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Our View, as Scientists, of the Grains We Grow and Use

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Abstract - Grain production worldwide (annually 3.5 billion tonnes) is equivalent to over one kilogram per person per day, accounting for over half of the energy and protein consumption in our food supply. In addition, grains provide animal feed, fuel, fibre, fats, brewed fluids and industrial uses. As consumers, we view the beneficial end-products from the bounty of grain. As scientists, we view the disciplines contributing to the many stages of the Grain Chain: breeding and genetics, agricultural production, and food technology, thereby providing expertise relevant to manipulation of each of the molecular stages-DNA (genome), mRNA (transcriptome), polypeptides (proteome), functional proteins (e.g., enzymes) and the range of molecules of general grain composition. Taxonomically, there are many grain species, offering a diversity of raw materials for processing to suit consumer needs. As scientists, we are working to adapt present and future grain species to provide improved nutritional benefits and decreased dietary intolerances (e.g., allergies and coeliac disease). The rising levels of atmospheric carbon dioxide have the potential to raise yields of grain due to 'carbon fertiliser', but the further consequences may include changes in the nutrient composition of grains. There is now promise for people with coeliac disease with the development of low-gluten wheat and barley, so that beers can be provided that are suitable for people that cannot tolerate 'normal' beers. New technologies, such as gene editing, offer new tools for plant breeders to innovate and provide us, as consumers, with new grain products.

Keywords: Taxonomy; Transcriptome; Proteome; Atmospheric CO_2; Gluten intolerance; Nutrition.

1. Introduction

The production of all agricultural grains worldwide totals three and a half billion tonnes (metric tons) per year! This enormous resource is equivalent to over a kilogram of grain per day for each person on earth, assuming a world population approaching eight billion. These statistics immediately pose the question: "Why is there any hunger on earth?" The answers lie in factors such as the diversity of uses of the grain; significant proportions of grain production are used for animal feed and for industrial purposes. In addition, the sites of production are often distant from many sites of need: transportation is a real cost added to the actual cost of the grain. Spoilage adds to the lack of grain in many situations.

Nevertheless, agricultural grains provide the basis of our food and, to a lesser extent, raw materials for industrial production. The grain-bearing plants provide **Fodder** and **Forage** for our animals; the mature grain is **Feed** for our farm animals-thereby contributing indirect **Food** sources for us all. Grains directly provide us with **Food**-over half of our energy and protein consumption. Industrially, grain species contribute **Fibre** (e.g., flax; cotton from cottonseed plants), **Fuel** (via oilseeds and the fermentation of grain starch), **Fats** (from oilseeds and cereal-grain germ); to complete the list of "**F**-words, grains are the raw material for many of our imbibed **Fluids** (considering grain-based beverages, such as beer and spirits).

We, as consumers, view the end-products from the bounty of the worldwide grain harvest, with little thought for the long route from "paddock to plate" ("paddock" is Australian for field).

We, as scientists, view the many stages of the Grain Chain (Fig. 1) progressing via breeding and genetics, through agricultural production, to the food technology that provides the great diversity of grain-based products.

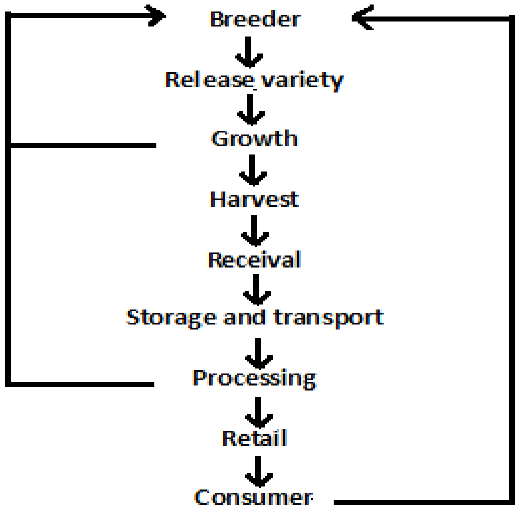

Figure 1. The physical Grain Chain is the pathway from seeds to harvested grain to foods to grain-based nutrition for the consumer. Stakeholders throughout the grain chain in turn provide feedback back up the grain chain. Reproduced from a lecture delivered in January, 2019, at Mahasarakham University, Thailand.

1. The taxonomic view. The many grain species

1.1. Monocots *versus* dicots

What are the grains that contribute to this annual harvest of over three billion tonnes of diverse grain types? All grain-bearing plants are flowering plants (Angiosperms). An example is a wheat flower. In the case of wheat, the pollination occurs generally within the flower (thus not 'out-crossing'). At anthesis (pollination), the outer glumes of the flower open wide. The feathery styles are ready to receive the pollen grains shed by the anthers. Maize (corn) is also a flowering plant, but in contrast to wheat, the equivalent functional parts are different from wheat in their anatomical locations (Fig. 2).

Taxonomically, we view the range of grain species as belonging to either one of two distinct taxonomic classes:

the monocotyledonous plants, including all the major agricultural cereals, are listed in (Table 1);

the dicotyledonous plants, especially the pulse and oilseed groups, are listed in (Table 2).

Monocotyledonous plants are often referred to as "monocots"; likewise, for "dicots". According to Morrison and Wrigley (2016):

"The terms monocot and dicot refer to the presence of one or two embryonic leaves (cotyledons) in the seed and young seedling. Other easily identifiable morphological traits differentiate between them. Monocots have flower parts in threes, parallel-veined leaves, scattered vascular bundles, and fibrous adventitious root system. Dicots have flower parts in fours or fives, net-veined leaves, vascular bundles located in a ring, and a primary tap root."

Maize stands out among the cereals (and all grains) as being the greatest in volume of production (Table 1). The common name for maize is 'corn' (especially in the Americas), but the word 'corn' is also used in Europe as a generic term for grain of any type. Missing from the list of cereals are the minor cereal crops of teff and coix (Arendt and Zannini, 2013; Wrigley et al., 2016). Out-of-place in this set of monocots (Table 1), are two dicots - the two pseudocereals, buckwheat and quinoa. Also missing is amaranth, another pseudocereal in minor agricultural production (Arendt and Zannini, 2013). The potential of pseudocereals has recently been emphasised by Schoenlechner and Bender (2020).

Global production of the dicot grains is much less than that of the cereal grains. Compare production totals for the monocot and dicot species, respectively 82% and 18% of total grain production in the year of 2018 (Tables 1 and 2). (Table 3) contrasts the different growth conditions of Thailand and Australia-either country suiting distinct grain species-rice and maize (corn) in Thailand *versus* wheat, sorghum and canola (rapeseed) in Australia.

The soybean is the dicot grain produced in greatest volume. Taxonomically, soy is a legume, but functionally it is an oilseed. The other oilseeds in (Table 2) are canola (rapeseed) and sunflower. Peas, beans and chickpeas are members of the legume family (*Leguminosae*, more recently named *Fabaceae*) and are also known as pulses. This classification name derives from the Latin words *puls* or *pultis* meaning "thick soup". Pulse crops are the seeds of legumes that are harvested as the dry seed in a pod. There has been renewed interest in the pulse-legume family of grains for their nutritional and health benefits (Havemeier and Slavin, 2020).

Figure 2. In contrast to wheat, the "flower" of maize (corn) is in two parts; the pollen-bearing tassels, at the top of the stalk, shed pollen which must fall on the 'silks' emerging from the outer end of the putative cob, halfway down the stalk. Adapted from Wrigley (2016).

(Table 1.) Grains from monocotyledonous plants (all are cereals, except the two pseudocereals-see footnote). They are listed by common and botanical names, in decreasing order of annual production, in thousands of tonnes (metric tons). See chapters relevant to specific grains and specific regions in Wrigley et al. (2016) for further information and comparisons of areas and yields of production.

Common name	**Genus and species**	**Annual Production (000 tonnes in 2018*)**
Maize (corn)	*Zea mays*	1,147,622
Rice (paddy), and wild rice	*Oryza sativa*, also *Zizania aquatica*	782,000
Wheat (bread and durum wheats)	*Triticum aestivum* and *Triticum durum*, respectively	734,045
Barley	*Hordeum vulgare*	141,423
Sorghum	*Sorghum bicolour*	59,342
Millets (Japanese, broom, pearl millet)	*Echinochloa esculentum, Panicum miliaceum, Pennisetum glaucum*	31,019
Oats	*Avena sativa*	23,051
Triticale	*xTriticosecale* sp.	12,803
Rye	*Secale cereale*	11,274
Buckwheat**	*Fagopyrum esculentum*	2,905
Quinoa**	*Chenopodium quinoa*	159
TOTAL		2,945,643

* 2018 statistics are the most recent available from http://www.fao.org/faostat/en/#data/QC
**Pseudocereals (dicots), but included with the true cereals in FAO statistics.

Table 2. Grains from dicotyledonous plants (pulses/legumes and oilseeds), listed by common and botanical name, in decreasing order of annual production, in thousands of tonnes (metric tons).

Common name	Genus and species	Annual Production (000 tonnes in 2018*)
Soybean	*Glycine max*	348,712
Canola, rape seed	*Brassica napus*	75,001
Cotton seed	*Gossypium* spp.	71,029
Sunflower	*Helianthus annuus*	51,955
Peanut (Groundnut)	*Arachis hypogaea*	45,951
Bean (dry, navy and broad bean)	Various species including: *Phaseolus vulgaris* and *Vicia faba*	30,434
Chickpea	*Cicer arietinum*	17,921
Pea (dry)	*Pisum sativum*	13,534
Linseed	*Linum usitatissimum*	3,183
Lupin (blue and white lupin)	*Lupinus angustifolius* and *Lupinus albus*	1,188
Safflower	*Carthamus tinctorius*	628
TOTAL		659,536

* 2018 statistics are the most recent available from http://www.fao.org/faostat/en/#data/QC

Table 3. Production volumes for common cereal grains grown in Thailand and Australia, according to a recent season's statistics.

Common name	Annual Production (in thousands of tonnes)	
	In Thailand	**In Australia**
Rice (as paddy)	33,383	807
Maize (corn)	4,962	436
Wheat (common & durum)	1	31,818
Rye	-	30
Sorghum	43	994
Soybean	54	65
Canola	-	4,313

1.2 Diversity and similarity of utilisation

What are the common uses of this diversity of grain species? Not all of the "**F-words**" of the Introduction can be applied to every one of the grains, but most provide **Fodder** and **Forage** for animals as growing plants (if "grazed off as young plants", as recommended for some cereals) and as plant residue and stubble, following grain harvesting. Virtually all grains enter into our foods, directly (e.g., rice and maize, as sweet corn) or indirectly (especially via the feeding of animals, fish and birds).

Some grain species have specific utilisation roles that cannot be filled by others. For example, common wheat (hexaploid, *T. aestivum*) alone provides the gluten-forming storage protein that can provide dough of sufficient cohesion for leavened-bread manufacture. The cereal buckwheat should not be confused with *Triticum* wheat.

1.3 Diversity and similarity of nomenclature

"The 'wheat' in buckwheat (*Fagopyrum esculentum*) and Indica wheat (*Amaranthus caudatus*) creates the false impression of a relationship with wheat (*Triticum* species) when in fact wheat and these two pseudocereal species are far apart from each other in evolutionary relationships, in biology and in grain attributes." (from Morrison and Wrigley, 2016). In these and many other cases, the use of botanical names for genus (e.g., *Fagopyrum*) and species (e.g., *esculentum*) clarifies possible confusion from the duplicated use of common names. See also the possible common-name confusion of "rice" and "wild rice".

Furthermore, taxonomic relationships are significant with respect to the utilisation properties of specific species. Of special mention is the storage protein of some cereal grains. When the endosperm (inner white material) of the crushed wheat grain is mixed with water, it forms into a cohesive dough. The viscoelastic properties of wheat dough (forming from the endosperm protein) are essential to the production of leavened bread. The gluten-forming properties of common wheat (*Triticum aestivum,* hexaploid-three genomes: A, B and D) are more effective for dough formation than is the endosperm protein of the tetraploid durum species (*Triticum durum*-two genomes: A and B).

On the other hand, rye is a near relative of wheat but its endosperm storage protein (secalin) makes only a weak dough on mixing with water. Rye bread, as bought from the baker, is often a blend of rye and wheat flours. The close taxonomic relationship between wheat and rye is indicated by the ability of these two genera to be crossed to form triticale-a wheat rye hybrid. The attempt thereby was to combine the survival ability of the rye plant with the bread-making ability of wheat, but triticale has only partly fulfilled the anticipated bread-making potential; commercially, triticale is mainly used for animal feed.

1.4 Diversity and similarity of dietary intolerances and inhalant allergies

Taxonomic relationships can also be helpful for us to understand dietary intolerances, as is evident with coeliac disease (CD, 'celiac' in US spelling). The gluten protein of wheat is the main cause of this condition (Koehler et al., 2016; Bekes et al., 2017), but to a lesser extent, the grain proteins of rye and triticale are causal for coeliac disease; the more distantly related oats is occasionally considered as being causal, but quite 'safe' are more distant relatives such as rice and maize.

The diversity of allergy/intolerance reactions also arises from the different sources of allergen in the plant-grain ingestion *versus* flour or pollen inhalation. Taxonomic relationships are also useful in predicting allergic reactions to the inhalation of pollens from plants broadly, but intolerances to pollens may not relate to ingestion intolerances (Tatham, 2016). Cross reactivities among pollens from different species may be relevant to the diagnosis of inhalant allergies, especially when 'skin-prick testing' with the pollen extract of one species is used to assess the immunological (IgE) reaction and clinical allergy to a taxonomically different source of pollen (Watson and Wrigley, 1984).

An extreme use of taxonomy has been the evaluation of distantly related grain species as possible 'safe' replacements for wheat in the diets of people with wheat intolerances (Bekes et al., 2017). Such grains considered have been einkorn (a diploid ancestral wheat, A genome), emmer wheat (a tetraploid ancestral wheat, A and B genomes) and spelt wheat (a hexaploid ancestral wheat, A, B and D genomes). However, all these ancient wheats could hardly be considered to be 'gluten-free', and thus not suitable for people with coeliac disease. In contrast, there are alternative non-cereal grains that could be considered as 'gluten-free', including the pseudocereals (Bekes et al., 2017; Geisslitz and Scherf, 2020).

For non-coeliac people, spelt has provided some potential: "There has been anecdotal clinical evidence for a long time that a large proportion of non-CD patients suffering from wheat-related health disorders can tolerate products made from certain spelt varieties." (From Bekes et al., 2017; see citation provided to Armentia et al. (2012).)

2. The production view. From paddock to plate

2.1 Relationships up and down the Grain Chain

The Grain Chain (Fig. 1) is the pathway from seeds to harvested grain to foods to grain-based nutrition for the consumer (Wrigley, 2016). In addition to the sequence of downward pointing arrows in (Fig. 1), there are feed-back arrows, indicating that stakeholders, such as the grain grower, are likely to tell the breeder about the degree of satisfaction (or otherwise) about the agronomy, yield and quality of the breeder's latest variety; whereas, the processer has a vested interest in the milling and baking quality of the breeder's latest variety, feeding that information back to the geneticists and breeders responsible. Feedback from all stakeholders throughout the Grain Chain is continuously being provided to each of those responsible at the earlier stages. In addition, all these stakeholders rely on researchers who are backing up the active players with research findings to improve the expertise and efficiency of the stages.

The ultimate opinion of 'accept or not' comes from the consumer, who has the power to buy this or that type of grain-based product, and this or that brand name. If there is a major shift in consumer buying, the effect is felt right up through the Grain Chain. Thus, the Grain Chain might better be seen as a circle, indicating the feedback involved as shown in (Wrigley, 2016).

Even before the seed producer (Fig. 1), there is the input of the geneticist to the plant breeder, who also collaborates with the cereal chemist, whose responsibility it is to evaluate the suitability of grain samples of putative varieties for the intended product. For wheat, the possible products include foods such as bread, noodles, pasta, pastry or cakes; or industrial products such as animal feeds, bioethanol, adhesives, or starch-gluten fractionation (Wrigley, 2016).

2.2 Value addition

The Grain Chain also illustrates the principle of Value Addition during progression down the series of arrows in (Fig. 1). For example, there would be a one hundred-fold multiplication in value when a "handful" of wheat grain is milled to flour, for use in making an item of pastry for sale in a patisserie. This route from farm gate to retail sale might involve long distances in cases where the wheat has been grown in an agricultural site very far from the pastry shop. It is also possible that the pastry item has been manufactured in a country very far from the retail outlet. The principle of value addition permits such long-range transactions (in space and time) to be economically feasible.

In contrast, this whole sequence of events may occur in the situation of subsistence farming in a village setting. The farmer takes grain to the village mill and returns home with the flour that is used in the home for baking. Despite the shorter distance and time factors in this case, value is added for the family who grew and consumed the grain.

2.3 Broader awareness of related disciplines needed

When this lecture was delivered to the audience of research students at Mahasarakham University (January, 2019), they were encouraged to see their specific project in the wider framework of the supply chain, for any situation of agri-food research. Although wheat-related products were the example given, the principles are relevant to a wide range of grain species and situations.

This broader attitude is needed because it is irrelevant to study a food product, for example, without being aware of its agricultural origins and the processing that leads to the final product. These stages are described by Wrigley (2016) for several agri-food situations. Also, there is the need to be aware of similar agri-food products that may compete with the item at the focus of the student's project. Broader awareness may involve looking back up the chain to understand relevant aspects of nutrition, processing, agronomy, harvesting, breeding and genetics.

3. The molecular view. It's all about G x E x P

In addition to the concept of the grain-based products that we eat and use, resulting from the physical grain chain, there is a parallel sequence viewed by us as scientists (Fig. 3); this molecular grain chain has chemical compounds substituted for physical functions. The eventual quality of grain-based foods can be tracked all the way back to the breeder (the genes in the variety, also called the genotype, **G**) and subsequently to the grower (the conditions of growth and storage environments, **E**). A third factor is the processing (**P**) stage at which the conditions of milling or mixing or baking (etc.) make their specific contributions to the quality of the consumer products.

3.1 Biochemical factors determining quality in grain-based products

As scientists, we need to understand the biochemistry and genetics underlying the pathway from **G**enes to grain-based products, plus the ways in which this pathway is modified by the **E**nvironmental and **P**rocessing conditions. Thus, there are potentially complex interactions of genotype with environment and processing or **G x E x P**. The chemistry would involve categories such as DNA, RNA, proteins, enzymes, starch, pentosans and lipids. The environmental factors would include climate, soil nutrients, soil moisture, insect and fungal attacks, plus (for now and into the future) the level of carbon dioxide in the atmosphere. Skilled manipulation of processing may permit compensation for deficiencies following the G and E stages; conversely, poor processing may well turn good-quality grain into poor product.

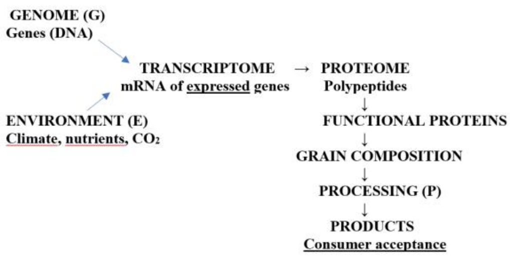

Figure 3. The molecular grain chain, showing the several chemical transformations that occur between the interaction of genes with growth environment and processing conditions, thus determining the quality of the ultimate consumer products. Reproduced from a lecture delivered in January, 2019, at Mahasarakham University, Thailand.

3.2 The molecular stages of gene to quality attribute

The 'genome' represents the full complement of DNA (the 'genes'). It is thus possibly the most significant determinant of agronomic factors and of ultimate product quality. The breeder selects potential parent lines according to knowledge of their desirable genes. However, in the case of wheat, the identification and subsequent selection of specific genes is especially difficult, given wheat's very large genome ('repository' of genes) (Fig. 4), compared to other plant genomes. Its large size is largely due to the hexaploid nature of common wheat, comprising sub-genomes A, B and D.

The 'transcriptome' (mRNA) is the first opportunity for the breeder to determine which genes are active in a specific genotype (e.g., breeder's line), because the transcriptome represents those genes that have actually been active under the environmental conditions, as indicated in (Fig. 3). Transcript searching is thus a valuable exercise, showing the actual genes that 'matter' for the specific G x E situation. This analysis is the first indication of which genes are being expressed plus indications of how much of each gene might be expected to be expressed under the existing conditions.

Thereafter, the 'proteome' is the summation of the polypeptides corresponding to the RNA transcripts. Either these transcripts or the polypeptides may be targets for breeder research and subsequent selection ('marker-assisted selection') to the extent that the function of these transcripts or polypeptides is understood. Research focused on the transcriptome has the advantage of dismissing the possible roles of inactive genes if correlation studies were directed towards the whole genome, many of the genes being inactive and thus irrelevant. Furthermore, analysis of the transcripts is the first opportunity of examining the effects of the growth environment on grain composition and thus on potential grain quality.

'Functional proteins' (e.g., enzymes and storage proteins) are next produced by the folding of the polypeptide chains and the formation of intra- and inter-chain disulphide bonds. Next, the functional proteins are active in the synthesis of the grain components-starch, cell walls and lipids.

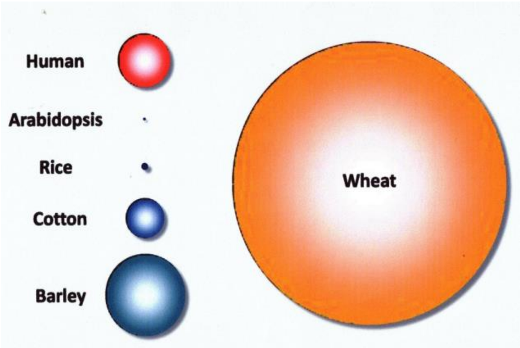

Figure 4. The respective sizes of the genomes of some plant species, compared to the human genome. The illustration was kindly supplied by Dr Colin Cavanagh, CSIRO Plant Industry, Canberra, Australia.

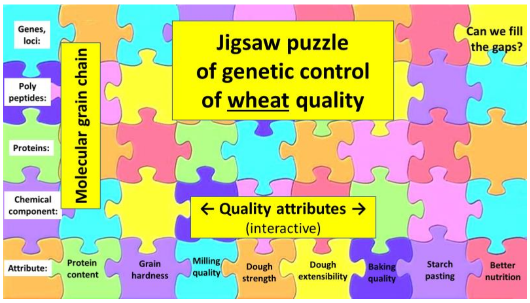

Figure 5. The interactions of the molecular grain chain with the quality attributes of wheat, illustrated (to the extent of our knowledge) in the form of a jigsaw puzzle. A more complete version is shown by Henry and Wrigley (2018).

The interaction of specific genes and related quality attributes can be viewed as a jigsaw puzzle. Across the bottom are the grain-quality attributes. In the case of wheat (X axis in (Fig. 5), these include protein content, grain hardness, milling quality, dough properties, etc. The gene(s) primarily responsible for each of these attributes are progressively being identified, as are also the corresponding polypeptides and active proteins through which the genes operate. In some cases, there is also a non-protein component involved.

This sequence is well established for dough properties in wheat, involving several groups of genes (*Gli-1* and *Gli-6; Glu-1* and *Glu3*) which in turn are responsible for the synthesis of gliadin and glutenin polypeptides. Thereafter, the folding and disulphide linkages of the glutenin polypeptides are critical for dough strength. Has our knowledge of genetic control advanced to the stage that all of these gaps can be filled? Many can be completed, as shown by (Henry and Wrigley, 2018).

4. The global view. CO_2-we can't do without it

4.1 A CO_2 story from 1662-long ago

Carbon dioxide? CO_2? Let's start with a story from the 16th century, as told for school students (Ball, 1999; Baptist van Helmont, 1662; Wrigley, 2012):

Johann Baptist van Helmont (born in Brussels in 1577) performed a plant experiment to challenge the long-held Aristotelian view of there being only four elements: water, earth, fire and air (presumably in addition to the chemical elements that they then recognised-sulphur, mercury, gold, silver and not much more).

Johann ('Jono Van') filled a pot with 200 pounds of dry earth, in which he planted a young willow tree (Fig. 6). For five years, Johann watered the pot, taking care that nothing but water was added to the pot as the tree grew. At the end of this period, Johann removed the tree. It weighed 164 pounds-an enormous increase in weight. He also dried and weighed the remaining soil, finding that it weighed only a few ounces less than it did five years earlier. Johann concluded that the tree's weight gain 'arose out of water only'. Thus 'wood is made of water' (wood, meaning the main material of the tree). From our position of knowledge a few centuries later, we may laugh at Johann's conclusion, but what did happen? We need to know, as scientists!

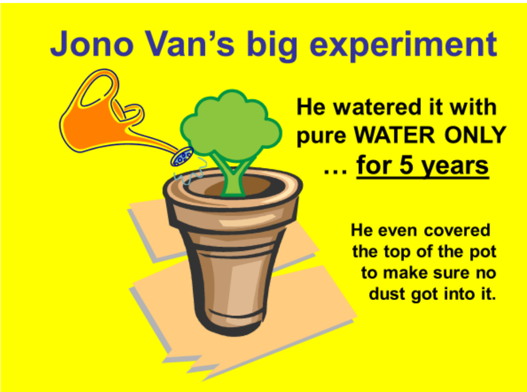

Figure 6. In the 16th century, Baptist van Helmont performed an experiment, designed to determine what a tree is made of. He watered the tree each day for five years. He concluded that the wood of the tree is made from water.

4.2 CO_2 and photosynthesis-essential to life on earth

What was really happening in Johann's experiment? The tree grew because of photosynthesis due to the assimilation of CO_2 from the air, taking energy from the sun. Obviously, Johann had no conception at that time of the principle of photosynthesis. In designing the experiment with proper control over the inputs, Johann's experiment should also have excluded air (containing carbon dioxide) and light. Both these critical factors were neglected in his planning, so he could not reach a valid conclusion.

Today, CO_2 is maligned as a cause of climate change and rising global temperatures, creating a fuzzy concept that CO_2 is bad in itself. However, Johann's story corrects any such misconceptions; in fact, CO_2 is essential to life on earth. Together with water and light energy, CO_2 is the basis of plant life, including the grains that are the topic of this review, according to the formula:

$$CO_2 + H_2O + \text{light} \rightarrow O_2 + \text{carbohydrates } (CH_2O)_n$$

The resulting sugars and carbohydrates are subsequently used for the synthesis of lignin, cellulose and other components of plant material, thus forming the material of grains and all other plant life-trees, leaves, flowers, vegetables and fruit.

Johann was a third right: water is one of the three factors needed for making 'wood'/plant material. To be fair to Johann, it is a big leap of faith to consider that his tree could have been made from air-actually, a very minor component of air. To illustrate this necessary 'leap of faith', consider what volume of air is required to provide for the carbon in just one of the grains that we have been considering.

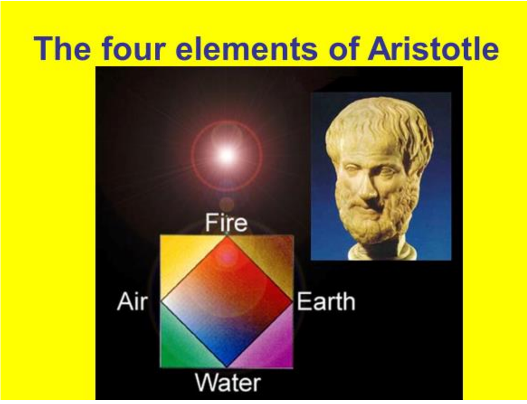

Figure 7. The Aristotelian view in the 16th century was that there are four elements: water, earth, fire and air.

Presumably, Johann's held to the Aristotelian view of his time that there are four elements: water, earth, fire and air (Fig. 7). From the advantage of a few more centuries of science, we can look again at these four elements and see that Johann's experiment illustrated a degree of truth for this axiom:

• **water**: Johann provided a five-year supply of water for his tree experiment.

• **earth**: Johann was meticulous in drying and weighing the soil in his pot, before and after the five-year experiment.

• **fire**: Johann could not have realised the overwhelming importance of sunlight (the fire in the sky) for the growth of his tree.

• **air**: Johann, again, could not have realised the overwhelming importance of carbon from the air-carbon (that black sooty stuff) floating in the air as CO_2!

4.3 CO_2 as a carbon fertiliser

The suggested exercise above (what volume of air …?) indicates that the level of CO_2 available in the air is likely to be a limiting factor in the growth of plants and also in the yield of grain generally in agriculture. That has been found to be true in experiments involving plant growth in synthetic atmospheres with enhanced levels of CO_2, which is acting as a (free) fertiliser. Or does the extra CO_2 come at a price?

A 2018 issue of Scientific American has a lead article (Sneed, 2018) entitled "Ask the Experts: Does Rising CO_2 Benefit Plants?" The article includes the following quotes:

"A higher concentration of carbon dioxide in our atmosphere would aid photosynthesis, which in turn contributes to increased plant growth."

"This correlates to a greater volume of food production and better quality food."

The article goes on to point out that the issue of rising levels of CO_2 is not so simplistic: "Climate change's negative effects on plants will likely outweigh any gains from elevated atmospheric carbon dioxide levels."

In an article entitled "A shifting climate for grains and flour", Ross (2019) has written about "the threat to the global food supply and the negative effects of rising atmospheric CO_2 levels and global heating on the nutrient composition of grains. … We are faced with the task of ensuring basic crop health and survival in the shadow of a world that is growing hotter with increasing atmospheric CO_2 levels. For temperate cereal crops, there is also the spectre of the possible drying out of the midlatitude regions where wheat, for example, grows best. … Higher atmospheric CO_2 concentrations have been associated with increased wheat yields, while heat waves have been reported to decrease yields. Despite an increase in protein content under acute heat stress, increased atmospheric CO_2 levels have regularly been associated with decreased protein and mineral contents in plants generally, and decreases in nitrogen-containing vitamins in rice specifically." [Please go to the original article for references to primary citations.]

5. A view into the future

5.1 Gene editing and dietary improvements

Viewing our future, do we foresee "higher atmospheric CO_2 concentrations" and "acute heat stress" of our grain crops, with dire consequences for grain production and quality? These and other possible disasters are part of our view of the future. Scientists and breeders also have views with promises to turn such problems into advantages.

It is heartening to read articles with titles such as: "Genomics and Gene-Editing Technologies Accelerating Grain Product Innovation." In this article, (Henry, 2020) states: "Genomics technologies are advancing rapidly, expanding our ability to edit plant genes. Improvements in DNA sequencing technology complement these technologies and are providing new opportunities to improve grain quality and develop new traits."

We, as consumers, "will be more likely to notice the availability of grain products with new quality attributes." We, as scientists, look forward to "gene-editing technology [delivering] a powerful new tool for plant breeding and grain product innovation. The technology has been widely applied to rice due to the extensive genomic resources and transformation systems available for this grain" (Henry, 2020). As examples, rice-quality genes that have been modified by using gene editing include shelf life, fragrance, amylose content, grain size and yield. Traits relevant to wheat and accessible via specific genes include grain size, grain hardness, flour yield (in milling) and loaf volume (in bread making) (Henry, 2020).

(Newberry et al., 2018) have also studied amylose content, as reported in an article entitled "High-amylose wheat foods: a new opportunity to meet dietary fibre targets for health". The resulting wheats showed significantly more "resistant starch" in various wheat-based products thus offering dietary benefits with respect to glycaemic index and digestive health.

5.2 Gluten intolerance

Recent research offers good news for people with coeliac condition and other forms of intolerance to wheat gluten protein. One approach has been to "silence" (switch off) genes for the synthesis of alpha-gliadin-an important part (for intolerance) of the gluten-forming part of endosperm grain protein (Altenbach et al., 2020). Gluten-reduction strategies in wheat, barley and rye are also leading to cereal-based beverages, especially beers, that are suitable for people who would not otherwise be able to tolerate conventionally made beverages (Howitt et al., 2018).

5.3 New and different agricultural grains

Annual canary seed is an example of a new whole-grain cereal that is offered by Patterson et al. (2018). Being glabrous (with a hairless hull), this canary seed is claimed as a new cereal for consumption as a whole grain.

New benefits to consumers are coming from innovations in grain types, even for traditional species, such as the cereals and pulses, as described in several articles in a recent issue of Cereal Foods World (Malcolmson and Sissons, 2018). One of the approaches described is the introduction of anthocyanins, which act as antioxidants, reputedly to scavenge free radicals. As a result, grains are appearing that are red, blue or purple, due to pigmentation of the pericarp or aleurone (Grausgruber et al., 2018; Gamel et al., 2020).

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