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Review

High amylose wheat: A platform for delivering human health benefits

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ABSTRACT

Non-communicable diseases such as diabetes, cardiovascular diseases and certain cancers are now the leading cause of death and disability, and their prevalence is rising worldwide. Poor diet is a major modifiable risk factor but changing eating habits has had limited success. Enhancing the nutritional quality of staple foods offers a complimentary intervention strategy for alleviating the burden of diet-related chronic disease. Wholegrain cereals, such as wheat, are prime targets. Their nutritional credentials and health-promoting potential are well established. Wheat is the major source of protein, minerals and vitamins, and dietary fibre for most people. Importantly, wheat is a versatile ingredient for producing foods that have high consumer appeal. Their popularity is expanding globally and small improvements in wheat grain composition conceivably translate to substantial dietary change across entire populations. A newly developed, high amylose wheat line illustrates the capacity for developing healthier processed staple food products with potential for remediating chronic disease risk. Dietary fibre density of this novel grain is markedly improved due to a >10 fold increase in resistant starch content. The sensory attributes of finished products are not compromised and preliminary studies demonstrate that consumption of the new wheat significantly improves indices of metabolic and digestive health.

Contents

1. Introduction

Wheat has been an important source of food since the end of the Paleolithic age (Jones et al., 2015; Bogaard, 2016). Countless people

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today depend on wheat for basic sustenance (Shewry and Hey, 2015), and wheat-based foods feature prominently in the cuisines, cultures and culinary histories of many nations. Early domestication, wide geographic and climatic adaptability, and versatility as a food ingredient to produce finished products of superior eating quality and widespread appeal have made wheat the most widely grown food crop and the most traded cereal in the world today. The popularity of and demand for processed wheat-based foods continues to rise as the human population grows and low and middle income countries prosper, urbanise and undergo transition to westernised diets (Drewnowski and Popkin, 1997). Given its widespread popularity and dietary prominence, wheat is the perfect foundation for raising the nutritional quality of the food supply to help improve overall health of communities worldwide.

The unique physicochemical properties of wheat are what permits its use in an extensive range of healthy staple and indulgent foods, including leavened breads, flat breads, cakes, cookies, biscuits, pastries, breakfast cereals, pasta and noodles. In contrast, other cereal flours are markedly limited in their application as food ingredients. Amongst the ever growing list of food products, bread made of wheat flour remains to be the most widely consumed food. Nevertheless, convenient, inexpensive and easy to cook foods such as pasta and noodles are also rapidly gaining popularity across the globe. Sensory pleasure and associated motivational factors are key drivers of consumer product acceptance and accordingly are of the utmost importance to food manufacturers and retailers. The past decade has seen a gradual shift in demand from snack foods rich in saturated fats and salt to indulgent choices that are healthier. As the demand for the so called healthy indulgent snack is rising, new product developments in this area are offering improved sensory qualities and nutritional advantage. Wheat products are playing a significant role in this newly emerging field that encompasses innovative products such as whole wheat snack rolls, nut-mixed wheat cookies, whole wheat crackers and crunchies.

2. Wholegrain cereals are nutritious and healthy

Cereals are a dietary pillar and major source of carbohydrates and energy for people worldwide (Cassman, 1999; Hansen, 1973; Poutanen et al., 2014). Most also are concentrated sources of dietary fibre as well as various trace elements and vitamins, and myriad phytochemicals, particularly phenolic acids. Wholegrains are synonymous with health, and wholegrain foods have long been recognised as an essential part of a healthy diet. A large and growing body of epidemiological studies consistently show that higher intakes of wholegrains are strongly associated with reduced risk of acute and chronic diseases, including type 2 diabetes, cardiovascular disease and certain cancers, namely colorectal cancer (Aune et al., 2016; Wu et al., 2015; Zong et al., 2016). These ailments are among the leading causes of global morbidity and premature mortality. Despite the collective methodological limitations of these studies, including wholegrain definition heterogeneity (Slavin et al., 2013) and resulting intake measurement error, the associations are robust, consistent and reinforced by evidence from randomised controlled trials and mechanistic studies, lending weight to the case for a causal relationship (Lucas and McMichael, 2005) between wholegrain intake and protection against a number of increasingly common non-communicable diseases.

3. Wholegrain wheat - nutrient rich and a major source of dietary fibre

The nutritional value of wheat per se is often overlooked as are its health benefits. Nearly all of the epidemiological evidence linking wholegrains with reduced incidence of chronic diseases comes from studies on western populations, mostly North American and European, where wheat is the predominant cereal in the diet (Dalton et al., 2012).

The nutritional profile of wheat is generally comparable to that of other wholegrain cereals. Carbohydrate and protein contents are similar, but the functional quality of the latter differs markedly in that it enables a greater range of milling and processed food applications as described earlier. Wheat is an excellent source of dietary fibre, containing about 30–100% more fibre than the other economically major cereals (De Moura et al., 2009; Lafiandra et al., 2014). It also is richer in betaine, choline, alkylresorcinols and several other health-related constituents (Lillioja et al., 2013; Shewry and Hey, 2015).

Potentially, all these constituents, either acting alone or in combination, might explain how wholegrain foods afford protection against noncommunicable diseases and improve long term health, but the evidence is strongest for dietary fibre (Cho et al., 2013; Kuijsten et al., 2015; Wu et al., 2015). High fibre diets are associated with lower incidences of cardiometabolic and gastrointestinal diseases, and consumption of foods rich in fibre may be especially important for longevity and optimal health later in life (Gopinath et al., 2016; InterAct Consortium, 2015).

There are many dietary sources of fibre but that from cereals appears to be especially effective in promoting health (InterAct Consortium, 2015; Maki and Phillips, 2015). Wheat is the major contributor to total dietary fibre intake of people in developed nations (Dalton et al., 2012; Smith and Tucker, 2011; Williams, 2012).

4. Fibre gap

Daily intake targets for wholegrains of 75–100 g have been set by various health authorities around the world. This equates to about 3 servings of wholegrain foods but very few individuals eat anywhere near this amount (Cho et al., 2013; Mann et al., 2015; Slavin, 2004). In some cohorts, such as children, adolescents and lower socioeconomic groups, the intake deficits may be even greater (Kamar et al., 2016). Consequently, dietary fibre intakes also fall well short of what they should be to realise the health benefits on offer. In the USA for instance, only 1% of the population consumes the recommended amount of wholegrains and more than 90% do not meet the intake target for dietary fibre (Jones, 2014). Fruit, vegetables and legumes also contain fibre but their intake in developing and developed countries is, as with cereal foods, well below suggested levels.

5. Fibre diversity is important for consumer health

Dietary fibre is an umbrella term that embraces an eclectic group of mainly nondigestible carbohydrates of plant origin, notably nonstarch polysaccharides, oligosaccharides (fructans) and resistant starch. The health benefits provided by dietary fibre depend on the amount and types eaten because they vary markedly in their physiological (and microbiological) actions and hence capacity to promote health and reduce disease risk. Variety is important given the functional diversity and synergies among different nondigestible carbohydrates, for instance, resistant starch and other fibres (Behall et al., 2006; Bird et al., 2009; Muir et al., 2004). There are also phytochemicals embedded with cereal cell wall polysaccharides (fibre co-passengers) that have also been suggested as having a role to play in disease protection. Their bioavailability in the upper gastrointestinal tract is low but they may have a positive impact on health through their interactions with the large bowel microbiota (Belobrajdic and Bird, 2013).

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Wheat is ubiquitous in western diets. It is the most commonly consumed cereal, which accounts for the lack of diversity of fibre types in many food supplies. Indeed, the dietary fibre profile of the western diet reflects that of (bread) wheat, that is, a prevalence of nonstarch polysaccharides, mostly insoluble arabinoxylans, cellulose and some β-glucan. Low molecular weight fibres such as fructans are also present but at low concentrations. Most processed foods made from conventional wheat cultivars contain negligible levels of resistant starch. Most other starchy foods in modern diets also supply little resistant starch.

6. Refined cereal foods are important fibre sources

Foods made from refined wheat flour (white flour) have high sensory appeal and so are decidedly more popular than those made with whole grain flour. Many are softer, lighter, more voluminous and easier to chew. Their overall acceptability and appeal usually exceeds that of the corresponding wholegrain product (Grigor et al., 2016) even though nutritional quality is much less as a consequence of the refining process. About 60–80% of the fibre, minerals & vitamins are contained in the bran and germ but these fractions are removed during milling to produce white flour (Jones et al., 2015; Slavin, 2004). Nevertheless, because of the quantity consumed, refined wheat products are a major source of dietary fibre for many urbanised/westernised populations (Shewry and Hey, 2015; Williams, 2012). For people in the USA and many other countries, refined wheat foods function as the primary source of dietary fibre by default.

7. High amylose wheats – ingredients for even healthier cereal foods

Most modern diets are incompatible with affluent (sedentary) lifestyles. Increased food energy availability and overconsumption of energy-dense, nutrient-dilute foods contribute to overweight and obesity and is responsible for considerable morbidity and mortality (Friedman, 2009; Vandevijvere et al., 2015). The incidence of type 2 diabetes, coronary artery disease, stroke, excessive adiposity, and other increasingly common public health problems is rising steadily worldwide. Many adults and an increasing number of children in advanced economies have concurrent degenerative disorders that are inextricably linked to poor food choices and unhealthy diets. Accordingly, these public health problems are potentially preventable.

Because wheat is the basis of many staple foods, small improvements in grain nutritional content or profile could conceivably have a disproportionately large impact on the nutritional quality of diets across entire communities and help individuals achieve recommended intakes for critical nutrients, such as fibre. Thus, wheat could serve as a functional platform for delivering human health benefits globally, through tailoring grain composition and subsequent incorporation of the ingredient in diverse food products. This approach offers a pragmatic, comprehensive and cost-effective means for improving national health by stalling or even reversing the rise in diet-induced chronic disease and lessening the associated economic burden and social impact. Improvements in nutritional quality cannot adversely affect the functional properties and resultant consumer appeal of these foods otherwise success will be compromised. Wheat with significantly elevated amylose content could potentially provide substantial health benefits at a global level through delivery of resistant starch.

8. Starch functionality, digestibility and health benefits

The nutritional composition of present-day conventional wheat lines is little different to that of ancient progenitor wheats and landraces (Jones, 2012; Shewry et al., 2016). This probably also applies to other cereals (Fitzgerald et al., 2011). However, modern milling and food processing practices have had an adverse effect on the fibre profile and content, and potential health benefits, of contemporary wheat-based foods. The starchy endosperm in extensively processed grain foods is more exposed and susceptible to the actions of intestinal hydrolases. Consequently, the starch is readily and extensively digested in the upper gut resulting in rapid delivery of glucose to the bloodstream and provision of little fermentable starch for the colonic microbiota. Most processed whole grain foods have a high glycemic impact and contain negligible amounts of resistant starch. Retrogradation of starch, as occurs with repeated cooking and cooling cycles, results in the formation of resistant starch but these foods are not a major feature of contemporary cuisines.

9. Resistant starch

A growing body of evidence points to the potential of resistant starch in the prevention and progression of the most common diet-related diseases. Resistant starch is that fraction of dietary starch that escapes digestion and absorption in the upper gut and consequently reaches the large bowel where it serves as a substrate for the colonic microbiota. Indeed, the health benefits of resistant starch are largely mediated through the end products of its fermentation by the gut microbiota, notably short chain fatty acids (SCFA). These agents are not only integral to bowel health but also influence metabolism of peripheral tissues, including skeletal muscle, adipose tissue depots and liver (Topping and Clifton, 2001). Recent evidence highlights their importance in regulating and strengthening immune system function and responses to infection (Kim et al., 2016).

Resistant starches stimulate the proliferation and metabolic activity of microbial populations considered conducive to host health while also discouraging growth of pathogenic bacteria (Bird et al., 2010; Hutkins et al., 2016). The resultant biochemical changes in the luminal environment, including acidification of the contents and raised levels of butyrate, are important for normal bowel function and health. Protection against DNA damage induced by unhealthy diets is correlated strongly with luminal levels of SCFA, especially butyrate (Conlon et al., 2009). There is increasing evidence that butyrate insufficiency contributes to the pathophysiology of colorectal cancer and other diseases (Fung et al., 2012; Higgins and Brown, 2013; Humphreys et al., 2014). It is an important regulator of colonocyte energy homeostasis and epithelial integrity and, accordingly, plays a pivotal role in gut barrier function through various mechanisms and pathways, including stimulating colonic mucus production (Guilloteau et al., 2010). Butyrate is also implicated in promoting mucosal immune system function and suppressing inflammation. Consumption of foods rich in resistant starch augment fecal butyrate levels (McOrist et al., 2011; Topping et al., 2003) and improve other indices of bowel health, including biomarkers of colorectal cancer (Higgins and Brown, 2013).

Interest in the potential of resistant starch for improving health has shifted from the gut to extra-intestinal tissues. Prolonged consumption of high glycemic impact diets increases the risk of developing cardiometabolic disease, such as heart disease and type 2 diabetes (Blaak, 2016). The mechanisms through which resistant starch reduces disease risk are fundamentally linked to starch assimilation along the gastrointestinal tract. By definition, resistant starch escapes digestion in the small intestine and, accordingly, does not as such contribute directly to postprandial rises in blood glucose and insulin concentrations, unlike rapidly digested starches. Substituting conventional (digestible) starches with

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resistant starches effectively dampens postprandial hyperglycemia and improves glucose control through stimulating insulin sensitivity in peripheral tissues and other inter-related physiological processes (Behall et al., 2006; Robertson, 2012).

Resistant starch has also been shown to promote satiety, reduce food intake and modulate postprandial energy partitioning, and so might be of benefit for weight prevention and control (Keenan et al., 2015). Systemic health benefits of resistant starches also relate to their luminal actions in the large bowel, namely fermentation to SCFA by the resident microbiota. These end products trigger release of gut peptides, such as PYY and GLP-1 from enteroendocrine cells, which are involved in energy homeostasis via regulatory feedback mechanisms that promote satiety and suppress hunger (Byrne et al., 2015). SCFA, such as butyrate, also have potent anti-inflammatory actions, as referred to earlier. Hyperglycemia initiates a cascade of proinflammatory responses that are intricately involved in the development of insulin resistance and type 2 diabetes. Persistent, low-grade systemic inflammation, a hallmark of chronic diseases, is linked to dysbiosis (disruption of the gut microbiota) and intestinal barrier dysfunction that are more common in individuals consuming a western dietary pattern (Conlon and Bird, 2015). Resistant starch is important for strengthening gut barrier function and integrity by reducing intestinal permeability and translocation of proinflammatory agents from the lumen into the systemic circulation. For overweight and obese individuals, especially their diets are rich in fat, greater intakes of resistant starch may be required to obtain the full range of benefits that this fermentable fibre offers (Bird and Conlon, 2015).

Cereal foods are the major source of dietary starch in high-income countries and therefore this food group accounts for most of the resistant starch that is consumed (Bird et al., 2012; Murphy et al., 2008). Wheat is popular and eaten more frequently and so is the main supplier of resistant starch. Other starchy foods, notably white vegetables such as potato, account for only a small proportion of total resistant starch consumption.

Resistant starch intake overall is low because most staple foods are highly refined and extensively processed. Ascertaining the amount of resistant starch in any diet is challenging because the available analytical methods for foods are problematic (Bird et al., 2012). Many reported values are unreliable because they were obtained using analytical techniques that had not been adequately validated. Current intakes for most people probably do not exceed 10 g per day (Baghurst et al., 1996; Cassidy et al., 1994; Murphy et al., 2008; Roberts et al., 2004). Indeed, typical western diets are likely to supply only about half this amount (Bird et al., 2012), which reflects the overall level of starch consumption and that most modern foods are extensively processed thereby increasing starch digestibility and depleting resistant starch. This quantity of resistant starch is probably too small to have a measurable effect on the gut microbiota. Dietary targets for resistant starch have been suggested (eg ~20 g/d for adults; Baghurst et al., 1996; Bird et al., 2012; Cassidy et al., 1994). Although epidemiological data supporting these targets are limited, randomised controlled trials suggest that intakes of this order have favourable health outcomes.

10. Starch structure and its influence on resistant starch

Amylose and amylopectin are the two glucose polymers that make up starch, both differing in their levels of α-1,4 and α-1,6 linkages and the length of individual glucan chains. Amylopectin is highly branched with ~6% of α-1,6 linkages and much larger polymer with a degree of polymerisation (DP) of 5000 to 100,000 compared to amylose which has few branches (<1%) and a smaller polymer of size of <5000 DP. Individual branches of amylopectin are shorter with an average DP of 17–25 compared to amylose in which the branches are significantly longer with an average DP of 10^3-10^4 (Gilbert et al., 2013). The individual chains, branched structure, semicrystalline arrangement (Bertoft et al., 2008; Jane et al., 1999; Jenkins and Donald, 1995), growth rings and the granular architecture (Pérez and Bertoft, 2010) all contribute to a multi-layered conformation that governs many functional properties of starch-containing materials (Gilbert et al., 2013). Wheat endosperm normally contains around three times more amylopectin than amylose. The ratio of amylose to amylopectin is a major determinant of the multi-level structure and functional characteristics of starch (Regina et al., 2012) that impact the transformational changes during processing as well as the digestibility of starch. The structural topologies of starch tend to change with increasing amylose content, with high amylose starches showing complex topologies arising from the combined macromolecular populations of amylose, amylopectin and distinct intermediate components that have a size similar to amylose and branching patterns similar to amylopectin, but with high proportion of longer branches (Vilaplana et al., 2014).

Amylose is less readily digested and the resultant delivery of glucose into the bloodstream slower than that of amylopectin. Also, the digestion of amylose is more likely to be incomplete in the upper gut and so starches that contain proportionately more amylose are higher in resistant starch (Regina et al., 2015). The rate and extent of starch digestion is less for cereals containing higher levels of amylose (Behall and Hallfrisch, 1988). Some of the mechanisms involved in enzyme resistance of high amylose starches are 1) starch granules maintained intact due to intertwining of amylose among the amylopectin crystallites, 2) restricted swelling of starch granules during heating due to increased amylose-lipid complexes 3) retrogradation of amylose and very long amylopectin branches to highly ordered crystalline structures on storage of gelatinised starch (Cui and Oates, 1999; Gidley et al., 1995; Gilbert et al., 2013; Hasjim et al., 2010).

11. Genetic development of high amylose wheat

Significant elevation of wheat amylose content (from wild type levels) can be achieved mainly through manipulating two diverse mechanisms that control starch biosynthesis. As in other cereals, starch production in wheat involved the concerted action of mainly four classes of enzymes: 1) ADP glucose pyrophosphorylase which produces ADP glucose from glucose-1-phosphate and ATP, 2) starch synthases that elongate glucan chains by addition of glucose residues to the non-reducing ends, 3) starch branching enzymes that creates branches of α-1,6 linkages and 4) de-branching enzymes that removes excess branches from starch molecules (reviewed in Regina et al., 2016). Fig. 1 depicts the various known isoforms of the different classes of starch biosynthetic enzymes. Other enzymes are involved in starch biosynthesis in cereals but these are not covered in this review. The two mechanisms that increased amylose content in wheat targeted two entirely different synthetic events, one was by suppressing the glucan elongation step by starch synthase (SS) IIa that also decreased the amylopectin synthesis, while the other one was by suppressing the starch branching event by either starch branching enzyme (SBE) IIa or by a combination of SBEIIa and SBEIIb. The impact of these two mechanisms differs widely with respect to the level of amylose increase, the structure and functionality of the resulting starch components and the morphology and the composition of the impacted wheat grain. Yamamori et al. (2000) reported the first SSIIa mediated high amylose wheat through combining single null mutants of SSIIa in each of the three genomes in wheat to produce a triple null mutant that resulted in a moderate elevation of amylose content to 40–50% of the starch. The

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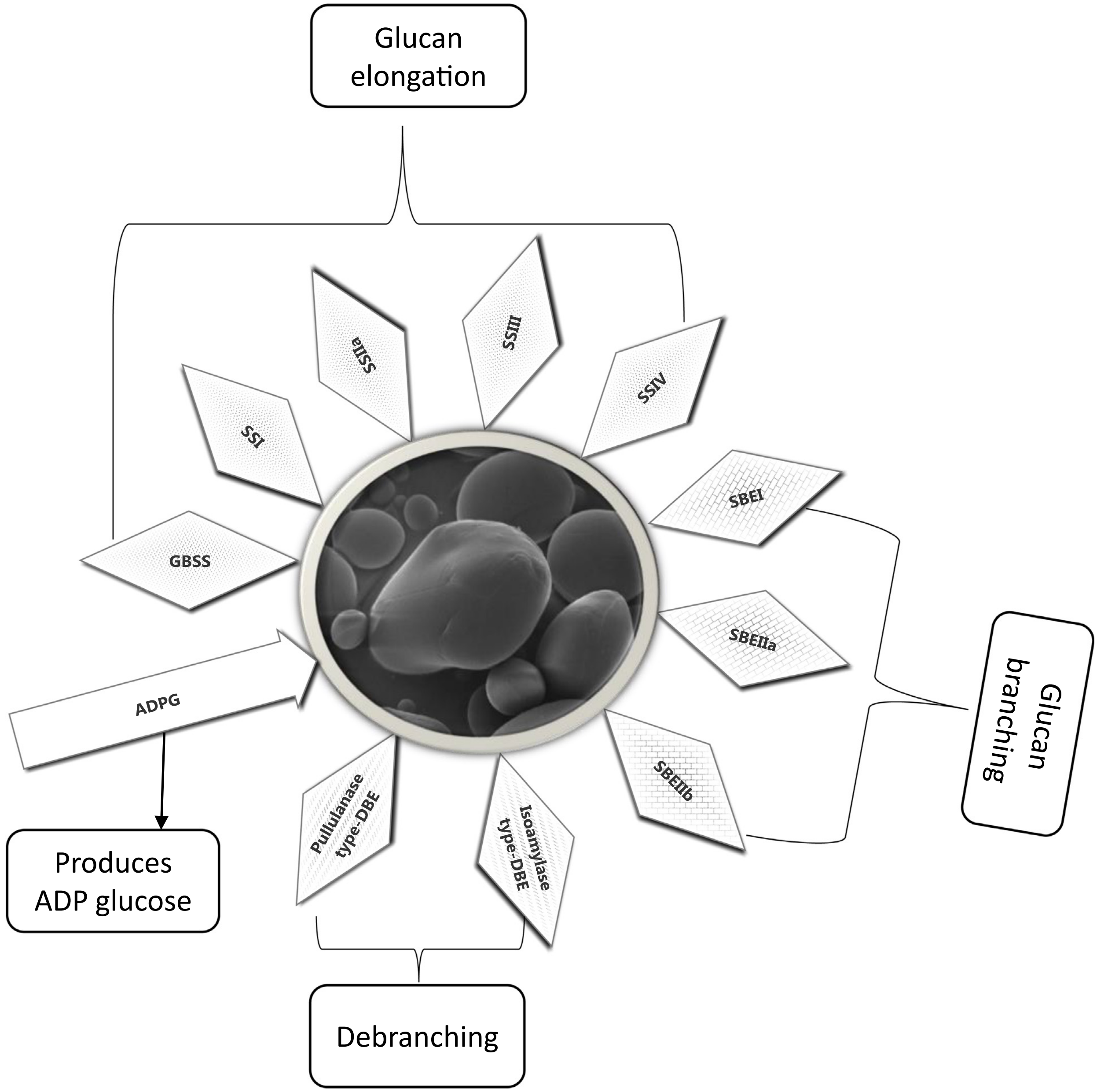

Fig. 1. A diagrammatic illustration of major cereal starch biosynthetic enzymes and their functional role in starch biosynthesis. ADPG: ADP glucose pyrophosphorylase; SS: starch synthase; SBE: starch branching enzyme; DBE: debranching enzymes.

first evidence of suppression of SBEIIa being critical in wheat in elevating the amylose content to ultra-high levels of >70% was obtained through RNAi gene silencing studies (Regina et al., 2006). However in these studies suppression of SBEIIa resulted in a concomitant reduction of SBEIIb. Initial attempts to increase the amylose content through non transgenic down regulation of SBEIIa exploiting allelic polymorphisms resulted in an elevation of amylose content of only as much as 55% in hexaploid wheat (Slade et al., 2012), and from 28% to 47% in durum wheat (Hazard et al., 2012; Slade et al., 2012). More recently, a genetic strategy that combined deletion and single nucleotide polymorphism (SNP) loss of function alleles generated wheat genotypes with varying levels of reduction in SBEIIa and SBEIIb, and elevated the amylose content to as high as ~85% in some genotypes (Regina et al., 2015).

The mechanism generating high amylose starches governs their molecular characteristics and unique functional properties. Whereas properties such as amylopectin chain length distribution and gelatinisation temperature clearly differ depending on whether the new starch is produced through SSIIa or SBEIIa down regulation, functional properties, such as reduced starch swelling, lowered viscosity and decreased digestibility are driven mainly by reduced granular order and increased amylose content (Regina et al., 2012; Yamamori et al., 2006). SSIIa down regulation resulted in a starch with amylopectin having a significantly higher proportion of DP 6–10, and proportionately fewer long chains of ~ DP 11–25 and lower gelatinisation temperature (~10 °C lower than the control) (Konik-Rose et al., 2007; Shimbata et al., 2012). Conversely, high amylose starches resulting from SBEIIa mutations showed a significantly reduced proportion of DP 9 to 13 and an increased proportion of larger chains of >24 DP, with the pattern of other chain segments varying depending on the extent to which the expression of SBEIIb is altered in these genotypes (Regina et al., 2015). The gelatinisation temperature of SBEIIa-mediated high amylose starches is increased unlike that of starch produced through SSIIa down regulation (unpublished). The fine features of high amylose starches produced by targeting the two aforesaid mechanisms no doubt will have an important influence of the eating quality and other attributes of end products, because starch granules play an important role during processing. For example, during bread making amylases act on starch granules releasing sugar substrates for yeast fermentation. Starch is also a major determinant of water absorption and contributes to viscoelastic properties of the dough and loaf volume of bread (Kusunose et al., 1999).

12. HAW – health benefits

A novel wheat that has a markedly elevated amylose content has been recently developed by selectively inhibiting the activity of branching enzymes pivotal in the starch biosynthetic pathway in the endosperm (Regina et al., 2015). Laboratory studies have established that this new wheat variety is greatly enriched in resistant starch (>10-fold increase). Consequently, it is markedly higher in total dietary fibre, and has as other favourable compositional changes in the grain (Table 1). Refined and wholemeal flours made from this grain have been used to produce a range of prototype bakery items, including breads and pasta, of comparable quality to the corresponding products incorporating standard wheats (Berbezy et al., 2015).

Acute and extended feeding studies in animal models, and pilot studies in humans, have demonstrated that the altered grain composition, specifically the increase in resistant starch, is physiologically meaningful and translates to measurable metabolic and bowel health benefits. A short-term trial in rats provided evidence to support the laboratory findings that high amylose wheat is higher in resistant starch (Regina et al., 2006). Subsequent animal and human dietary intervention studies have established that wholemeal and refined high amylose flours, and processed foods from them, deliver substantially more resistant starch to the large bowel than those formulated from control flours (Bird et al., unpublished results). Those studies have also demonstrated that dietary incorporation of high amylose wheat (as wholemeal flour) prompts physicochemical changes in the large bowel lumen important for maintenance of mucosal health, notably greater amounts of digesta and SCFA and a concomitant reduction in luminal pH. An extended feeding trial (3 months) in rats has shown that the positive effects of high amylose wheat is sustained and comparable to that of high amylose maize starches (Conlon et al., 2012), including a butyrylated form that delivers additional butyrate to the colon (Clarke et al., 2011). Enhanced fermentation in rats fed a high amylose durum wheat was also demonstrated by Hazard et al. (2015). In the study of Conlon et al. (2012), high amylose wheat and maize sources were equally effective in negating colonic DNA damage induced by the western diet that was fed to the rats although the mechanisms of benefit, including maintenance of genomic homeostasis, differed depending on dietary resistant starch source.

Recently, pilot studies in healthy volunteers and a meal-fed rat model have also shown that refined and wholemeal foods containing high amylose wheat elicit postprandial glycemic responses significantly lower than those recorded for comparable products made from conventional wheat flours. The rise in blood glucose concentration is slower and less pronounced for high amylose wheat foods resulting in a smaller area under the post-ingestion incremental glucose concentration curve (iAUC). Large dietary intervention studies in humans are underway to further investigate high amylose wheat-mediated responses in indices of digestive and metabolic health for a range of processed food and beverage products.

13. Conclusion

Wholegrain cereal foods, especially those made from wheat, are dietary staples for diverse populations. For millennia, these foods have been a nutritional cornerstone for humankind, providing not only energy in the form of digestible carbohydrates, but other vital nutrients as well, such as protein, trace elements and vitamins. The health benefits of wholegrains is well established, as is the role of cereal fibre in mediating those benefits. The evidence base for the health benefits of resistant starch also continues to build.

However, total dietary fibre intakes in many industrialised countries are woefully low. Consumption of wholegrain foods declines in general with increasing economic prosperity, often replaced by refined carbohydrates, and protein-dense foods such as red and processed meats. Starch and dietary fibre intakes fall as a consequence. Despite the wide variety of foods eaten nowadays in affluent countries, cereal foods, and those made from wheat especially, are the main source of dietary fibre.

Modern milling and food processing methods have diminished the nutritional quality and health promoting potential of cereal foods. The starch in many cereal foods and from other dietary sources is rapidly and almost completely digested and absorbed in the small intestine. As a consequence, the glycaemic impact and metabolisable energy yield is maximised whereas carbohydrate delivery to the large bowel (resistant starch) is reduced

Table 1
Dietary fibre profile of grain, flour and breads made from conventional and high amylose wheat.

Type of sample	Total Fibre (AOAC 985)	Soluble Fibre	Insoluble Fibre	Sum of Fibre (AOAC 991.43)	Resistant starch	
			g/100 g		(g/100 g, 'as is')	(g/100 g starch)
Grain						
Standard wheat	11.7	2.3	10.6	12.9	0.2	0.4
HAW	17.4	2.6	14.2	16.8	6.5	14.5
FLOUR						
Standard wheat	2.2	1.7	0.4	2.1	0.1	0.2
HAW		3.5	3.2	6.7	8.5	14.5
BREAD						
Standard wheat						
Refined	2.7	1.4	2.3	3.7	0.8	2.0
Wholemeal	5.4	1.2	6.7	8.0	0.6	2.0
HAW						
Refined	7.2	1.5	6.9	8.4	6.5	19.7
Wholemeal	12.9	1.7	12.1	13.8	5.1	21.1

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substantially. Potential health-promoting synergies between resistant starch and other fibre components are also not realised.

Low dietary fibre intake coupled with diminution of fibre diversity of the food supply of many contemporary communities is a contributing factor in the global chronic disease pandemic. As well as aiming to raise fibre intake, national dietary fibre recommendations should also emphasise the importance of dietary fibre diversity, especially inclusion in the diet of fermentable carbohydrates, such as resistant starches, that have broad reaching benefits. However, lifestyle modification at the public health level tends to be a long term proposition. Given the urgency in tackling the escalating prevalence of diet-related chronic diseases, and lessening attendant socioeconomic costs, provision of healthy staple foods richer in an expanded range of different types of dietary fibre might be a faster and more effective remedy.

Foods rich in resistant starch contribute to fibre intake and so can help fill the fibre quantity and quality gap. To have a meaningful impact on public health they need to be staple foods, eaten frequently and at most meals. The proportion of amylose must be sufficiently high to ensure that resultant processed food products deliver enough resistant starch to the gut microbiota in order to have a measurable physiological effect on the host. Wheat is an obvious vehicle given its versatility as a food ingredient and widespread popularity and appeal of wheat-based foods, such as breads, pasta and noodles. Even modest changes in the nutritional quality and fibre profile of wheat flour has the potential to deliver significant population-wide health benefits through chronic disease risk reduction. However, the success of this strategy hinges on several prerequisites. Consumer acceptance of foods enriched in resistant starch, such as those made from high amylose wheat, is obviously paramount. Any change in wheat grain composition must not negatively affect eating quality of foods formulated to contain this ingredient. Scientific substantiation of the physiological efficacy of these foods, and the health benefits they impart, will also be important for facilitating their uptake in the marketplace.

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