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Shewry, P. R., Hazard, B., Lovegrove, A. and Uauy, C. 2020. Improving starch and fibre in wheat grain for human health. *The Biochemist.* 42 (4), pp. 40-45. https://doi.org/10.1042/BIO20200051

Improving starch and fibre in wheat grain for human health

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Reducing the prevalence of diet-related diseases, including obesity and type 2 diabetes, is a major challenge for health professionals, food manufacturers and governments in both developed and developing countries. Cereals are key targets in meeting this challenge as they are staple foods throughout the world and major sources of energy (derived principally from starch) and dietary fibre. Wheat is the staple cereal in the UK and Europe, and the UK Biotechnology and Biological Sciences Research Council (BBSRC)-supported Designing Future Wheat programme is focused on manipulating the content and composition of starch and fibre to improve health impacts, including reducing the glycaemic response and improving fermentation in the colon. This work is contributing to the development of improved cultivars by breeders and foods by processors. It is also increasing our understanding of the behaviour of these components in the human gastrointestinal (GI) tract and will contribute to the establishment of targets and recommendations for regulatory authorities.

The role of wheat in nutrition and health

Wheat has been the staple food crop in the UK and Europe for millennia and, although its contribution to diets has declined in recent years with increased prosperity and availability of a wider range of foods, it continues to underpin the nutrition and health of the vast majority of the population.

About 5.5m tonnes of wheat flour are produced annually in the UK, of which about 45% is white flour and 5% is wholemeal flour for commercial breadmaking and about 10% is flour for making biscuits and cakes. These figures demonstrate not only the continued dominance of white bread, which may surprise many readers in light of the promotion of the health benefits of wholemeal products, but also the pervasiveness of wheat in the food system. Hence, it is not surprising that bread alone contributes about 10% of the total energy and protein and 20% of total dietary fibre (DF) in the UK.

White flour is produced by milling, which separates the major storage tissue (the starchy endosperm, representing over 80% of the whole grain) from the embryo and outer layers (Figure 1). White flour is therefore highly refined, comprising about 85% starch and 5% fibre, compared with 75% and 11%–15% of these components, respectively, in wholemeal flour. Highly refined starchy foods tend to be rapidly digested in the small intestine, leading to a sharp spike in blood glucose, a risk factor of type two diabetes (T2D) if occurring habitually. Hence, the role of wheat in the increases in T2D and other adverse conditions associated with the 'western diet' has been widely debated.

The UK Biotechnology and Biological Sciences Research Council-supported Designing Future Wheat programme

The importance of wheat in food security is recognized by the UK Biotechnology and Biological Sciences Research Council (BBSRC) which supports the Designing Future Wheat (DFW) programme. The UK has a strong research base in wheat, and DFW has brought several groups together in an integrated 5-year (2017–2022) 'pre-breeding' programme comprising eight partners with a total budget of £24m. The programme works closely with breeders, providing improved germplasm and tools (molecular markers) to facilitate crop improvement, and with other stakeholders. It has a clear focus on the concerns and priorities of consumers, including the role of wheat in a healthy diet. Because products made from white flour continue to be dominant, it focuses on improving the composition of the starchy endosperm and on the two major components that contribute to health outcomes: starch and DF (Figure 1).

Reducing the digestibility of wheat starch in the gastrointestinal tract

An important goal is to reduce the digestibility of starch in wheat-based foods as this should lead to slower glucose release and more gradual increase in blood glucose levels. The rates of starch digestion and the absorption of glucose in the upper gastrointestinal (GI) tract are affected by a number of factors, including the structures of the starch polymers, their organization

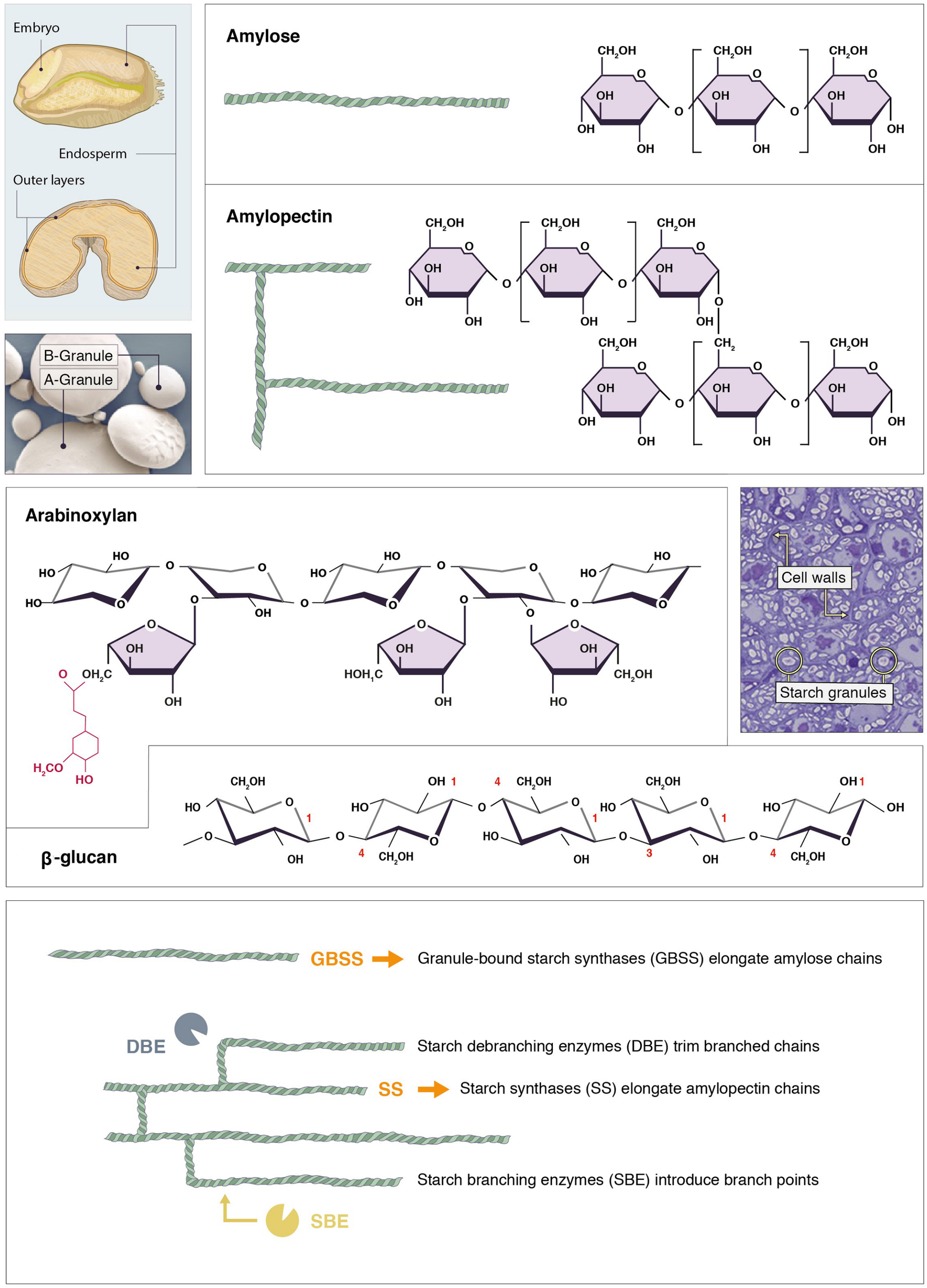

Figure 1. The major carbohydrates in wheat grain and flour: starch (amylose and amylopectin) and fibre (arabinoxylan and β-glucan). Starch is located in the starchy endosperm cells. It consists of two populations of granules, large A-granules which are 5–40 µm in diameter and disc-shaped and small B-granules which are <10 µm in diameter and near-spherical, which may be digested at different rates. Arabinoxylan and β-glucan are cell wall components. Starch composition and structure are determined by the activities of starch synthases (SS and GBSS), starch branching enzymes (SBEs) and starch debranching enzymes (SDE) and can be manipulated by down-regulation of these enzymes.

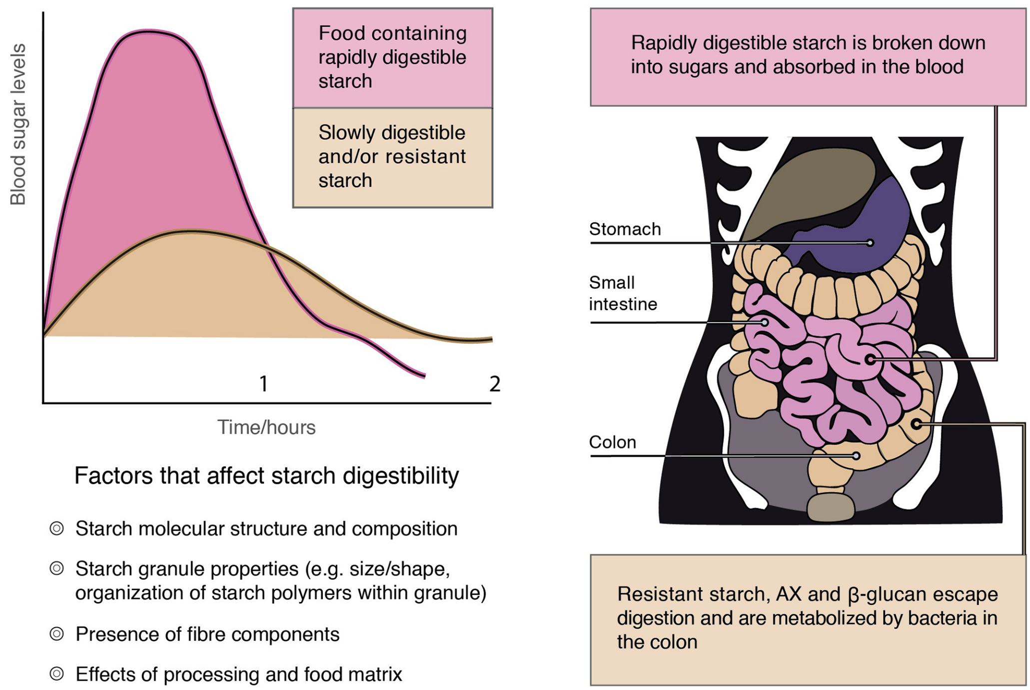

Figure 2. Factors controlling starch digestion and fermentation in the human gastrointestinal tract

into granules, the presence of fibre and the effects of processing (Figure 2).

Most starches are easily digested in our small intestine, but resistant starch (RS) resists digestion and reaches the colon intact. It is, therefore, a component of DF (see below). Despite its potential health benefits, the general consumption of RS is low, probably about 3 g/day. However, this can be addressed by increasing the levels of RS in widely consumed staple foods such as wheat.

Starch is composed of two glucose polymers: amylose (~20%–30%), which has long chains with a few branches, and amylopectin (~70%–80%), which is highly branched (Figure 1). Three types of enzymes are required for the synthesis of amylose and amylopectin: starch synthases and granule-bound starch synthase (SSs and GBSS, respectively), starch branching enzymes (SBEs) and starch debranching enzymes (DBEs). Starch polymers form granules which have alternating amorphous and crystalline layers; the ordered packing of short amylopectin chains provides crystallinity, whilst both amylopectin and amylose contribute to amorphous starch. Starches with high levels of amylose tend to have high levels of RS, while other characteristics of polymer structure also influence digestibility, including molecular size, amount of branching as well as glucose chain lengths.

The levels of amylose and RS in wheat can be increased by modification of starch biosynthesis, the main approach being to down-regulate SSs and SBEs (Figure 1). However, adverse effects on yield components, including grain weight, and on grain quality mean that commercial development of these lines is difficult.

Targeting other key starch biosynthesis genes or producing new combinations of mutant alleles may offer an opportunity to achieve elevated levels of RS while minimizing impacts on yield and quality. Until recently, this has been particularly challenging in wheat due to lack of genomic resources and the presence of related gene copies (homoeologues) in the three genomes (A, B, D) of hexaploid bread wheat. However, advances in wheat genomic resources, specifically the exome capture and resequencing of wheat TILLING mutants, allow induced mutations in different genes (including homoeologues) to be identified and combined by crossing supported by marker-assisted selection. We have, therefore, developed a set of lines in order to understand the roles of key genes and their interactions in controlling starch synthesis and their effects on starch structure and properties.

Processing also has strong effects on the digestibility of starch in foods. During cooking, starch is gelatinized and amylose leaches out of the swollen amylopectin matrix of the granule, making it more digestible. When starch cools, crystallization or retrogradation of the polymers occurs. Amylose molecules rapidly crystallize to form structures that are more resistant to digestion, while amylopectin retrogrades much more slowly, remaining susceptible to hydrolysis. Thus, understanding the effects of processing on the digestibility of novel wheat starches

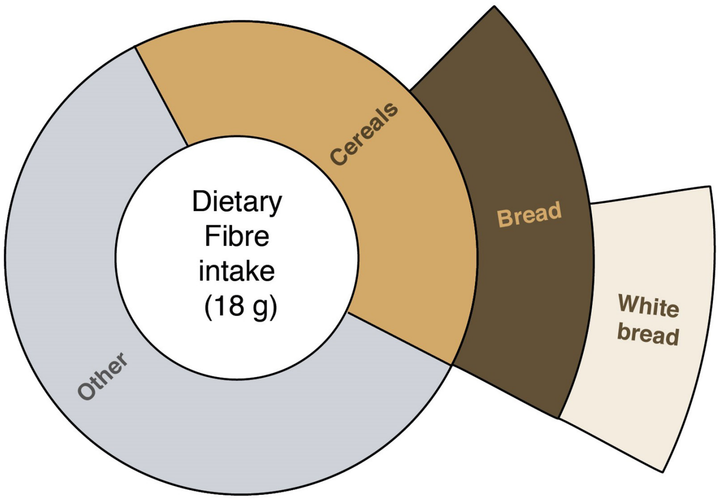

Figure 3. Current sources of fibre in the diet of UK adults. Total breads contribute about 20%, and white breads contribute to half of this (Steer et al., Proceedings of the Nutrition Society 2008, 67, E363).

is critical for delivering more RS to consumers. For example, we have shown that the digestibility of starch in durum wheat *sbeII* mutants decreases after processing.

The development of wheat starch mutants will also facilitate intervention studies in humans. Although the European Food Safety Authority (EFSA) has approved a health claim that the replacement of digestible starch with RS (high-amylose maize) in high-carbohydrate baked foods leads to a lower blood glucose response after a meal, the target levels for RS in wheat starch have not been defined. Furthermore, the behaviour of high RS wheat starches in the GI tract have not been studied. The design of human intervention studies with complex foods is challenging, with comparisons frequently being made between disparate types of foods. The new types of wheat with specific starch modifications described here, for example, the *sbeII* mutants, will allow more precise intervention studies to measure the effects on digestion and glycaemic response.

These studies will, therefore, underpin the development of health claims for RS in wheat and recommended daily intake levels for modified wheat-based foods, as well as identify targets for wheat breeders.

Increasing the content of cell wall–derived dietary fibre in white flour

DF is predominantly derived from plant foods. It is essential for health, having a range of benefits that include lowering the glycaemic response, lowering blood pressure and serum cholesterol and reducing the incidence of certain types of cancer. These benefits result partly from physical effects, but also from fermentation in the colon to produce short-chain fatty acids (acetate, propionate and butyrate) that have beneficial effects. Whereas soluble fibre is mainly fermented in the proximal colon, insoluble fibre is mainly fermented in the distal colon (ameliorating the detrimental effects of protein fermentation). Increases in the contents of both soluble and insoluble fibre will, therefore, improve the health benefits of white wheat flour.

The recommended intake of DF varies between countries, being 30 g/day for adults in the UK. However, few individuals achieve this level, with the current adult intake in the UK being about 18 g. About 40% of the DF intake in the UK comes from cereals, and about half of this from breads (and half of this from white bread) (Figure 3). Increasing the fibre content of wheat is, therefore, an attractive strategy for delivering health benefits to large populations.

DF comprises carbohydrate oligomers and polymers that are not digested and absorbed in the small intestine and are partially or completely fermented in the colon. The major components in plant tissues are cell wall polysaccharides, together with lignin where present. Wheat starchy endosperm cell walls comprise about 70% arabinoxylan (sometimes called pentosan) and 20% β-1,3–1,4-D-glucan (β-glucan), with small proportions of other polysaccharides (Figure 1). These components together account for 2%–3% of the dry weight of white flour, with other DF components (notably fructo-oligosaccharides and resistant starch) together accounting for a further 2%–3% dry weight. Hence, total DF accounts for about 5% of the dry weight of white flour.

Because AX forms half of the total DF in white flour, this fraction has been the major focus of research. A comparison of white flours from 150 wheat genotypes showed wide variation in total arabinoxylan (AX) content, from about 1.4% to 2.8% dry wt., with between a quarter and half of the total being soluble. Furthermore, about 70% of the variation in total AX and 60% of that in soluble AX could be ascribed to genotype, meaning that the variation should be amenable to exploitation by breeders.

The comparison of genotypes also identified two cultivars with unusually high contents of AX, the Chinese cultivar Yumai 34 and the French cultivar Valoris. We have, therefore, analysed a cross between these two cultivars and crosses between Yumai 34 and three other cultivars and identified two chromosome regions which control substantial proportions of the variation in total AX in flour; these are on chromosome 1B from Yumai 34 and on chromosome 6B from Valoris. We have also developed a molecular marker for the chromosome 1B region and validated this in high AX lines produced by conventional breeding. The use of the molecular marker circumvents the need for expensive low-throughput chemical screening and allows selection of high AX lines earlier within the breeding process (Figure 4).

Current work is focusing on identifying further genetic sources of increases in the contents of both AX and β-glucan, in order to combine them with the two chromosome regions discussed above (1B and 6B). The impacts of the increases in these DF components on human health will then be determined in collaboration with biomedical scientists.

Conclusions

The DFW programme is developing improved types of wheat for human health by decreasing the digestibility of starch and increasing the content of DF (Figure 4). These wheat lines also provide opportunities to explore effects on human health using intervention studies. However, their delivery into improved products requires the commitment of breeders, processors and retailers, as

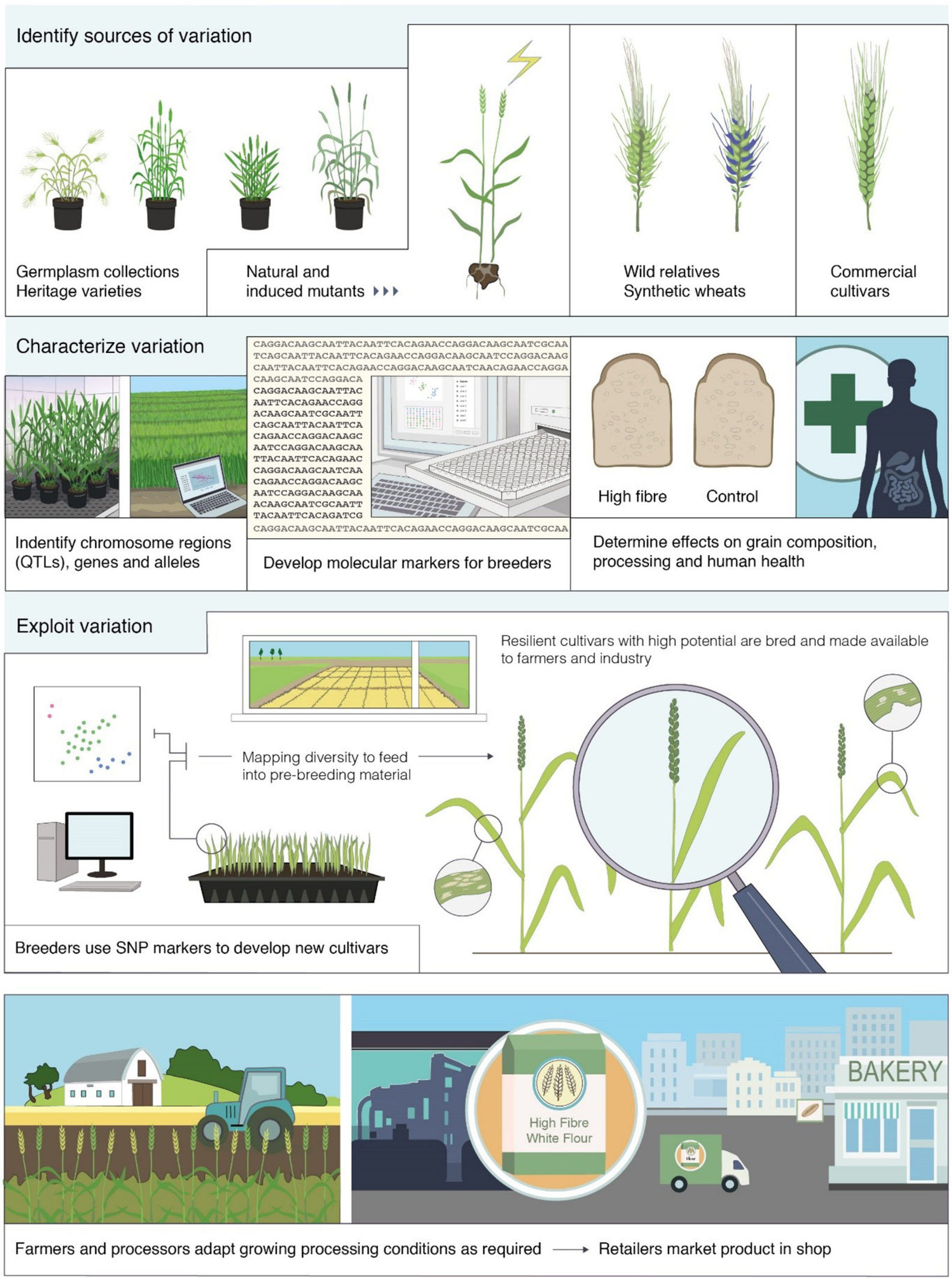

Figure 4. Increasing the content of fibre in white bread by identifying and exploiting genetic variation in collaboration with breeders and processors

well as demand from consumers. For this to occur, it is crucial that the 'improved' wheats should have consistent agronomic performance, good processing properties and high consumer acceptability without increased cost; the DFW programme is working to ensure that this is the case! ■

Further reading

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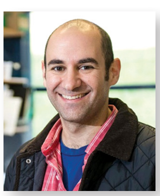
Brittany Hazard is a Career-track Group Leader at Quadram Institute Bioscience. Her research programme focuses on improving starch quality in wheat for human health and is a joint project between the Quadram Institute and the John Innes Centre. The research in her lab is interdisciplinary and spans across wheat genetics, food and health sciences. An ultimate aim is to develop novel wheat germplasm that can deliver resistant starch to consumers and to understand its impacts on health. Email: brittany.hazard@quadram.ac.uk

Alison Lovegrove is a Senior Research Scientist at Rothamsted Research. Her research focuses on wheat quality, exploiting cereal grains for improved human health and processing, specifically the content and composition of dietary fibre components. Her work contributes to the cross-institute strategic programme, Designing Future Wheat, exploiting natural and induced genetic variations in wheat to deliver novel wheat germplasm for use by plant breeders and processors. Email: alison.lovegrove@rothamsted.ac.uk



Cristobal Uauy is a Group Leader in wheat genetics and genomics at the John Innes Centre. His programme focuses on using genetics and genomics to improve both yield and quality components in wheat. His lab uses molecular genetic approaches to identify genes involved in wheat productivity traits and enhance the translation of this knowledge into improved varieties for industry and consumers. His lab also develops open-access tools and resources to enhance scientific discovery. Email: cristobal.uauy@jic.ac.uk

