal conditions and cholesterol metabolism, suggesting prebiotic effects. Further potato carbohydrate studies by Khodaei et al (2016), this time focussing on rhamnogalacturonan I pectic polysaccharides, highlighted associated prebiotic activities, specifically stimulating the growth of Bifidobacterium spp. and Lactobacillus spp.

Clinical trials and Intervention studies

Dietary fibre and potato has been the focus of clinical trialling with several registered: Effect of Potato Fibre on Appetite and Fecal Fat Excretion (POFIBA, NCT02957318, 2016); Potato Fiber and Gastrointestinal Function: Phase 3 (NCT01964599, 2013); Soluble Fibre Enriched CHO Food Study (NCT01898026); Effects of MSPrebiotic on Gut Health in the Elderly (NCT01977183, 2013); Role of Gastrointestinal Microbes on Digestion of Resistant Starch and Tryptophan Availability to Humans (NCT02974699). Of these there is only data published for the second trial (NCT01964599, 2013) by Dahl et al (2016) who studied the effects of resistant potato starches on gastrointestinal (GI) function and microbiota in healthy individuals. A 6-week, double-blind, cross-over study found that intake of chemically modified potato starches (RS4-A, soluble, viscous; RS4-B, soluble, non-viscous; RS4-C, insoluble, non-viscous) saw an increase in stool firmness and frequency. GI symptoms were minimal with slight increases in flatulence with all interventions. In addition, RS4-B intake decreased Firmicutes and the ratio of Firmicutes to Bacteroidetes. Resistant potato starches vary in their effects on GI function, which may be related to shifts in intestinal microbiota.

As well as the clinical studies smaller intervention studies have been performed targeting potato and dietary fibre. Scheppach et al (1991) looked at the effect of freeze thawing potato on colonic fermentability. Meals of (A) potatoes boiled and consumed fresh at 60 degrees C; (B) potatoes boiled, frozen, thawed and consumed at 20ºC; and (C) potatoes boiled, frozen, thawed, reheated to 90 ºC, and consumed at 60 ºC were trialled and it was found that the extent of colonic carbohydrate fermentation in B was significantly higher than in experiment A with the value for C somewhere in between. It was suggested that structural alterations of the starch molecule occur during freezing, thawing, and reheating and alter the availability of carbohydrates for fermentation by colonic anaerobes. Other studies on resistant starch have been undertaken with Raben et al (1994) reporting the replacement of digestible starch with RS resulted in significant reductions in postprandial glycaemia and insulinemia, and in the subjective sensations of satiety

Cherbut et al (1997) compared potato (PF) and maize (MF) dietary fibres in an intervention study and found that MF resisted fermentation better than PF and had lower digestibility. However, both fibres increased faecal output of dry matter, neutral sugars and water. Orocaecal transit was lengthened by PF, probably because of its high water binding capacity and PF ingestion also decreased postprandial plasma levels of total and esterified cholesterol but had no effect on fasting concentrations.

A recent review by Lockyer and Nugent (2017) comprehensively reviewed the health effects of resistant starch and identified that potato can contribute to good gut health predominantly by RS3 (cooked, then cooled) starch

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Potato polyphenols and flavonoids

Polyphenolics have been the focus of many research papers and these are best summarised by Friedman (1997) Tsao (2009), Zhao et al (2009), Ezekiel et al (2013) and Akyol et al (2016).

Potato is an accepted good source of (poly)phenolic compounds and measured as a total phenol content these can range from almost zero up to 50m/g dry weight depending on the variety and the tissue (whole, pulp and skin). There is a good diversity of phenolic compounds in potato with the major ones being chlorogenic acid, benzoic acids, flavonols (e.g. quercetin and kaempferrol – 3 rutinosides), flavon-3-ols (catechin) and anthocyanins on red or purple fleshed potatoes.

With regard to the health benefits of polyphenols the majority of the studies have been conducted with fruit and vegetables rich in these but there is a sizable body of work on potato polyphenols and human health. In particular antioxidant, antiproliferative, and anticancer effects of potato polyphenols (PPs) have been a focus for research (Singh and Rajini, 2008; Kaspar et al 2010; Madiwale et al, 2012). In these and other studies the PPs showed benefits in animal studies with regard to retarding damage associated with oxidative stress (Han et al. 2007; Singh and Rajini, 2008), breast (Leo et al, 2008; Thompson et al, 2009) and colon (Lim et al, 2013; Madimale et al 2011 & 2012) cancer proliferation, anti-inflammatory activity (Kaspar et al 2010) and liver neuroprotection (Ji et al 2011). It is interesting to note that there are few studies linking PPS and neuroprotection but literature mining has revealed that chlorogenic acid, the main PP, has been attributed with significant neuroprotective abilities encompassing therapeutic treatment of Alzheimers disease (Gray et al., 2014), protection against neurodegenerative disorder characterized by loss of learning and memory (Ha et al., 2015) and hypoxic-ischemic (brain damage caused by oxygen loss; Keddy et al, 2012) and general maintenance of maintain brain homeostasis, neuronal stress adaptation and ultimately the prevention of the progression of neurodegenerative pathologies (Vazour, 2012).

By far the greatest interest in PPs has centred on the anthocyanin derived coloured flesh potatoes (Zhao et al, 2009). Vinson et al (2012) under took a small intervention study with the cultivar Purple Majesty with 18 overweight (average BMI of 29) men and found that there was an anthocyanin related reduction in both systolic and diastolic blood pressure. Kaspar et al (2011) also under took a limited intervention with yellow and purple pigmented potato (carotenoid and anthocyanin, respectively). They found that men who consumed purple potato PP had lower levels of C-reactive protein (CRP, a potentially clinically useful marker for increased cardiovascular risk). The pigmented potato consuming group showed evidence of reduced DNA oxidative damage compared to the white potato consumers. In addition pigmented potato consumption reduced markers of inflammation in healthy subjects.

Anthocyanin pigmented potatoes also have evidence of efficacy in model studies targeting cancer, gut health as well as hepaprotective and antiviral activities. With respect to cancer there have been several cell model studies identifying that purple potato extracts have delivered protective effects in against leukemia (Xie et al., 2003, 2004) stomach (Hayashi et al, 2006), prostate (Reddivari et al, 2007), colon (Charepalli, 2015) and breast (Thompson et al, 2009) cancers. Clearly this class of compounds in potato merit full intervention studies to finally establish efficacy.

Finally, polyphenols in general have an innate ability to intercalate/adsorb to protein and if they are enzymes, inhibit activity. Chlorogenic acid has been reported to inhibit starch digestion both competitively and non-competitively (Karim et al, 2017).

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Potato tuber carotenoids.

Carotenoids are components of the photosynthetic machinery, intermediates in the biosynthesis of abscisic acid and other apocarotenoids and act as coloured pigments particularly in floral and fruit tissue. About 750 different naturally occurring carotenoids have been identified (Britton et al., 2004). Carotenoids can only be synthesized *de novo* by plants, certain bacteria, and fungi. In contrast, animals are unable to synthesize carotenoids, so they need to obtain them from the diet. Humans benefit in a number of ways from dietary carotenoids present in green leaf tissue and many fruits, seeds, roots and tubers. Carotenoids with a β-ring end group are required for the synthesis of vitamin A, and deficiency for this vitamin remains a major health problem in some parts of the world. Epidemiological studies suggest that carotenoids also have important roles in a range of diseases including age-related macular degradation and some cancers (Taylor and Ramsay, 2005).

Accumulation of carotenoids confers a yellow or orange colour to the flesh of potatoes with lutein, violaxanthin and zeaxanthin being the predominant carotenoids (Brown et al., 1993). Notably, potatoes only contain trace amounts of provitamin A carotenoids such as β-carotene. Lutein and zeaxanthin are components of the human retina (Landrum and Bone, 2001) which must be obtained from the diet in order to prevent from age-related macular degeneration (AMD). Green leafy vegetables are good dietary sources of lutein but poor sources of zeaxanthin, which is found in significant concentrations in fewer foods (Sajilata et al., 2008).

Carotenoid levels in potato tubers exhibit wide-variation with levels in yellow-fleshed cultivars ca. 20-fold higher than in white fleshed varieties. A summary of potato tuber carotenoid contents, compiling data from several studies has been published recently (Lachman et al., 2016). Basal carotenoid levels in potato are low in comparison to most fruits and vegetables (Fraser and Bramley 2004). For example, the maximum total potato tuber carotenoid content is ca. 20 mg/kg fresh weight whereas total carotenoid content in Brussel sprouts is ca. 1100 mg/kg fresh weight and in carrots is maximally ca. 14000 mg/kg fresh weight. However despite the relatively low level of carotenoids in potato tubers, as potatoes are a staple part of the diet, the content of carotenoids in potato tubers is of dietary significance.

The genetic factors that underpin potato tuber carotenoid variation have been identified in several studies (Brown et al., 2006; Wolters et al., 2010; Campbell et al., 2014). Allelic variation in two carotenoid biosynthetic pathway genes, β-carotene hydroxylase (Brown et al., 2006) and zeaxanthin epoxidase (Wolters et al., 2010) are particularly associated with elevated tuber carotenoid content. Furthermore, other unidentified genes may also contribute significantly to tuber carotenoid variation (Campbell et al, 2014). These studies indicate that the deployment of marker-based approaches could be useful in breeding programmes aimed at enhancing tuber carotenoid content.

Genetic engineering approaches in potato have aimed to modulate carotenoid biosynthesis (Romer et al., 2002; Ducreux et al., 2005; Diretto et al., 2007). Metabolic engineering has recently applied to potato in a similar strategy used for the creation of ‘‘golden rice’’ in order to increase the provitamin A content (Ducreux et al., 2005 Diretto et al., 2007), with a resulting increase of 20-fold and 3600-fold for total carotenoid and β-carotene content, respectively, in the biofortified “golden potato”. More recently potato tubers have been engineered to accumulate ketocarotenoids, high value compounds used extensively in aquaculture (Campbell et al., 2015; Mortimer et al., 2016)

Agronomic and environmental factors impact on tuber carotenoid content. For example elevated temperature during the growing season resulted in higher total tuber carotenoid contents (Hamouz et al. 2016). Kotíková et al. (2007) also confirmed that the year of cultivation had a significant effect on total carotenoids content.

The bioavailability of zeaxanthin and lutein was recently assessed for yellow fleshed potatoes using in vitro assessment technique (Burgos et al., 2013). The levels of bioavailability were considered to be good and the authors concluded that for a mean potato intake of 500 g per day, the best accessions tested could provide up to 14 % of the lutein intake suggested for health benefits and 50 % more than the suggested zeaxanthin intake.

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Glycoalkaloids

Potatoes and other Solanaceae species produce biologically active secondary metabolites called steroidal glycoalkaloids (GAs) which have antimicrobial, fungicidal, antiviral and insecticidal properties (Friedman, 2006; Nemaetal, 2008). These compounds probably evolved as a protection mechanism and accumulate in tubers and above ground plant parts. GAs are toxic to animals and humans causing symptoms such as nausea, fever and in extreme cases excessive ingestion can be fatal (Mensinga et al., 2005). Safe limits for consumption have been set at 200 mg kg^{-1} fresh weight (Smith et al., 1996; Valkonen et al., 1996). At moderate levels (ca. 14 mg kg^{-1}) GAs give rise to a bitter taste (Amer et al., 2014) whereas at levels above 22 mg kg^{-1} GAs give rise to a burning sensation (Friedman, 2006). Commercial potato cultivars primarily used for everyday consumption have very low contents of GAs however in wild species the safe limit can be exceeded by 100-fold (Sinden et al., 1984). Attempts to use wild species for breeding traits are increasingly common and so the GA levels need to be monitored carefully. In cultivated potato, SGAs are present in all tissues, but predominantly in the green parts. The two most common SGAs are α-solanine and α-chaconine accounting for ~95% of all glycoalkaloids (Ramsay et al. 2005; Smith et al. 1996).

The biochemical pathways that lead to GA are not yet fully understood although significant advances have been made recently (Itkin et al., 2013; Umemoto et al., 2016). In transgenic lines, manipulation of the GA biosynthetic pathway has been achieved, resulting in lowered GA content (Shepherd et al., 2015; Umemoto et al., 2016). The application of genomic approaches to develop markers for tuber GA content is also at an early phase but recent work has already identified potential markers for tuber GA content (Manrique-Carpintero et al., 2014; Kaminski et al., 2016)

Although the genotype is the most important factor for SGA content (Vreugdenhil et al. 2007), the SGA concentration can also be influenced and elevated by factors such as storage (Griffiths et al.1998), temperature (Dimenstein et al. 1997), light (Dimenstein et al. 1997; Percival 1999) or damage/bruising (Mondy et al. 1987; Petersson et al., 2013). The relationship between tuber greening and GA accumulation is not well understood as both processes are induced by light exposure. Research funded by the Scottish Government and Innovate UK is currently addressing these relationships (M Taylor pers comm).

Despite being generally regarded as an anti-nutrient (Friedman, 2006) more recent studies have identified some beneficial effects. Ji et al (2012) surveyed a range of potato clones for both phenolic and glycoalkaloid contents and found that extracts of the 20 potato clones (peel, tuber, and granule) showed mild activity in enhancing LDL cholesterol uptake in liver HepG2 cells, and also protected cortical neurons against oxygen glucose deprivation induced cell death, with extracts from granules of six of the potato clones showing significant neuroprotective effects. The bioactive components are not dependent on pigmentation of potato clones suggesting that the benefits were derived from the glycoalkaloids. In support of this Friedman delivered another review (Friedman, 2015) on the anticarcinogenic mechanisms of (potato) glycoalkaloids and this highlighted a host of studies supporting the protective effects against liver, colon, prostate and lung cancers. In light of this, the benefits of glycoalkaloids as a nutraceutical are worth re-evaluation.

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Potatoes and obesity

In recent decades potato consumption has increasingly been associated with obesity and its associated consequences. Consequently, chips have been banned from many school cafeterias (http://www.cbc.ca/news/canada/windsor/story/2011/08/31/wdr-ontario-school-junk-food-ban-to-take-effect.html) and portion sizes for chips have decreased in many fast food outlets (Baertlein, 2012). This negative association has undoubtedly contributed to the 41% decrease in per capita potato consumption over the past 40 years (http://ers.usda.gov/data-products/food-availability-(per-capita)-data-system.aspx), whilst consumption of other energy-dense starchy foods such as pasta and rice has increased. This trend has occurred despite the fact that potato is rich in nutrient content (Freedman 2011, 2012; Weichselbaum, 2016) giving rise to other functional and beneficial health components (reviewed in Ezekiel et al., 2013).

Not surprisingly obesity was (and continues) to be a target for potato trialling to determine the impact it has on this increasing important medical condition. It is worth noting that a recent review of clinical intervention and observational studies centred on potatoes and risk of obesity, type 2 diabetes, and cardiovascular disease in apparently healthy adults (Borch et al, 2016) came to the conclusion that the identified studies ***did not*** provide convincing evidence to suggest an association between intake of potatoes and risks of obesity, Type II diabetes (T2D), or CVD. French fries may be associated with increased risks of obesity and T2D although confounding factors were reported to be present that somewhat clouded the associations. In this systematic review, only observational studies were identified. These findings underline the need for long-term randomized controlled trials. In fact such trials are ongoing: Effects of Potatoes in a Weight Loss Program (BBFUSPB, NCT01186393, 2015).

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Glycaemic Index

Glycaemic index (GI) was developed as a means to classify foods based upon their blood glucose response after carbohydrate consumption and is defined by Jenkins et al (1987) as "the increase in area under the blood glucose response curve after consuming a food portion containing 50g available carbohydrate as a percentage of the response to a 50g dose of glucose". Thus low GI diets are recommended to individuals that suffer from diabetes as a tool to modulate the disease. Foods are ranked into 3 categories: high (GI value >70); medium (GI value 56-59); low (GI value <55).

The GI of potato is generally high but extends over a wide range (56-104) (Ek et al 2012). Study to study variability is a problem despite there being an International Organization for Standardization (ISO) approved method for determining the GI of foodstuffs. There is also inherent variation between genotypes. Ffor example the potato variety Marfona has a GI value of 56 and Maris Piper has a GI value of 85 (Henry et al 2005). Intrinsic factors such as starch characteristics e.g. amylose: amylopectin ratio; starch granule size; starch phosphate content, tissue structure e.g. cell walls, can affect the GI of potatoes (Singh et al 2010), along with food processing techniques, textural and rheological characteristics of the food and the presence of other nutrients (Henry et al 2006; Monro et al 2009 and Kinnear et al 2011). The perception of potato as a high GI food is likely to have been one of the factors contributing to the decline in consumption of potatoes (Riley 2010).

Although generally regarded as having a high GI, several studies have investigated variation in this trait between potato varieties. The Carisma cultivar (also named Almera in Europe) was classified as low GI and the Nicola cultivar (GI = 69) as medium GI and the other five cultivars were classified as high GI according to ISO guidelines. The GI values were strongly and positively correlated with the percentage of *in vitro* enzymatic hydrolysis of starch in the cooked potatoes. Amylose, dietary fibre and total starch content was not correlated with either *in vitro* starch digestibility or GI. The findings suggest that low-GI potato cultivars can be identified by screening using a high-throughput *in vitro* digestion procedure, while chemical composition, including amylose and fibre content, is not indicative (Ek et al., 2014). The cultivar Carisma is now marketed in Australia on the basis of its low GI (http://www.carismapotatoes.com.au/). Unpublished work from JHI also indicates wide variation in *in vitro* starch digestibility in a study of 300 potato varieties (M Taylor, unpublished).

By a significantly large margin, glycaemia is the main focus of the published intervention studies and clinical trials (https://clinicaltrials.gov/) in relation to potato. Of the true clinical trials there were 13 registered in the Clinical trials database but few had updated with data or associated publications. However, the study "Glycemic Index (GI) and Polyphenol Bioavailability of Potatoes" (ClinicalTrials.gov Identifier,NCT01053793) look at varietal variation in GI and, following consumption of white, yellow, red and purple potato, identified that neither total blood glucose load nor insulin was significantly different among the various potatoes studied despite a (not significant) variation in the mean GI values for the potato types varied (purple = 77.0 ± 9.0; red = 78.0 ± 14.0; yellow = 81.0 ± 16.0; and white = 93.0 ± 17.0). The mean polyphenol content (mg GAE/100 g DW) was 234 ± 28; 190 ± 15; 108 ± 39; 82 ± 1 for purple, red, yellow and white potatoes, respectively (Ramdath et al, 2014). Interestingly, there was a significant inverse correlation between polyphenol content and GI of the potatoes.

More commonly the studies into glycaemia either targeted variation in varieties (Henry et al, 2005; Fernandes et al, 2005) and identified that significant variation was evident, or products in comparison to other foodstuffs such as potato fries (The Food Intake, Satiety and Blood

Glucose After Ingestion of Potato Chips Produced From Three Potato Cultivars, NCT02014220; The Effects of Carbohydrate Source on Food Intake, Blood Glucose and Gut Hormone Response in Healthy Children, NCT02499107; The Effect of Potato Fries Processing on Food Intake, Satiety and Blood Glucose, NCT02014207).

Studies in adults (Barbour et al, 2014) looking at GI, weight loss and snacking generated equivocal results with regard to potato intake and GI. Randolph et al (2014) looked at energy reduction, GI and potato intake in overweight people and undertook a 12 week intervention of low and high GI, but total energy reduced, diets compared to a group with no energy restriction, GI provision, or nutritional counselling. They found that in a free-living population of men and women, weight loss is associated with energy intake reduction. Potato intake did **not** cause weight gain.

More encouraging are the interventions where potato consumption is considered properly as part of a meal rather than as a single foodstuff. Thazhath et al (2014) found that, in an intervention with potato, potato mixed with guar gum and the former but given as small potions (but equalling the same total potato), the potato/guar gum meal (equivalent to potatoes and vegetables) was associated with slower gastric emptying, lower postprandial blood glucose and insulin, and a delayed, but more sustained, suppression of flow mediated dilation of the arteries (a blood pressure measure and a consequence of reduced blood glucose levels). The intake of the same amount of potato alone but in smaller, frequent doses also reduced blood glucose levels and flow mediated dilation of the arteries. Clearly what is eaten along with potato and the portion size are important with regard to glycaemia and the associated pathologies

It is interesting to note that several papers have identified that perhaps potato has been incorrectly attributed with such a high GI and this plays into the aforementioned need to consider it as part of a meal but also the technological approaches for its measurement. Dodd et al (2011) performed an intervention where they tested foodstuffs individually and as part of a normal meal and found that the use of the standard GI formula targeting individual food components routinely overestimated the GI of the meals by between 22% and 50%.

The co-consumption of foods (basically a meal) with potato was shown to have definite impact on GI etc. An intervention study by Hätönen et al (2011) found that the GI of pure mashed potato was 108, whereas combined with chicken breast, rapeseed oil and salad, it was only 54. The latter GI also differed considerably from its predicted value of 103 based on the individual GI of the components of the meal. In conclusion, the protein, fat and salad contents of a meal exert considerable influence on the glycaemic responses to mashed potatoes. Furthermore, the estimation of the GI of a mixed meal by calculation was noted to be imprecise.

Schäfer et al (2003) undertook an intervention study comparing glycaemic responses to 3 different meals based on dried peas, potatoes, or both in patients with type 2 diabetes undergoing dietary treatment. They found that increases in postprandial plasma glucose and insulin concentrations were delayed and significantly smaller after the pea rather than after the potato meal. However, the co-consumption of peas and potato reduced postprandial plasma glucose to a level between both individual component meals. In addition, Cunnigham and Read (1989) found that incorporation of fat to the meal (here margarine in the potato mash) delayed gastric emptying of the mashed potato. This was supported by Hätönen et al (2011) who found that use of rapeseed oil, rather than margarine in the mash gave an analogous postprandial reduction in blood sugar responses. This again highlights the confounding nature of using GI as a measure of sugar release in isolation for potato and when part of a meal

Further confounding glycaemic responses arise post-food preparation. Leeman et al (2005) performed an intervention study with four meals; freshly boiled potatoes, boiled and cold stored potatoes (8 ºC, 24 h), boiled and cold stored potatoes (8ºC, 24 h) with addition of vinaigrette sauce (8 g olive oil and 28 g white vinegar (6% acetic acid)) and white wheat bread as reference. The meals were all carbohydrate equivalent. The GI of cold potatoes and those with added with added vinegar (GI/II=96/128) were significantly reduced by 43 and 31%, respectively, compared with GI of freshly boiled potatoes (168/185). The conclusions from the study were that cold storage of boiled potatoes generated appreciable amounts of resistant starch and that the addition of vinegar reduced acute glycaemia in healthy subjects after a potato meal. This supports the findings highlighted in the section **Starch and Dietary Fibre**.

Interestingly there are two studies registered on GM potatoes where the starch had been modified (Metabolic Changes Induced by Genetically Modified Potatoes, CT identifier - NCT00953966; Long Time Metabolic Changes Induced by Genetically Modified Potatoes, CT identifier - NCT00953602) but these have had no data uploaded since registration (2009) by Prof Spranger, Charite University, Berlin, Germany. Prof Spranger was been contacted for an update and identified that the trail was closed due to commercial concerns by the sponsor (not GM related) but that some of the modified starches showed promise for health improvements and benefits.

An interesting theme that is currently emerging is that potato tuber components are capable of inhibiting starch digesting enzymes and thus lead to a lower GI. For example one study indicates that tuber polyphenol levels are inversely related to GI (Ramdath et al., 2014). Recently chlorogenic acid has been shown to have inhibitory effects on potato starch digestion and thus could also be inversely related to GI (Karim et al., 2017). Further research in this area would be of value.

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Satiety

Satiety is a reduced feeling of appetite or desire for food that arises after the consumption of food or beverage (Anderson et al., 2013). Satiety is measured by subjective assessment of consumer panels or by measurements of food intake. The subjective measures of satiety are highly variable, and large sample sizes are required to detect treatment effects. A more quantitative measure of the effect of foods on satiety is to measure food intake from an *ad lib*itum meal at a later time after consumption of the test food (Anderson et al., 2004). Satiety index (SI) is expressed as the effect of the test food relative to white bread or glucose when 50 g of carbohydrates is consumed (Holt et al., 1996). Several studies report that potato has a very high SI compared with a wide range of foods including those with anequivalent carbohydrate content (Holt et al., 1995; Akilen et al., 2016).

Two recent study indicate that for potato, cooking method is important for satiety effects (Akilen et al., 2016; Diaz-Toledo et alo., 2016). Both studies reported higher levels of satiety following a meal where the principal carbohydrate source was French fries, compared with an energy-matched meal containing carbohydrate in the form of pasta. All other potato preparations (boiled, mashed etc) had similar effects on satiety as pasta. It was concluded that participants perceived a meal with French fries as providing greater satiety than a pasta control meal.

A possible explanation for the higher than expected SI of some potato products is the high level of protease inhibitors present in potato tubers. In particular, potatoes contain proteins that inhibit trypsin's proteolytic activity in the small intestine, which in turn extends the activity of the peptide satiety hormone cholecystokinin (CCK) (Hill et al., 1990; Nakajima et al., 2011; Komarnytsky et al., 2011). This inhibitor is often referred to as protease inhibitor II (PI2) (Hill et al., 1990; 2011; Komarnytsky et al., 2011), although the term trypsin inhibitor is also used (Nakajima et al., 2011). CCK levels are negatively controlled by trypsin and chymotrypsin; thus, the inhibition of trypsin by PI2 promotes elevated levels of circulating CCK. Several studies indicate that PI2 extracted from potato tubers can result in satiety effects. For example, the consumption of 1.5 g of potato PI2 in a high-protein soup vehicle results in increased CCK levels and decreased energy intake in human subjects (Hill et al., 1990). Komarnytsky et al., (2011) demonstrated that potato PI2 was heat stable and crude PI2 extracts from tubers was effective in reducing food intake and body weight gain in healthy rats when administered orally by increasing circulating CCK levels through a trypsin-dependent mechanism. A product called Slendesta, based on PI2 extracted from potato, has been marketed since 2006 by the food company Kemin as an aid to weight management. Very recently Kemin scientists published data that demonstrates that doses of potato PI2 as low as 15 mg show satiety benefits for healthy women via a CCK-based mechanism (Zhu et al., 2017). However, it still remains to be fully resolved whether the levels of PI2 in potato food preparations are sufficient to impact on CCK levels. It would also be of interest to determine the variation in PI2 activity in different potato types and to investigate whether this activity survives cooking and digestion.

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Inflamation/CVD

Inflammation/CVD has, allied to glycaemia, been a target for clinical and intervention trials with two currently ongoing and yet to report results: Postprandial Inflammatory Response in Healthy Men: Effect of Dietary Fat Source, Obesity and Age, NCT01066091; Effects of Purple Vegetables on Cardiovascular Disease (CVD) Risk Factors, NCT01564498. Of those completed, Vinson et al (2012), focussed on purple polyphenolic rich potato consumption in comparison to a comparable amount of refined starch (as cooked biscuits). The potato group had comparatively elevated plasma and urine antioxidant capacity, whereas the refined starch caused a decrease in both, i.e. acted as a pro-oxidant. Extension of this to a crossover study with 18 hypertensive subjects found that purple potato intake was associated with blood pressure reductions and no weight gain.

A similar study by Kaspar et al (2011), but this time targeting free-living healthy men, reported that intake of pigmented potatoes was accompanied by reduced inflammation and DNA damage, highlighting an improved nutritional choice in potato consumption.

A more recent a study by Würtz et al (2016) looked at the impact of replacing red meat in the diet with vegetables, including potatoes, on the risk of myocardial infarction (MI): vegetable consumption having previously/repeatedly been found to be protective. Within the study they followed up 29,142 women and 26,029 men, part of the Danish Diet, Cancer and Health study, aged 50–64 years with no known history of MI at baseline. Via standard dietary assessments and hazard modelling it was reported that during a median follow-up of 13·6 years the hazard risk for MI when replacing red meat with vegetables was reduced but replacing fatty fish with vegetables was associated with a higher risk of MI. More specifically the findings for substitution with potatoes were similar to findings for vegetables. Among men, a similar pattern was observed, but the associations were weak and mostly statistically non-significant. The study concluded with the statement that ***replacing red meat with vegetables or potatoes is associated with a lower risk of MI***, whereas replacing fatty fish with vegetables or potatoes is associated with a higher risk of MI.

Conversely, another recent broad study (Atkins et al, 2016), analysed the dietary patterns of 3226 older British men, aged 60–79 years and free from CVD at baseline, from the British Regional Heart Study. This identified three interpretable dietary patterns: 'high fat/low fibre' (high in red meat, meat products, white bread, **fried potato**, eggs), 'prudent' (high in poultry, fish, fruits, vegetables, legumes, pasta, rice, wholemeal bread, eggs, olive oil) and 'high sugar' (high in biscuits, puddings, chocolates, sweets, sweet spreads, breakfast cereals). During 11 years of follow-up the 'high-fat/low-fibre' dietary pattern was associated with an increased risk of all-cause mortality but the specific impact of potato was not teased out nor identified. It was not clear if potato (not fried) formed part of the 'prudent' diet which did ***not*** show a significant trend with cardiovascular outcomes or mortality.

Unlike the above studies there have been more focussed potato intakes studies looking at CVD and hypertension. Larsson and Wolk (2016) found that, as part of a study accruing data from 69,313 men and women, free of CVD and diabetes, as part of the Cohort of Swedish Men and the Swedish Mammography Cohort, potato consumption was ***not*** associated with the risk of CVD in this population

An analogous study in the USA by Borgi et al (2016) aimed to determine whether higher intake of baked or boiled potatoes, French fries, or potato chips is associated with incidence of hypertension. Using the data from the 62,175 women in Nurses' Health Study, 88,475 women in Nurses' Health Study II, and 36,803 men in Health Professionals Follow-up Study who were non-hypertensive at baseline, Borgi et al (2016) that reported that a higher intake of baked, boiled, or mashed potatoes and French fries was independently and prospectively associated with an increased risk of developing hypertension in three large cohorts of adult men and women. This result is opposite to that found above by Larsson and Wolk (2016).

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Cognitive Function

Some efforts have been made to look at the impact of diet on cognitive ability but with regard to potato this is often as part of a mixed diet or classed within the broad vegetable grouping. At the clinical level two studies were identified (Consumption of Potatoes, Avocados and Chickpeas and Cognitive Function in Older Adults, NCT01620567; Dietary Carbohydrate Consumption on Memory Performance and Mood in Children, NCT02820805). Neither of these has yet yielded data or publications. However, a study by Kaplan et al (2000) on aged (60-82 y) individuals given 50g carbohydrate as glucose, potatoes, or barley or a placebo on 4 separate mornings reported that although the subsequent difference in plasma glucose after food consumption [glucose > potatoes > barley > placebo] did not predict performance the intake of glucose (simple or complex), glucose regulation was associated with cognitive performance in elderly subjects with normal glucose tolerance. Furthermore, dietary carbohydrates (**potatoes** and barley) enhanced cognition in subjects with poor memories or beta cell function independently of plasma glucose.

On a larger scale Nurk et al (2010), reported that as part of the Hordaland Health Study (2031 elderly subjects, aged 70-74 years; 55% women) extensive cognitive testing was undertaken and food frequency questionnaires completed. They found that the majority of participants reported consumption of potatoes (97 %) with a daily intake of about 130 g and that the mean scores of all six cognitive tests (except TMT-A: a trail making tests and an indicator of organic brain damage) were better among potato eaters as compared with non-eaters.

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Potato nutraceuticals

The market for nutraceuticals, encompassing functional foods, beverages and dietary supplements market was valued at around $250 billion in 2016 and is expected to reach around $385 billion by 2021, at a CAGR of 7.5% from 2016 to 2021 (Anon. 2016). In general this growth is seen to be a reactive response by consumers to ward off ill health rather than treating existing symptoms. Driving this growth are the following

- Growing affluent middle -class populations with their increasing disposable incomes in developing countries.
- Women and senior citizens preferring a good digestive health.
- Physiological benefits of functional foods, which reduce the risk of chronic diseases related to cardiovascular problems and diabetes.

These factors along with the fact that the product can be made with limited requirements for expensive R&D via exploitation of existing refereed literature have meant this option is seen as an attractive business proposition. Hand in hand with this development is the exponential growth for clean label products natural ingredients with no artificial ingredients and chemicals.

Potato can deliver in to many of these expectations, it being a rich source of many biofunctional components: (poly)phenols, polysaccharides protein and glycolaklakoids.

The health benefits of potato compounds has been the subject of several generalist reviews (Burlingame et al., 2009; Tsao, 2009; Ezekiel et al., 2013; Lui, 2013; Zaheer and Akhtar, 2016). In general these reviews cover similar ground outlining potato's place in the human food chain and its generalist benefits such as impact on cardiovascular disease, glycaemic load, type II diabetes, cancer, colon health etc. The reviews do however have some interesting specific facts such as;

- Potatoes provide 25% of vegetable phenolics in the American diet, the largest contributors among the 27 vegetables commonly consumed in the United States, including flavonoids (quercetin and kaempferol) and phenolic acids (chlorogenic acid and caffeic acid) (Lui, 2013)
- Potato as an energy source is significantly different in the developed (540 kJ (130 kcal) per person per day) and developing (170 kJ (42 kcal) per person per day) worlds (Burlingame et al., 2009)
- The reviews have consensus in the range estimations of bioactive/nutraceutical components with many varieties of potatoes contributing nutritionally important amounts of dietary fibre (up to 3.3%), ascorbic acid (up to 42 mg/100 g), potassium (up to 693.8 mg/100 g), total carotenoids (up to 2700 μg/100 g), and antioxidant phenols such as chlorogenic acid (up to 1570 mcg/100 g) and its polymers, and anti-nutrients such as α-solanine (0.001–47.2 mg/100 g); and lesser amounts of protein (0.85–4.2%), amino acids, other minerals and vitamins, and other beneficial and harmful bioactive components.

Interestingly there are fewer studies assessing the impact of processing on the bioactive complement but the recent review of Furrer et al (2016) has specifically addressed this and has highlighted some interesting points. For example, potatoes may only contain 1-2% of fibre but the method of processing/preparation and consumption of cooled potato products can have a significant impact on final fibre content and potentially impact health endpoints including as glycaemic response (Slavin, 2013). This property means that new processing strategies can be developed if dietary fibre (and therefore modulation of glycaemic response) is seen to be a selling point for potato products.

Here we will delve further into the specifics of some of these components that display the potential to be exploited by potato breeders, producers, processors and retailers, all to the benefit of the consumer.

Polyphenolics

Polyphenols are recognized as the most abundant antioxidants, or better non nutrient health beneficial compounds, in our diet (Manach, Scalbert, Morand, Remesy, & Jimenez, 2004). Potatoes are recognised as a good source of this class of compounds and indeed phenolic compounds represent a large group of minor chemical constituents in potatoes. These have been estimated to be present over the range from 530 to 1770 μg/g (Al-Saikhan, Howard, & Miller, 1995) and are considered the third most important source of phenols after apples and oranges (Chun et al., 2005). Although Talburt et al. (1987) (1987) reported presence of lignin, coumarins, anthocyanins and flavones, tannins, monohydric phenols and polyhydric phenols in potatoes, the largest proportion comprised of chlorogenic acid, being more than 90% of phenolics (Malenberg & Theander, 1985) with the body of the tuber and skin containing 30 to 900 mg/kg and 1000–4000 mg/kg, respectively of chlorogenic acid.

Dietary polyphenolics have attracted significant attention as routes to human health (Scalbert and Williamson, 2000) and this has driven significant activity with regards to potato polyphenols. The coloured, anthocyanin rich potatoes have been the focus of considerable research, building on the benefits to be had from anthocyanins in fruit. Reyes et al (2005) studies a range of purple and red-fleshed potatoes and assayed these for total anthocyanin and phenolic contents and antioxidant capacity. This highlighted a defined distribution of anthocyanin and phenolics with higher concentrations found at the stem-end than the bud-end and the peel contributed to 20% of their combined contents. These results provide useful and important information for potato breeders and researchers in order to increase the antioxidant capacity and functional value of purple- and red-fleshed potatoes for the food and nutraceutical industries. This is supported by the many reviews and research (e.g. Williamson, 2017) highlighting the positive impact on human health via interaction with the colonic microbiome.

Vinson et al (2012) focussed on anthocyanin rich versus refined potato starch (as a biscuit) via an intervention trial. They found that anthocyanin rich potato consumption caused an increase in plasma and urine antioxidant capacity, and a significant reduction in diastolic blood pressure (4.3%). Impressively, this blood pressure drop occurred despite the fact that 14 of 18 subjects were taking antihypertensive drugs and highlighted that anthocyanin rich potatoes show potential as effective hypotensive agents to lower the risk of heart disease and stroke in hypertensive subjects without weight gain.

Anthocyanin rich potatoes were also the focus of arterial inflammation (hypertension-related) studies (Kaspar et al., 2011) and research into cancer prevention abilities on cancer prevention (Stutte, 2006; Zhao et al., 2009; Madiwale al., 2012). The intervention study of

Kaspar et al (2011) identified that pigmented potato consumption reduced inflammation (measured as inflammation marker reduction) and DNA damage in healthy adult males whilst the cancer studies all identified suppression of cancer proliferation and elevated apoptosis (cancer cell death). All these studies highlight the potential of potato (poly)phenolics as (nutraceutical) oxidative damage disease prevention routes

Protein

Potato protein is recognised as a nutraceutical component and sold as such. More recently there have been studies into its inflammation and hypertension reductive abilities. Gong (2010) in cell and animal models that potato protein hydrolysates suppressed tumour necrosis factor (TNF)-α release and Reactive Oxygen Species secretion in the cells. In addition, markers of inflammation were also reduced indicating that the potato protein hydrolysates possess physiological anti-inflammatory properties. Furthermore some of the hydrolysates were found to be potentially stable to gastric proteases identifying them as putative nutraceuticals.

Pihlanto et al (2008) also focussed on potato protein hydrolysates and reported varying inhibition of the angiotensin-converting enzyme (ACE; a central component of the blood pressure control system) and the radical-scavenging activity depending on the hydrolysate studied. The antioxidant activities of potato protein hydrolysates was also reported on by Kudo et al (2009) who reported that they were able to protect the gastric mucosal layer against oxidative damage in rats.

More specific effects were identified by Hu et al (2015) for potato protein hydrolysates in a rat model system wherein consumption as part of a high fat diet was accompanied by reduced serum triacylglycerol (TG), total cholesterol (TC), and low density lipoprotein (LDL) levels to the normal levels expressed in the control group.

A completely different route to health via potato protein has been developed recently. Work by Yoav Livney at Technion (the Israel Institute of Technology; http://biopolymeric-nano-carriers-4-health.net.technion.ac.il/) has focussed on the generation of nanoparticles from potato protein and their use as a vehicles for the transport and delivery of bioactive agents (Liveney, 2014; David and Liveney, 2016). This approach has been used to bind Vit D and as, a non-allergenic complex, provided significant protection during pasteurization and shelf life. This opens up significant possibilities for potato protein nanotechnology since it can be considered natural and applicable in vegan and Kosher-Parve foods and in addition can be exploited as a promising nanovehicle of hydrophobic nutraceuticals for food enrichment. Significantly the nano-systems are soluble in water and can therefore be used without any appearance issues in clear beverages.

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Potato Flavour and Texture

One of the most important factors in consumer purchase is product quality. “Quality” *per se* is a nebulous term that encompasses a wide-range of traits but the most important aspects are the organoleptic drivers: appearance, texture and flavour (McGregor, 2007). Within a price range appearance drives the initial purchase whilst cooking performance, including the flavour components taste, texture and volatile aroma compounds, underpin continued purchase. Potatoes with improved flavour would encourage consumption and potentially enable the nutritional benefits of potato to be realised.

Despite the increasing importance of potato flavour to consumers, there is still much to be learnt about the complex flavour trait and the key components that contribute to it. A particular problem is how to breed for good tuber flavour. With the emphasis on breeders to produce cultivars that yield well and are disease resistant, there has been less attention paid to potato flavour. In fact breeders lack the tools to assess flavour as this trait is very difficult to phenotype (Klee, 2010). Flavour assessments depend on quantitative descriptive analysis carried out by trained taste panels. Taste panels are expensive and have a relatively low throughput and so flavour is generally only assessed in the later stages of a breeding programme after selection for more easily quantifiable traits. In fact, most of the potential flavour and texture improvements are likely to be discarded and to a large extent the market place determines whether a new cultivar is acceptable to consumers (Wang and Kays, 2003). Means of analytically determining flavour that can be efficiently applied to germplasm are obvious requirements for improvement of the potato crop. Additionally breeders require clear target phenotypes for flavour as preferences are likely to vary depending on consumer groups, market classes and cooking methods. 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/).

Compared with other fruit and vegetables such as tomatoes, there are still significant gaps in our knowledge linking metabolites to flavour metabolites. The analytical tools are now available to address this issue, however there are still relatively few studies linking metabolites and quantitative descriptive analysis. The use of germplasm that shows wide variation in flavor characteristics such as Phureja compared with Tuberosum has proved useful (Morris et al., 2007, 2010), but only begins to investigate the full diversity available within potato germplasm collections. Producers, processors and consumers alike wish to have potato tubers that show consistent and high quality flavour properties, and to achieve this goal we need to link the metabolites with quality traits. The interaction between genotype, environment and agronomy in developing potato flavour is an area that requires urgent attention. This will result in a metabolite “blueprint” for sensory quality that can be used to predict product consistency and acceptability of different genotypes.

Potato tuber texture is another organoleptic quality determinant of cooked potato and a major trait that influences consumer preference (McGregor, 2007), influencing both mouthfeel and cooking time. Tuber texture is also a key issue in potato processing and is known to be affected both by pre-processing procedures such as blanching, peeling and by storage (Shomer and Kaaber, 2006; Thybo *et al*., 2006). Factors that may impact on cooked potato texture include starch content and distribution within the tuber (Storey and Davies, 1992; Matsuura-Endo *et al*., 2002a), starch swelling pressure (Jarvis *et al*., 1992; Shomer,1995a; 1995b), cell size (Hoff, 1972), cell-wall structure and composition (Hoff, 1973), and the breakdown of the cell wall middle lamella (Van Marle *et al*., 1994; Matsuura-Endo *et al*., 2002b) during cooking. It is not yet clear which are the over-riding factors and the relative importance of the different factors involved.

Several studies have described potato germplasm that produces tubers with markedly different textural properties (Van Marle *et al*., 1994; De Maine *et al*., 2000; Ducreux *et al* 2008; Ross *et al*; 2010). In particular, members of *Solanum tuberosum* group Phureja (Phureja) have been identified which exhibit a boiled tuber texture described as extremely floury or crumbly (De Maine *et al*., 1993, 1998). The cooking (by steaming) time of Phureja tubers is generally in the order of half that taken for typical *Solanum tubersum* group Tuberosum (Tuberosum) tubers at the same developmental stage (Ducreux *et al*, 2008, Ross *et al*., 2010).

Several mechanical methods have been developed for the quantitative assessment of textural properties. A wedge fracture test was first developed by Vincent et al. (1991) to provide a method that more closely reflects the sensory experience of the consumer and is a standard test morphology (technically Mode I fracture, in-plane crack opening). Good correlations between the wedge fracture and panel sensory tests for a range of different textured cheeses were demonstrated. More recently the method has been developed to assess cooked potato tuber texture (Ross et al., 2010). Using this method, it was demonstrated that tubers from *Solanum tuberosum* group Phureja have a greatly reduced cooking (by steaming or boiling) time than typically observed for those from *Solanum tuberosum* group Tuberosum and hence represent an extreme variant in textural properties.

Microarray studies identified differences in tuber gene expression between Phureja and Tuberosum potato types (Ducreux et al., 2008). Significant differences in expression were noted for genes involved in cell wall modification and these could potentially contribute to textural differences (Ducreux et al., 2008). In particular, the differentially expressed genes included a pectin methyl esterase gene (PME; EC 3.1.1.11) involved in the modification of pectin structure, which makes up to 35% of primary potato cell walls. Enzyme activity measurements clearly demonstrated significantly lower activity in Phureja genotypes and transgenic experiments have demonstrated that manipulation of the expression of the major tuber PME gene resulted in corresponding impacts on tuber texture and cooking time (Ross et al., 2011). Further genetic studies identified a Quantitative Trait Locus for tuber texture on Chromosome 7 mapping to a region close to the location of the PME gene (D. Lloyd, PhD thesis). In other genetic populations, other genes have been identified that impact on cooking type. For example Kloosterman et al. 2010, identified a gene encoding a tyrosine-lysine rich protein as a factor in tuber cooking time. In view of these strong candidate genes, there is clear scope to develop and test gene markers that could enable selection for tuber cooking characteristics.

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Potato Waste Valorisation

Potato waste and processing by products are viewed as ideal sources for exploitation for the development of new product may focusses at the human health market. Besides industrial (Arapoglou et al., 2010) and potable alcohol production (Anon, 2105) the high level of starch in potato waste has attracted interest from the industrial biotechnology sector with a view to using it as a feedstock for glucose generation that would feed into enzyme and pharma production, biodegradable plastic production (Rusendi and Sheppard, 1995) and lactic acid production (Smerilli et al, 2015) to name but a few applications.

Potato starch has been developed as a feedstock for nanotechnology vehicles for bioactive components such a polyphenols by Qiu et al (2016). They developed worm-like amylopectin nanoparticles (APNPs) and spherical amylose nanoparticles (AMNPs) from potato starch and successfully adsorbed the bioactive polyphenols procyanidins, epicatechins, and catechins at levels significantly beyond their normal bioavailability levels. The results suggested that APNPs and AMNPs can be applied as an effective nanocarrier by delivering active compounds for nutraceutical and pharmaceutical industries.

Potato polyphenols were also a target of valorisation with various optimisation methods pursued. Amado et al (2014) used a solvent-water mix to optimise antioxidants (predominantly chlorgenic and ferulic acid) extraction from potato peel and test the extract efficacy in a soybean oxidation system. More specialist approaches were used by Singh and Saldaña (2012), Wu et al (2012) and Paleologou et al (2016) who applied subcritical water, microwave and ultrasound technologies, respectively, to potato peel. All were effective at stripping out the polyphenolics but there was no selectivity with regard to chemical classes or individual polyphenolics.

An extension of these technologies was undertaken by Hosain et al (2015) who applied pulsed electric fields and lights to potato peel with the aim of extracting glycoalkaloids. They highlighted that the pulsed electric field approach facilitated glycoalkaloid extraction over the light approach. Pulsed light (PL) treatment increased the initial level of steroidal alkaloids in potato peels to the degree that potato peel was demonstrated to be an excellent untapped sources of these compounds and that pulsed electric field assisted extraction was a quick, cheap, efficient and environment friendly technique which would help maximising the extraction of potato steroidal alkaloids.

The potato polysaccharides (starch and cell wall polymers) are also targets for valorisation as biodegradable (Arvanitoyannis et al., 1998; Kim and Lee, 2002; Talja et al., 2007; Hu et al, 2009) and edible (Osés et al, 2009) films, and biocomposites (Dufresne et al., 2000; Chen et al., 2102)

Protein is also viewed as a valuable feedstock in potato waste. Some protein isolates and peptides have been shown to display interesting properties as emulsifiers in oil/water systems and they generate some unique viscoelastic properties of the interfacial films formed between oil and water (Romero et al. 2011; Cheng et al, 2014).

A very different enduse for potato proteins was highlighted by the research of Narasimhamoorthy et al (2013) and Waglay et al (2014) both of which were very recently put into context by Matharu et al 2016. They identified that the potato (and waste) have appreciable levels of protease inhibitors and these could find a use in the food ingredients market and deliver into the obesity prevention market space.

Finally, a recent paper by Campbell et al (2016) highlighted that potato leaves could be considered as chemical feedstocks also and a rich source of solanesol, a high value 45-carbon, unsaturated, all-trans-nonaprenol isoprenoid. In the pharmaceutical industry solanesol is used as an intermediate in the synthesis (both chemically and biotechnologically) of metabolically active quinones such as coenzyme Q10 and vitamin K analogs. There is also a growing awareness that solanesol may have useful properties in its own right with reports of anti-bacterial, anti-inflammation, and anti-ulcer activities. There is considerable variation in the levels of solanesol found in potato foliage, ranging from 0.04 - 1.5% of dry weight and therefore this represents a significantly undervalued potato waste to be exploited.

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Breeding technologies to enhance the human health and nutrition of potato.

F1 hybrid breeding

It is clear that there is wide variation in varietal panels, bi-parental crosses and in genebank accessions of wild relatives for potato metabolites that impact on human health and nutrition. However deployment of beneficial alleles has been made difficult by bottlenecks in potato breeding. Currently, the traditional potato breeding cycle is rigid and inefficient, with a low level of innovation. Potato is tetraploid (it has 4 sets of each chromosome), exhibits tetrasomic inheritance and is highly heterozygous, which makes the inheritance of traits, especially complex ones, very difficult to manipulate in breeding crosses. Hidden in the genome are numerous unfavourable alleles that 'pop-up' at any cross, leading poor agronomic properties. Due to these limitations it has not been possible until recently to introgress (move a gene from a 'donor' genotype to a recipient one by repeated backcrossing) and combine several different traits into an existing potato variety in a way that is facile in inbred diploid crops. Proof-of-concept for the development of homogeneous F_1 hybrid potatoes by crossing different self-fertile inbred diploid lines unlocks this constraint and has the potential to allow rapid introgression of advantageous genetic factors once they have been identified (Lindhout et al., 2011). This approach has great promise for capturing genetic gain in potato and is the basis for F1 hybrid breeding, currently being developed by Solynta (http://www.solynta.com/). Although promising, developing commercially acceptable varieties based on this approach remains to be demonstrated. The approach does have the potential to "stack" beneficial alleles in a good genetic background, so that several benefits can be incorporated in one variety. Genetic mapping using in-bred lines also has great potential as a tool for gene discovery (Endelman and Jansky, 2016).

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Genomic Selection in Potato

Another approach that may lead to accelerated potato breeding is the deployment of genomic selection. Genomic selection was first proposed by (Hayes, B.J. and Goddard, M.E., 2001) and uses genome-wide marker effects estimated in a phenotyped and genotyped reference population to predict the phenotypes of otherwise uncharacterized selection candidates. Genomic selection differs from marker assisted selection (MAS) in that it jointly analyzes all marker data and can therefore capture all the genetic variance, whereas MAS will only capture the variance from a limited number of genetic loci. With the completion of the potato genome sequence and the identification of a large number of genome-wide SNPs (Uitdewilligen et al., 2013), application of genomic selection in potato is expected in the near future, although the heterozygous nature of potato (Slater et al., 2014)_will require some considered strategies (reviewed in Slater et al., 2016).

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Gene editing in potato

A range of breeding technologies have been developed recently based on site-directed mutagenesis (SDM). The use of site-directed mutagenesis allows mutations to be introduced at precise points in the genome (reviewed in Podevin et al., 2013), in contrast to chemical and physical mutagenesis. In order to achieve site-directed mutagenesis, site-directed nucleases have been developed. Zinc finger nuclease technology (ZFN), TAL effector nucleases (TALEN) and clustered regularly interspaced short palindromic repeat (CRISPR) and CRISPR-associated protein 9 (Cas9) are the main SDM techniques currently in use (Schiml and Puchta 2016). CRISPR-Cas9 has emerged as the most user-friendly and cost-efficient of these techniques (Quétier, 2016). Initially developed in test plants, more recently studies using TALEN and CRISPR-Cas9 in potato have been published.

CRISPR-Cas9 has, in two different studies, been shown to induce mutations in potato by *Agrobacterium*-mediated stable transformation. In the first study, a gene encoding an Aux/IAA protein, *StIAA2*, was targeted in a double haploid potato cultivar (Wang et al. 2015) while in the second study with this method, the ALS gene was targeted in both a diploid and tetraploid potato (Butler et al. 2015). With confirmed stable integration, the studies yielded mutation rates of 83 and 60 % of regenerated lines, respectively. Furthermore, lines with mutations in multiple alleles were detected in both cases. Most recently, TALEN and CRISPR-Cas9 were stably introduced targeting ALS and using a geminivirus-mediated guide, to facilitate designed mutations (Butler et al. 2016). A potential problem with CRISPR-Cas9 using stable transformation of the Cas9 gene is the requirement for laborious subsequent crossing to remove the Cas9 transgene. The use of a self-compatible homozygous diploid may make this approach more tractable. However the use of a transient expression system, in which all four alleles a single locus can be simultaneously edited without integration of vector-derived DNA also shows significant promise (Andersson et al., 2017). However the regulatory landscape surrounding the use of gene editing remains complex and will delay the commercial deployment of such approaches (Podevin et al., 2013; Flavell, 2017).

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Alternative Potato Products

Globally the main uses of potato are in crisps (chips) and French fries or as powdered product for instant mash etc. More recently a report by Mintel[1] which identified that "sales of potato crisps are estimated to have declined to £1.34 billion in 2015, sales of potato-based and other snacks are estimated to have reached £1.39 billion." This shows a shift in potato utilisation and probably a broadening (lowering?) of the specification of potato used. Also at the UK level potato snack innovation has reduced with one in five (20%) snacks launched in 2010 based on potato whilst this fell to just one in eight (12%) snack launches in 2015. One factor underpinning this may be popcorn as 7% of snack products launched in the UK were popcorn products in 2015, up from just 3% in 2010.

This is in part driven by the healthier image popcorn has but there are signs potato can come back with over two-thirds (68%) of those who eat crisps and crisp-style snacks saying they would be interested in crisps made using healthier cooking oils, such as olive oil or coconut oil. This is corroborated by IBIS world[2] who state that the Potato Crisps and Snacks Production industry revenue is expected to grow at a compound annual rate of 2% over the five years through 2016-17, reaching just over £2 billion but that the growth of health consciousness amongst UK consumers has impacted negatively on this growth.

One route to turn around the decline is the use of anthocyanin rich potatoes or combining standard potatoes in products with other potatoes (sweet) or vegetables. The impact of potato polyphenols and anthocyanins has been covered earlier and this has been translated through to a multitude of different products on the market (see below[3]). Helping this is a shift, in the US at least, to a two-stage frying process, in which after about 80 percent of the frying time in an atmospheric fryer, products are transferred to a vacuum fryer to finish the frying process at lower temperatures and in milder conditions. The low temperatures at the end of the process are reported to preserve the natural colours (and flavours) of the product, while at the same time enabling the significant reduction of acrylamide levels.

Potato noodles are another area that has an established market in Asia but is poorly exploited elsewhere. They have been the subject of studies with noodles from other crops and overall the findings were that "potato starch is preferable over cereal starches for manufacturing starch noodles because of its neutral taste, much higher transparency and the elasticity of the noodles produced" (Singh et al 2002). In a large study of Asian noodles Fu (2008) suggests that potato starch is more suitable for instant noodles. Furthermore Sandhu et al (2010) reported that potato starch gels displayed higher hardness, cohesiveness and chewiness compared with rice and that potato noodles were scored higher than rice noodles by sensory panellists especially with respect to transparency and slipperiness.

Another potential potato product, albeit minor, is potato juice. In studies by Chrubasik et al (2006a,b) potato juice was trialled as a route to alleviate problems for patients with dyspeptic complaints and dyspepsia (2006a), and inflammatory gastric/gastroduodenal diseases (2006b). Both studies reported efficacy but were not followed by a clinical trial. Regardless of

[1] http://www.mintel.com/press-centre/food-and-drink/sales-of-crisps-lose-their-crunch-potato-based-snacks-overtook-sales-of-crisps-in-2015

[2] https://www.ibisworld.co.uk/market-research/potato-crisps-snacks-production.html

[3] https://www.google.co.uk/search?q=anthocyanin+potato+chips&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwjs3oDspO_SAhULDcAKHcDtD84Q7AkIQw&biw=1691&bih=970

this, potato juice products are already on the market e.g. http://biotta.ch/en/products/biotta-classic/potato/.

An alternative route to exploiting these anti-dyspeptic properties was reported by Kowalczewski et al (2015). They aimed to design a sensorially attractive product addressed to consumers with inflammatory bowel disease. The inclusion of potato juice with turkey and pork meat formulated into frankfurters proved successful and indicated that sausages produced with potato juice addition generated satisfactory consumer acceptance. The form that the potato juice impacted on the sensorial experience with the addition of spray-dried juice impacting on the free water content and fat emulsification enough to significantly change the texture of the frankfurters, and generating a better dispersion and smaller size of fat droplets. This was accompanied by increased maximum shear force.

Potato juice has also been developed as a base for a probiotic functional beverage. Kim et al (2012) found that potato juice was an excellent substrate for the production of proposed gut-health beneficial *Lactobacillus casei* and that the bacterial survival rate following exposure to *in vivo* digestion (acid and bile) was excellent (50-80%). They suggested that fermented potato juice might serve as a probiotic functional beverage for vegetarians or consumers who are allergic to dairy products.

Dietary fibre is already a feature in the food sector but given the benefits derived from it (see Starch and dietary fibre) much more can be made of this. Several products are on sale targeting the commercial (FITCEL (http://www.greencel.sk/en/products/dietary-fibre-fitcel/potato-dietary-fibre), SANACEL, AVEBE etc) and the home cooking (POFIBER) ingredients markets. Other examples are listed below[4]

With regard to the development of new products a recent publication by Lacy and Huffman (2016) is worth considering. They looked at the role of food labels and information and how these affect consumers' valuation of food safety achieved through application of biotechnological methods. Through lab auctions where food is bid for with (or without) information about the food safety risks and benefits of new biotech potato products they reported that the willingness-to-pay for these new potato products are not significantly different from conventional potato products under no information. However, exposure to scientific and scientific-plus-industry perspectives increased participants' willingness to pay for the new potato products and reduced willingness to pay for conventional products. Conversely, exposure to the negative perspective on the new technology significantly reduced willingness to pay. This study has put anecdotal evidence regarding the consumers perception to, and understanding of, biotechnologically generated products on a sounder scientific footing and identifies that a consumer information program could be needed to gain consumer acceptance of these potato products or other foods that have been genetically modified.

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[4] http://www.orchardvalleyfoodingredients.co.uk/product/potato-fibre-pf-200/; http://www.lyckeby.com/en/food-ingredients/products/fiber/potex; http://www.jrs.eu/jrs_en/life-science/food/products/dietary-fibers/index.php; http://por.ingredientsnetwork.com/potex-crown-prod609216.html; http://www.foodnavigator-usa.com/Suppliers2/Penford-rolls-out-fibre-with-resistant-potato-starch-product.

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Policy Landscape

There are several policies relating to diet and health in the UK or the devolved governments. At the UK level this rests with the outputs of the document "2010 to 2015 government policy: obesity and healthy eating". As part of this the 5-a-day and Change4 Life programmes were identified and described. The 5 a day programme identified that fruit and vegetables are part of a healthy, balanced diet and can help us stay healthy. Within this regime potatoes are not counted as one of the 5 a day rather they are described as "a starchy food and a great source of energy, fibre, B vitamins and potassium". When eaten as part of a meal, potatoes are generally used in place of other sources of starch, such as bread, pasta or rice. However, because of this, they do not count towards the 5 A DAY. This rather underestimates recent literature highlighting the benefits of potato (see earlier) but it does identify they are a good source of fibre and that the skins should be left on where possible to keep in more of the fibre and vitamins. The Change4Life programme is more concerned with reducing sugar, salt and fat in the diet and as part of this recipes, food choices and apps to assist these choices have been developed. In all of these potatoes do feature as health choices if eaten as part of a balanced diet.

In the devolved governments there are several policies dealing with diet and nutrition. In wales this centres on Welsh Government's Food Strategy, 'Food for Wales, Food From Wales 2010-2020 (2010) and the subsequent Action Plan "Towards Sustainable Growth: Action Plan for the Food and Drink Industry 2014-2020' (Welsh Government, 2014). In these the focus is largely on food production but a balanced diet is targeted and potato production is highlighted.

In 2013, the Scottish Government and Food Standards Scotland set out their ambition to work collaboratively with partners to improve the nation's health and tackle health inequalities through the Supporting Healthy Choices[5] framework. The final 'Supporting healthier choices'[6] proposals were launched in Spring 2014 and have a particular focus on children's health, promotions, helping consumers with better information, and making products and menus healthier. In these potato is identified positively as part of targets for calorific reductions "A reduction in calorie intake by 120 kcal/person/day. Average energy density of the diet to be lowered to 125 kcal/100g by reducing intake of high fat and/or sugary products and by replacing with starchy carbohydrates (e.g. bread, pasta, rice and potatoes), fruits and vegetables".

At the EU level, there is a plethora of documents around diet and nutrition and in general they have been the basis of the aforementioned national and devolved government policies/ strategies. The Commission established a coherent and comprehensive Community Strategy to address the issues of overweight and obesity, by adopting the White Paper "A Strategy on Nutrition, Overweight, and Obesity-related health issues" (Anon, 2007). In this the promotion of fruit and vegetable consumption is targeted for promotion. This is further supported by the EU scoping paper "*Delivering on EU food safety and nutrition in 2050 - Scenarios of future change and policy responses*" that identified that consumption of fresh fruits and vegetables is steadily decreasing" and that "*Incentives to promote crops such as whole grains fruit and*

[5] http://www.gov.scot/Publications/2014/06/8253
[6] http://www.gov.scot/Topics/Health/Healthy-Living/Food-Health/supportinghealthierchoices

vegetables" are needed to reverse this trend and impact positively on human nutritional outcomes. Potatoes considered as a vegetable in this.

- Food Chain Evaluation Consortium (2013) Scoping study: Delivering on EU food safety and nutrition in 2050 - Scenarios of future change and policy responses: Final report. DG SANCO Framework Contract on Evaluation, Impact Assessment and Related Services – Lot 3 (Food Chain),
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Stakeholder Responses

Responses were obtained from a UK Potato Packer and a 2 major retailers and a combined response representing the Potato Processors.

Q1 How important are nutritional and/or health beneficial properties of potatoes to your customers?

It is important, however, the industry is suffering from mixed messages on the health benefits to an extent that consumers don't rely on it anymore. There is a huge opportunity to market better if a robust, science backed public information on health benefit of potato is made available. (3 respondents shared this view)

Nutrition / health benefits in our customer research do factor in the decision making process for our customers but it is not a high priority / key driver for purchase. (1 respondent)

Q2 Is there an increased awareness of your customers about the nutritional and/or health properties of potatoes?

Yes, but confused with mixed messages. Also, there is often a perception that healthier choice might not necessarily a tastier choice.(retailers, packer)

No. Most customers are broadly aware that potatoes are naturally healthy however they know that most cooking methods such as roasting / frying make them very unhealthy. (retailers)

Q3 What are the most important aspects of potato nutrition to your customers (please rank – vitamins, minerals, starch, dietary fibre, polyphenols, flavonoids, carotenoids and antinutrients (glycoalkaloids), glycaemic index?

I/We don't know what is the most important but I would say that this is exactly the problem in that there is so much goodness but not concise articulation of the message. (3 respondents shared this view)

General calorie content is an important aspect (customers have a good understanding of calories) followed by vitamins / minerals and starch. (retailers)

Q4 Do you detect increased interest consumers in relation to healthy pigments in potatoes such as carotenoids in yellow-fleshed potatoes or anthocyanins in purple fleshed potatoes?

Widely, UK consumers are starting to buy yellow fleshed potatoes not because of healthy pigments but because of perceptive butteriness and point of difference to what else is available. However, if messages of anthocyanins and carotenoids are concisely communicated in a very simple way, it might drive increased interest (2 respondents)

No, but we haven't asked them in relation to carotenoids or anthocyanins. (1 respondent)

Q5 How important are potato flavour and texture to your customers?

Very – consistency of flavour and texture within a sub group is equally important. (2 respondents)

Flavour and texture are very important to our customers, especially when they are buying a potato for a specific use (e.g. roasts). This is also one of the ways we differentiate across the different tiers within our stores. (1 retailer)

Q6 Will your customers pay a premium for potatoes that taste better or have a better nutritional content?

For better taste maybe yes but unknown for better nutritional content (2 respondents)

Our premier lines are selected for their flavour and these retail at a higher price point, so this would indicate that customers are willing to pay more for a premium taste. (1 retailer)

Q7 Are you actively researching the nutritional / flavour/ texture or have plans to do so?

Yes we are actively researching the above.(3 respondents)

Should these areas be a priority for AHDB-Potatoes research projects/ please rank alongside other priority areas such as disease tolerance, heat/drought resistance

Yes - Conveying a simple, concise, science backed health message on potatoes should be one of AHDB potatoes priority (1 respondent)

Yes – but flavour would also need to go hand in hand with projects looking into disease tolerance which are key areas of focus for our growers. If a new variety ranks highly for disease tolerance for example, but is a poor eater in relation to the benchmark then it wouldn't be selected as an approved variety. (2 respondents)

Whilst we consider it important to promote the health credentials of potato, as the raw material for our products, (virtually fat-free, allergy-free, energy-rich carbohydrate, that is a good source of dietary fibre, potassium, iron and vitamins B1, B6 and C), we do not consider the area of research that you outlined below as a priority for AHDB or levy investment. We would rather see greater investment of the levy in research to address the challenges that the industry faces in terms of management of pests and diseases (as the availability of actives reduces), improved storage and sprout suppression and use-efficiency of land, soil, water and crop nutrition. It is likely that there are other funding sources available for the type of research you outline and we would support AHDB playing a facilitation role in identifying these opportunities. (1 respondent)

Science Groups

Responses were obtained from potato groups in US: Cornell, University of Idaho, Washington State University , Oregon State University, ARS USDA; Europe: Leeds University, Wageningen, University, Norwegian Institute of Bioeconomy Research, Leatherhead, UK, Australia: Centre for AgriBioscience, Victoria and CIP, Lima, Peru.

Q1. Are you actively involved in potato research in relation to nutritional and/or health beneficial properties of tubers?

Most respondents indicated they were working in this area.

Q2 What are your target nutrients and/or health beneficial compounds?

Topics in this area included:

Anthocyanins

Acrylamide (indirectly targeted by lowering glucose/fructose levels in cold-stored processing potatoes)

Carotenoids

Shotgun evaluation of potato metabolites through GC-MS, to identify correlations between metabolites and with genetic markers

Starch; glycemic response

The B-vitamins.

Glycoalkaloids

Protein content

Q3 Are you actively involved in potato research in relation to tuber flavour and or texture?

5 respondents indicated they were active in flavour and texture research

Q4 Do you detect an increase in stakeholder interest in these areas?

Most respondents indicated there was a growing interest but several comments were:

"Yes and no. Some stakeholders have told me that they see flavour/nutrition information as a way to boost interest in potato consumption. Others, though, have told me that they don't want to add to the long list of traits that must be promoted to market the crop."

"Yes. From large food companies. Perceive it is a bandwagon, though. Best way to get all needed nutrients is.. a diversified diet!"

"yes and no. In view of our capabilities to provide stakeholders with new insight in the inheritance (SNPs) involved in such traits, I hardly see interest to generate research money. On the other hand, their in-house spending of research budget is increasing."