WHEAT AND OTHER CEREAL GRAINS

1. Introduction

The various cereal grains (Table 1) make a major contribution to the food needs of humanity. These grains reach dinner tables in a wide variety of processed forms, although many of these foods may not be readily recognizable as being of grain origin. Most obvious among the cereal-based foods are breads, cookies, cakes, pasta, noodles, breakfast cereals, porridge, atta, bulgar and cous-cous, muesli, boiled and fried rice, corn-on-the-cob, polenta, semolina and tortilla. Less obvious are the many beverages derived from cereals, such as beer and liquers, plus soft drinks containing sweeteners derived from the starch of cereal grains. Grain-based foods are recommended for the many health-promoting advantages that they offer when incorporated appropriately in one's diet (1).

Cereal grains are also incorporated in a wide diversity of processed foods, including many canned foods, soups, confectionary, licorice, processed meats, malt vinegar, and seafood analogs. It is also likely that the meat dishes have their origins in the feeding of grain, and even fish may have been fed on grain-based feeds in aquaculture. Cereals also impact lives via their many industrial uses, such as the separation of wheat starch from gluten, the production of

Table 1. **World Production and International Trade ($\times 10^6$ t) for Grain Commodities Produced in more than 1×10^6 t**[a]

Grain species			
Common name	Botanical name	Annual production, in 2005	Annual trade, in 2002
	Grains from Monocotyledonous Plants		
Cereals			
barley	*Hordeum vulgare*	138.3	17.9
maize (corn)	*Zea mays*	692.0	79.1
millet (Japanese, broom, pearl millet)	various species including *Echinochloa esculentum, Panicum miliaceum, Pennisetum glaucum*	27.3	0.1
oats	*Avena sativa*	24.6	2.0
rice, also wild rice	*Oryza sativa*, also *Zizania aquatica*	614.7 (as paddy)	28.0 (paddy)
rye	*Secale cereale*	15.0	1.5
sorghum	*Sorghum bicolour*	57.0	6.0
triticale	*xTriticosecale* sp.	13.5	0
wheat (bread and durum wheats)	*Triticum aestivum* and *Triticum durum*	626.5	99.6
	Grains from Dicotyledonous Plants		
Pulses and oilseeds			
bean (dry, navy and broad bean)	various species including *Phaseolus vulgaris* and *Vicia faba*	19.2	
buckwheat	*Fagopyrum esculentum*	2.7	
canola, rape seed	*Brassica napus*	46.4	
chickpea	*Cicer arietinum*	9.1	
cotton seed	*Gossypium* spp.	66.7	
linseed	*Linum usitatissimum*	2.7	
lupin (blue and white lupin)	*Lupinus angustifolius* and *Lupinus albus*	1.1	
pea (dry)	*Pisum sativum*	11.3	
peanut	*Arachis hypogaea*	36.5	
safflower	*Carthamus tinctorius*	0.8	
soybean	*Glycine max*	209.5	
sunflower	*Helianthus annuus*	30.7	

[a]From www.fao.org.

fuel alcohol, and the manufacture of grain-based syrups, adhesives, thickening agents, and feed materials for pets, fish and agricultural animals (2,3).

The cereals can be defined as "flowering plants of the Grass Family (Poaceae or Gramineae), whose seeds are used as food". Of the more common ones listed in Table 1, wheat, corn and rice are grown to the greatest extent. Reliance on the cereals, on wheat and on the resulting foods is indicated by the many ways in which they enter in people's culture and vocabulary. These foods have even become symbols of social interaction. As examples, "Give us this day our daily bread", "Man shall not live by bread alone", and "Cast thy

Fig. 1. Polish celebration of the grain harvest (*dozynki*) traditionally involves making wreaths and ornamental structures made of cereal stalks, wheat and flowers. These emblems are paraded through the village. From http://e.powiatbrzeski.pl/galeria/dozynki2005/.

bread upon the waters" are everyday expressions in English derived from the bible. There are equivalent expressions in other languages, cultures, and religions.

Bread ("*chleb*") is a sacred item in the lives of Polish and Russian people. In these cultures, the end of the grain harvest is traditionally a great occasion for celebration (*dozynki*). Villagers, in colorful folk costumes, sing and play instruments for the lord and lady of the manor to celebrate the completion of harvest. Wreaths made of corn, wheat and a variety of flowers (Fig. 1) and a loaf of bread, baked from the freshly harvested wheat, is presented to the lord and lady of the manor, who, in turn, give a slice to each worker who has made the harvest possible. In this culture, an honored guest is welcomed by the presentation of a loaf of bread, well presented on a platter with a lace cloth.

In Iran, bread (Persian "*nan*") is often taken as a gift when visiting friends. In this case, the bread should be a sweet type, probably with cream or frosting. Bread also has a central role in an Iranian wedding ceremony, with a loaf of bread being placed on the table in front of the married couple. Bread is central to the Jewish Passover celebration; in this case, the bread must be unleavened, as a reminder of the Israelites' hurried departure from slavery in Egypt, when there was no time to leave the bread to rise overnight.

An ear of wheat has been adopted as the symbol of the FAO (the Food and Agriculture Organization of the United Nation). Below the wheat ear is the Latin inscription, *Fiat panis* ("Let there be bread") (Fig. 2). The icon of a stylized wheat head has also been used in the logo of many companies and organizations that are involved with the production and processing of wheat.

Fig. 2. The FAO logo.

2. Origins of the Cereal Grains

The word "cereal" derives from the name of the Roman goddess, Ceres, in whose honor a spring festival, the Cerealis, was celebrated in Roman times. Much earlier, the ancient Egyptians attributed wheat to their god Osiris (4). The Greek god, Demeter, may have been adopted by the Romans and renamed Ceres. Demeter is depicted in Figure 3 with awned wheat heads and stalks forming her head-dress, a sheaf of wheat in her arm and more wheat stalks in the basket at her feet. This illustration was drawn from a painting found in Pompeii (4).

Fig. 3. The Greek god of wheat, Demeter (4).

These origins indicate the antiquity of cereals as everyday foods. They have long been recognized and revered, and have played an important role in the diets of ancient peoples. Cereals have continued to be an important dietary ingredient throughout human history. As the world population continues to grow, cereals will become an increasing fraction of the diets for more and more people, not only the major three (wheat, corn, and rice), but also some of the species that are not now cultivated to a great extent. The great advantage of the grains as a food source has always been their ability to be stored for long periods, without significant loss of quality provided the conditions of storage are dry and free of vermin.

Early cultivation of cereal grains relates to the "Fertile Crescent", which extends from Egypt through Syria to the Tigris–Euphrates Valley (5). The likely progenitors of modern hexaploid (bread) wheats have been found in this region; they are the diploid einkorn wheats (*Triticum boeoticum* and *T. monococcum*) and the tetraploid emmer wheats (*T. dicoccoides* and *T. dicoccum*). These wild grains still grow in the area extending eastward from Asia Minor to Iran and Afghanistan. Hexaploid bread wheats first appeared over 10,000 years ago in these regions as a result of natural hybridizations between such tetraploid wheats and the diploid species *T. tauschii* (also called *Aegilops tauschii*) (6).

Rice may have originated in Africa or Asia but probably was first cultivated somewhere between the southern People's Republic of China and southern Vietnam (7). In contrast, corn (maize) originated in the Western Hemisphere, the Spanish conquistadors coming in contact with corn during their early explorations of Central and South America (7). Corn probably originated in the lowlands of South America, in Mexico or in Guatemala (8). By the time Columbus made his first voyage of exploration, corn as a food crop had spread over much of the Americas as well as to the West Indies (8). By 1492, the Indians had developed corn culture to such a high state that it is thought to have then ranked highest among cereals in efficiency of food production (8).

The origin of rye is more difficult to ascertain. There appears to be no reference to it prior to the Christian era. It is still a principal ingredient in the diet of some peoples in northern Europe as it was in Britain until the late eighteenth century (5). Since barley grows wild in the Syria–Palestine area, it is likely to have originated there (5). Millet may have originated in the Sudan, where pearl millet is still widely cultivated (7).

3. The Cereal Grains in History

Cereals were among the earliest plants cultivated. They were related to some of the wild grasses indigenous to those parts of the world where civilizations had their origins. All of them are ideally suited for use as food under both primitive and advanced conditions. The outstanding value of grains as a food source is that they can be stored for long periods, thereby providing a reserve against food shortages. A record of this advantage is provided by the biblical account of Joseph, in ancient Egypt, advising the Pharaoh to store grain during the seven "plenteous" years to be used in the following seven "lean" years.

In addition, cereals are nutritious foods that can be used in many ways, thus facilitating their incorporation in the diet at high levels over long periods of time. Even today, there are some areas, such as rural Iran, where wheat products, especially in the form of the flat breads indigenous to that region, provide as much as 70–90% of the daily caloric intake. Most of the cereals also respond well to primitive methods of agriculture with good yields. More recently, with advanced technology and improved varieties, large yields per worker can be secured. Much more food is secured from fields planted in grains than can be obtained from cattle or other animals on the same land.

The importance of grains as an efficient form of food production became evident during World War I. In the early stages of the war, the German High Command made a conscious decision to continue the prewar levels of meat, milk, and egg production to provide adequate nutrition for the men in the armed services, as well as for the civilians who would be called on for arduous work in connection with the war. Had they decided instead on conversion of meadows and pastures to wheat fields and the direct consumption of the grain by human beings, the yield of food for the German people would have been far greater than it was when the land was given over to raising cattle, pigs, sheep, and poultry.

This observation led a group of Scottish physicians to suggest that this mistake probably did more than any army general to lose the war for the Germans under Kaiser Wilhelm II (9,10). Wheat production became such an important issue in World War I that posters appeared, such as Figure 4, encouraging the eating of less wheat, so that it would be available for the war effort. Following the war, an embroidered flour bag (Fig. 5) was returned from Belgium to a Minneapolis flour milling company, giving thanks for the supply of flour during their hard times.

4. Grain Species

Cereals grow in a wide variety of climatic and soil conditions, and they successfully compete with weeds for the limited amounts of nutrients and water where these plant factors are in short supply. This is an important reason why cereals have played, and continue to play, such an important role in the development of the human race.

Colloquially, the word cereal is in everyday use to describe ready-to-eat breakfast foods, such as corn flakes. Breakfast cereals are mainly manufactured from various cereal grains, but the term cereal basically refers to a botanical family of species in the grass family (Poaceae of Gramineae), whose seeds are used for human food and animal feed. The cereals belong to the monocotyledonous ("monocot") taxonomic group (Table 1). Other food grains, such as oilseeds, pulses and soybeans, are dicotyledonous belonging to the second major class of grain crops ("dicots"). These terms (monocots and dicots) refer to the presence of one or two embryonic leaves (cotyledons) in the seed and young seedling. The soybean is the most significant of the dicot grains in terms of volume of production. The range of commercially grown grain species extends beyond those listed in Table 1, which is restricted to species produced in excess of a million

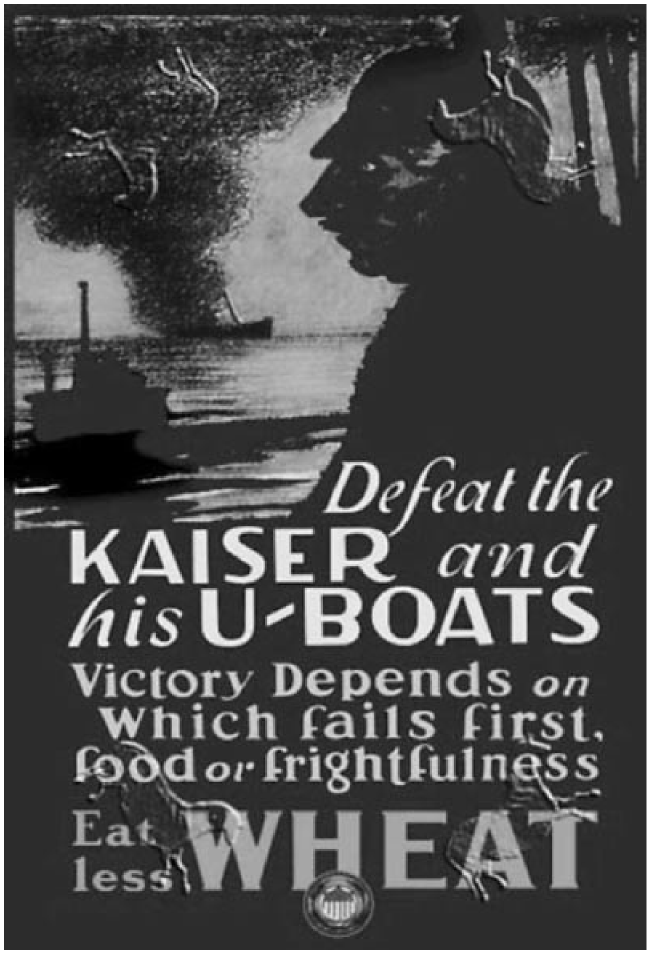

Fig. 4. A poster from World War I encouraging the eating of less wheat, so that it would be available for the war effort. Original photo taken by Luc De Bry, and reproduced with his permission from Ref. 10.

tons in 2005. Other grains of significance include amaranth, lentils, coix, sesame, quinoa, mustard, and various other species of wheat, barley, millet, pea and bean. Many of these are reviewed by Graybosch (11) and by Adel-Aal and Wood (12).

5. Production and Trade

Annual production, worldwide, of all the grains listed in Table 1 exceeds 2.5 billion tons; most of this production involves the cereal crops (about 2.2 billion tons). Wheat, rice and maize (corn) are the most important cereal species with respect to volume of production (about two billion tons), so they deserve special prominence in this review of the cereal species. Nevertheless, many other cereal species are of economic importance. It should be realized that the production and

Fig. 5. Embroidered flour bag thanking a Minneapolis flour milling company for the supply of flour during World War I. Original photo taken by Luc De Bry, and reproduced with his permission from Ref. 10.

trade figures of Table 1 provide a single year's "snapshot" of these parameters. Significant fluctuations from year to year are likely to alter these statistics.

Consideration of the volumes of grain that enter world trade indicates that the bulk of some species is consumed within the country of production, with little being exported. Such grains include millet, oats, sorghum, rye and triticale. In some of these cases, the grain species is mainly used for subsistence farming, eg, sorghum and millet (13). In other cases, much of production may be used on-farm or nearby for animal feeding, eg, sorghum and triticale. Although the volumes of rice and barley that enter world trade are large, they are much less than their respective production volumes, since they are produced in regions where they are consumed locally.

Production methods for the cereal grains vary around the world, ranging from traditional farming methods in some developing countries to sophisticated approaches such as "precision agriculture" in highly developed farming systems (14). Precision agriculture involves the mapping of grain yield, possibly down to differences from one square meter to the next, so that poorly performing regions of the field can be identified, and remedial treatments can be applied, such as changing the sowing or fertilizer applications, or improving drainage if waterlogging is shown to cause poor yields.

The volumes given in Table 1 for rice indicate the amounts equivalent to "paddy rice" or "rough rice", that is, the grain as it is harvested with the outer protective covering of hulls or husks. The inedible hulls represent about 20% of the mass of paddy, so the production and trade figures in Table 1 need to be reduced accordingly to indicate the amounts of de-hulled rice (also known as "cargo" or brown rice). Brown rice still has the pericarp adhering, so further processing (polishing or milling) is needed to produce the familiar white rice product.

Wheat is the major grain traded internationally, both in volume and in considerations of quality type. Wheat is unique in being the only grain with gluten proteins capable of forming the elastic dough needed to bake leavened bread. The corresponding proteins of cereal rye and triticale provide a weak dough, but they lack the rheological properties of wheat, and bread made from rye is often combined with wheat flour or vital wheat gluten to bolster dough quality, thus to achieve good bread quality.

6. Grain Composition and Morphology

The cereal grasses have narrow leaves, hollow jointed stems, and spikes or clusters of membranous flowers. Figure 6 shows the flower of part of a head of wheat.

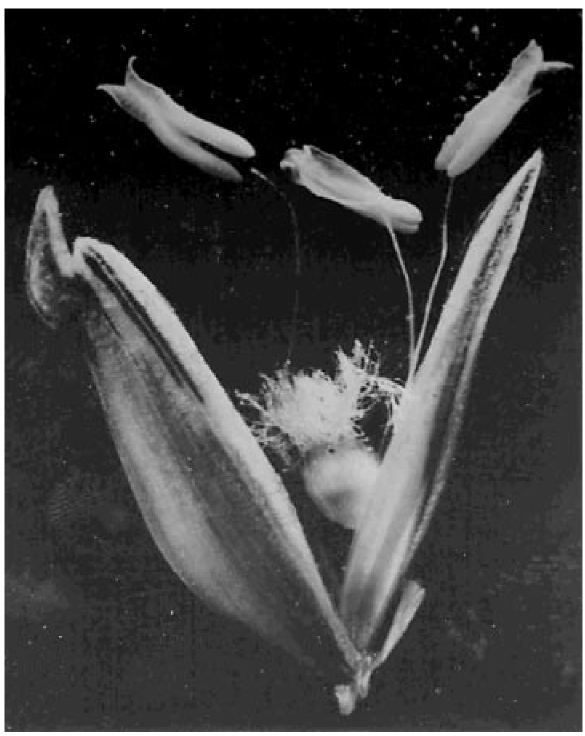

Fig. 6. The flower of wheat, open at the time of anthesis.

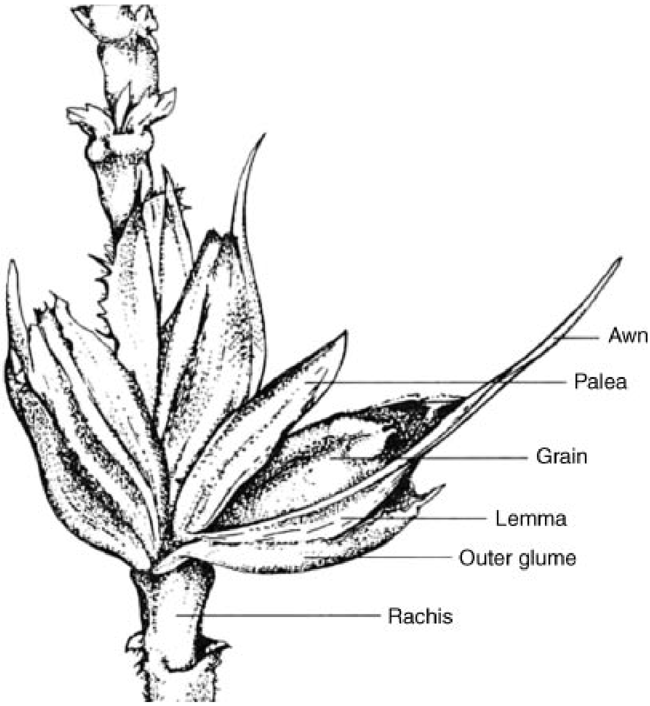

Fig. 7. The wheat grain is released at harvest from the surrounding outer glumes (the palea and lemma). Reproduced from Ref. 16 with permission from CSIRO.

At the flowering stage (anthesis), the anthers are extended, and they have dropped pollen onto the hair-like structures of the stigma at the center of the flower. Wheat is generally self-fertilizing, but this is not so for other members of the cereal family. For example, maize pollen falls from the tassle at the top of the plant onto the silks extended from the tip of the structure that will become the corn cob (15).

The mature wheat grain is surrounded in the head by husks (glumes). As shown in Figure 7, the outer glumes are called the palea and the lemma (16). Wheat is free threshing, so that the kariopsis is released free of the glumes when it is harvest-ripe. In general, the barley grain is harvested with these glumes attached, although there are some barley genotypes that are free threshing (17). Rice too is harvested with the hulls adhering, and processing is needed to reveal the kariopsis (18).

6.1. Starch. The bulk of the cereal grain is made up of the "floury" endosperm, which is enclosed by the outer bran layers; the aleurone layer surrounds the endosperm and the pericarp layers provide the external covering (Fig. 8). The scanning electron micrograph of a broken wheat grain in Figure 9 shows that the starch is contained in distinct granules, embedded in a matrix of storage protein. The endosperm is made up of a series of cells, the walls of which are mainly cellulose, being clearly seen in Figure 9.

In the wheat grain, the starch granules have a bimodal size distribution, the 'A' granules being over about 15 μm in diameter (up to about 30 μm), and

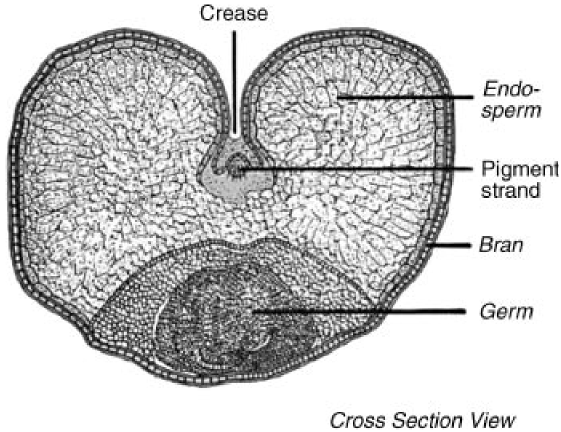

Fig. 8. Diagrammatic cross section of a wheat grain, cut through near the end close to the point of attachment to the rachis, showing part of the germ and scutellum.

the small spherical 'B' granules being less than about 10 μm. The A granules of wheat are lenticular in shape (flattened sphere). The starch granules of other cereals also have distinctive shapes; those of rice and corn are shown in Figure 10. The internal morphology of a wheat starch granule is revealed as being lamellar (Fig. 11) by subjecting the starch to amylase action. The B-granules, surrounding the eroded A granule in Fig. 11, are seen to be more resistant to the hydrolytic action.

The high proportion of starch in cereal grains in evident in the chemical composition of the barley grain (Fig. 12), which is generally typical of cereals.

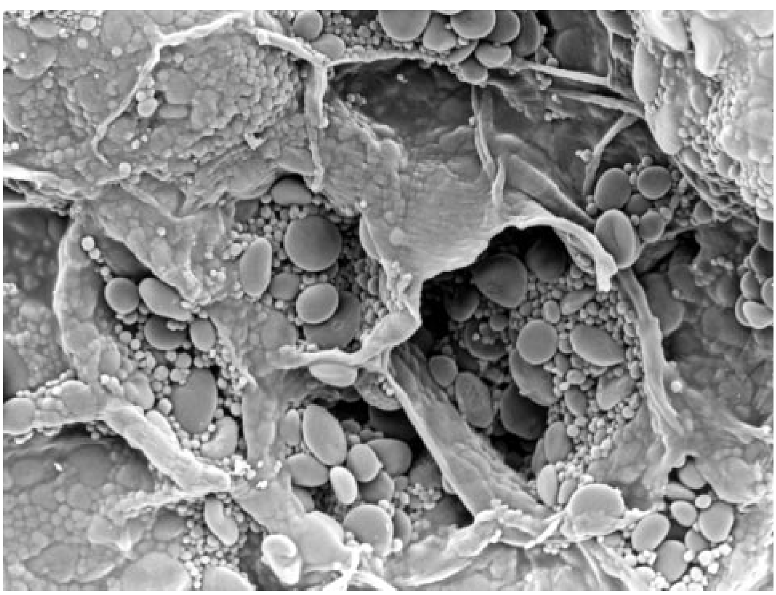

Fig. 9. Scanning electron micrograph of the floury endosperm tissue of the wheat grain.

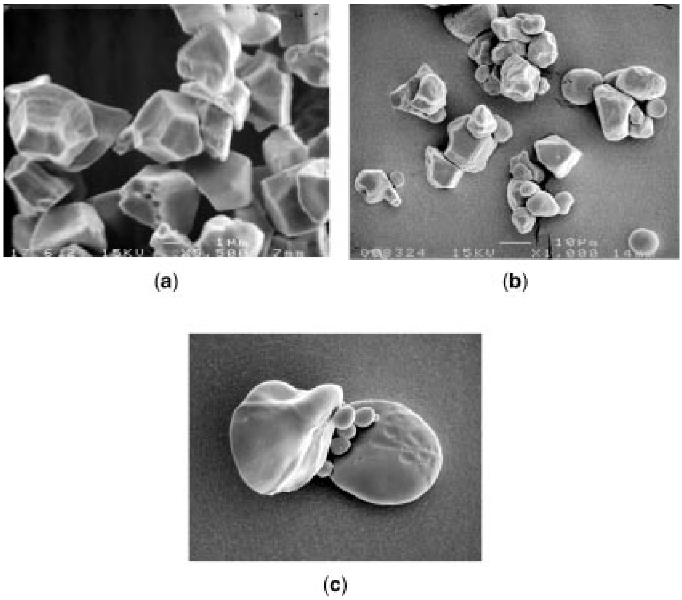

Fig. 10. Starch-granule morphology for (**a**) rice, (**b**) maize and (**c**) wheat.

The contrast in composition of the endosperm, compared to the outer layers ("hulls"), can be seen by abrading ("pearling") the outside of the barley grain to produce pearled barley (17), which is familiar in the diet as an ingredient of soup. The bulk of the fiber and fat is removed in the hulls by the pearling action (Fig. 12), together with a significant proportion of the grain protein.

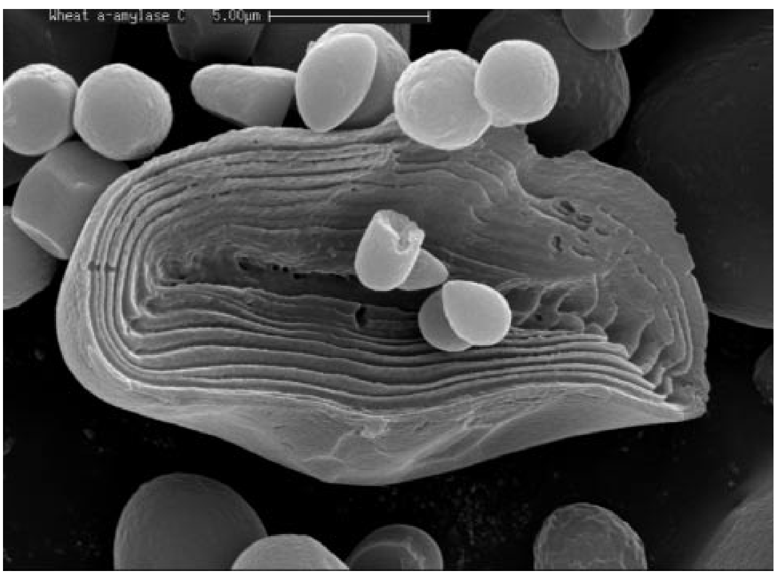

Fig. 11. An A-type starch granule of wheat that has been digested by amylase. It is surrounded by smaller B-type starch granules.

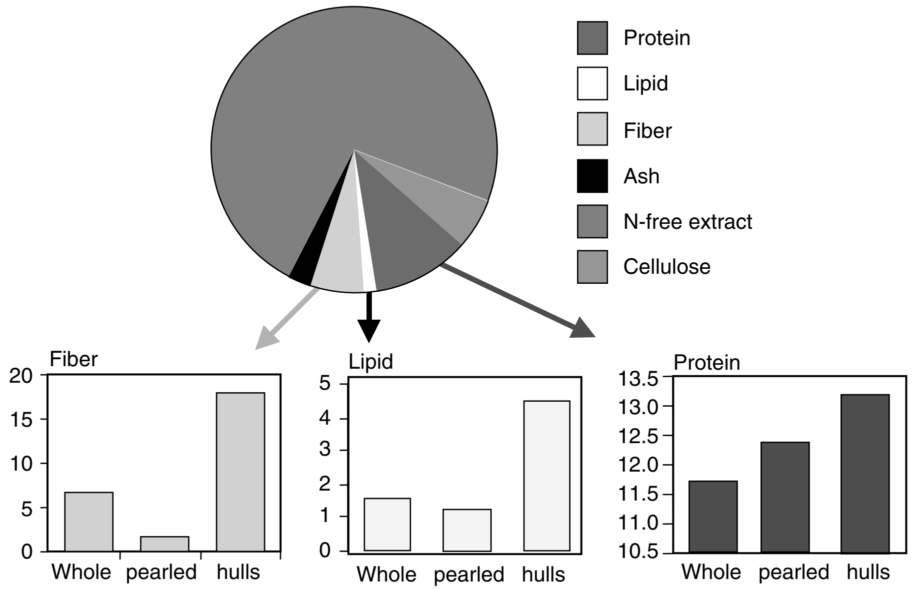

Fig. 12. The chemical composition of barley seed and the distribution of components among the anatomical parts.

Industrially, the production of fuel alcohol has become a significant use of the starch fraction of cereal grains. Ethanol production from corn by fermentation is increasing in the United States, with an output of tens of billions of liters predicted. Further predictions claim that biofuel will be produced industrially from straw and related agricultural waste. These measures promise to lead to the replacement of a significant proportion of gasoline. Wheat is another source of fuel ethanol, based on the fermentation of the starch residue after the separation of gluten and A-type starch.

6.2. Lipid. The relatively small amount of lipid (fat) of cereal grains is mainly associated with the germ (embryo) and scutellum tissues. In most cases, the lipids in cereals contain a high concentration of unsaturated fatty acids, which are protected in the intact grain from oxidation by the presence of tocopherols. The oil from wheat germ was the starting material for the isolation of α-tocopherol (vitamin E).

As long as the antioxidants are in proximity to the lipids, oxidation of the lipids and the accompanying rancidity is minimized. Accordingly, cereal grains are stored as the whole kernel because the various forms of milling destroy the integrety of the grain, bringing lipases in contact with their substrates. The resulting rancidity is a special problem with the oat grain, which has a relatively high lipid content, and it is usual for milled oats to be steamed to inactivate lipase activity immediately after removal of the husks by abrasive milling.

Similarly, wheat is stored as the grain rather than as flour. However, even in the intact kernel, the lipids are subject to hydrolytic rancidity, which together with oxidative rancidity can be estimated by determining the free fatty-acid content. That is done by determining the amount (in mg) of potassium hydroxide required to neutralize the free fatty acids from 100 g of moisture-free grain.

The result is called the fat acidity value. One of the main purposes of milling, in addition to producing an acceptable flour, is to remove the wheat germ and bran intact to the extent that this is possible. Thereby, the concentration of the lipids is decreased, the risk of oxidative rancidity is reduced, and the shelf life of the flour is extended.

6.3. Protein. The protein of cereal grain is an important nutrient source in the human diet, as well as being a significant source of essential amino acids in the formulation of animal feeds. In general, cereal grains are deficient in the amino acid lysine. This deficiency can be complemented by the inclusion of dicot grains, such as soybean, which are adequate in lysine, but lower in methionine than the cereals.

In addition to their roles in nutrition, the grain proteins perform various roles in determining the end-use capabilities of grains. In many cases, groups of proteins are causal agents that are responsible for the functional properties relating to the utilization of the grain. For example, the gluten proteins of wheat are essential to the dough-forming properties needed for bread making (19,20). In other cases, the proteins serve this role in combination with other grain components. For example, the hydrolytic enzymes make a critical contribution in the malting of barley (17). For all grains, protein content and protein composition are important factors that determine the price of grain in animal feeding.

In all cases, the proteins are critical grain components because they are the first products of gene action. For this reason, specific proteins are likely to be significant markers of aspects of end-use properties. In addition, protein composition provides a valuable indication of genotype (the genetic constitution of a grain sample), useful for distinguishing between varieties within a species, as well as serving in analyses of taxonomic relationships (21). Protein composition is critical at several levels, namely, as amino acids (composition being relevant to feed value), as the amino acid sequence (relating to characterization), as polypeptides (valuable to indicate genotype), and as native proteins (as enzymes or with other functional properties).

All these aspects of protein composition relate to grain quality for wheat. Most obviously, the many polypeptides of the gluten complex are valuable indicators of dough properties. However, the causal aspects of dough quality relate to the manner of the association of the glutenin subunits into large disulfide-linked polymers, their overall size being a critical factor for dough strength (21). Other proteins of wheat endosperm have been identified as markers of important quality attributes, namely, granule-bound starch synthase (for starch properties), the purindolines (in relation to grain hardness), and various hydrolytic enzymes (produced in relation to grain defects) (22).

Protein content is a critical aspect of grain quality for virtually all grains, whether the protein relates to feed quality or to more specific functional properties, such as for barley and wheat. In the latter case, a higher protein content generally attracts better market value, yet a lower protein content (not too low) is desirable for malting barley as a high potential for starch modification is needed during malting and brewing (17).

The traditional nexus between the needs for high protein content and increased grain yield has led to the proposal of making the gluten protein "work harder" in bread wheats. This concept of breeding for yield and blending very strong "ingredient wheats" requires better knowledge of how to make gluten proteins with better functionality, but is offers a basis for research and for future achievements in wheat breeding and production.

A century of concerted research activity has failed to provide a complete molecular explanation for the unique bread-making properties of the gluten protein complex. A recent approach to the problem has been to take a nonrheological protein (such as the hordein of barley) and to attempt to modify it such that it can demonstrate gluten-like properties (24). The result of these experiments was to emphasize the importance of the disulfide crosslinks and of the chain lengths of the component polypeptides in building up the enormous polymers that we know as native glutenin (22,24). Other approaches have involved the transfer of subunits of glutenin from primitive wheats into bread or durum wheats. Such possibilities may provide success in achieving long-held dreams of conferring satisfactory baking properties on grain species that are near relatives of wheat, namely, rye, triticale, trithordeum, and even barley.

7. Wheat

7.1. Production, Trade, and Uses. Wheat is cultivated in most countries on all continents except Antarctica. Countries producing over one million tons are listed in Table 2. Wheat-production regions of the world range through a great diversity of climates, and through countries of varying degrees of "development". Production statistics fluctuate from year to year, so the following ten-year averages (1993–2002) provide a better basis for comparing production volumes for the top producers: China, 94 million of tons, also called metric tons; the European Union, 92; India, 69; U.S., 53; the Russian Federation, 47; Canada, 21; and Australia, 19 (25).

Yield statistics (Table 2) vary greatly between countries and regions, depending on the intensity of cultivation, especially on the availability of water. European countries are seen to be among those having the highest yield, due to the adequacy of precipitation and the intensity of fertilizer use. Dry, hot countries, on the other hand, are seen to have relatively low yields, but large areas of production compensate in many cases.

In any specific wheat-growing region, a diversity of varieties is available, being bred to suit the agronomic needs of specific regions, as well as the utilization quality appropriate to the targeted market. Breeding is thus an important initial part of the sequence from the registration of a new variety through its production and harvesting to processing, transport and marketing, leading eventually to the consumer, the most important part of the "grain chain". Figure 13 shows a few breeder's plots, demonstrating a little of the diversity of appearance of growing wheat. Differences in plant height are immediately obvious, as are also the differences in head color. Recent trends have been towards shorter stemmed varieties. The nearest two plots are awnless varieties, in contrast to the awned wheat beside them.

In reasonably cool climates, winter wheats are planted in the fall. After the grasslike seedlings emerge from the ground, they lie dormant during the winter.

Table 2. **Wheat Production and Yield in 2005 for Countries Producing more than 1×10^6 t**[a]

Country	Production, $\times 10^6$ t	Yield, t/hectare
China	96	4.2
India	72	2.7
United States	57	2.8
Spain	38	1.7
France	37	7.0
Canada	26	2.6
Australia	24	2.1
Germany	24	7.4
Pakistan	22	2.6
Turkey	21	2.6
Argentina	16	2.6
Iran	15	2.3
United Kingdom	15	8.0
Poland	9	3.8
Egypt	8	6.5
Italy	8	3.5
Romania	7	2.9
Brazil	5	2.2
Denmark	5	7.2
Hungary	5	4.5
Syrian Arab Republic	5	2.6
Bulgaria	4	3.2
Algeria	3	1.4
Mexico	3	5.0
Morocco	3	1.0
Belgium	2	8.3
Chile	2	4.4
Greece	2	2.1
Saudi Arabia	2	5.2
South Africa	2	2.5
Sweden	2	6.3
Austria	1	5.0
Bangladesh	1	2.0
Nepal	1	2.1
Netherlands	1	8.7
Tunisia	1	1.6

[a]From www.fao.org.

These varieties have a vernalization requirement, that is, they must go through a cool period before they will come into head. They come up again in the spring, ripen, and are harvested in early summer (20). Winter wheats grow best in areas where the winters are not too harsh for the young plants. Spring wheats are planted in the spring and harvested in late summer. Spring wheats grow best in the northern areas of North America and Europe, where the summers are not too hot for the young plants. In regions where winters are mild, a vernalization requirement is not appropriate, and the distinction between winter and spring type is not meaningful.

Quality type is an important aspect of breeding, so that growers can maximize their economic returns on the basis of both yield and market price. The

Fig. 13. A glimpse at the diversity of wheat-plant types in a few breeder's experimental plots.

class a variety fits into is determined by grain hardness (hard or soft), kernel color (red or white), grain protein content and its potential for behaving well in the processing for which it is intended. Such processing is generally milling into flour, so the expected yield of white flour is important (26), and baking into bread. This latter attribute is more difficult to anticipate, as there are many types of manufacturing processes and breads.

In general flour that produces a strong extensible dough is required for bread manufacture by western baking methods, whereas the potential to produce dough of medium strength may be better suited to Arabic-type flat breads. Weak, extensible dough of lower protein content from soft varieties is more appropriate for the manufacture of cookies, cakes, pastries and for grocery flour (20). Figure 14 lists the broad categories of food products made from wheat. The positions of the food products in the graph indicate the combinations of grain hardness and protein content that are preferred for their production (27,28).

Pasta products appear at the extreme top right of Figure 14, as these foods require grain of extreme hardness and high protein content, such as are provided by durum wheat, a distinct species (Table 1). Pasta are produced from a relatively dry dough (lower moisture content than bread dough) by extrusion through a die. Variation of the die shape produces the many shapes that are traditional for pasta. Noodles, on the other hand, are made from hexaploid ("bread") wheat by the cutting of a sheet of dough into long strands. They are thus distinct from pasta in their grain-quality requirements (Fig. 14).

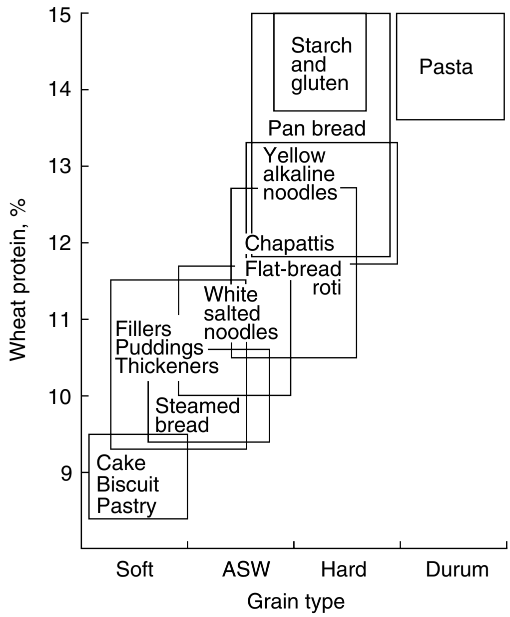

Fig. 14. The diversity of foods made from wheat, and the desirable combinations of grain hardness and protein contents for each use (28).

7.2. The Milling of Wheat. The first stage of food production from wheat generally is milling, the crushing of the grain, plus the removal of the germ and bran layers (see Fig. 8) (26). The series of steps involved includes wheat selection (according to quality potential), blending (to combine grain of suitable qualities), cleaning (to remove contaminants), conditioning (to raise the moisture content of the grain, usually to 14–16%), milling (crushing and sieving) and further blending ("gristing") of specific flour streams.

The endosperm, which forms about 83% of the kernel, is the source of white flour (Fig. 8). It contains 70–75% of the grain protein (Fig. 12). The bran, forming about 14% of the kernel, is included in whole-wheat flour ("wholemeal"), but it is more often removed and used in animal or poultry feed. The cellulosic material of the bran cannot be digested by nonruminants, so it tends to accelerate the passage of food through the digestive tract. Thus, the total nutritive contribution of whole-wheat flour is less than that found in enriched white flour products, but wholemeal offers the nutritional advantages of being an additional source of vitamins and minerals. The germ, forming about 3% of the kernel, is the embryo or sprouting tissue of the seed. It is usually separated out because it contains oil, which limits the keeping quality of flour.

The mill flow begins with a separator, where the wheat first passes through a vibrating screen that removes straw and other coarse materials, and then over a second screen through which drop small foreign materials like seeds. An aspirator lifts off lighter impurities in the wheat. After the aspirator, wheat moves into a disk separator, consisting of disks revolving on a horizontal axis. The disk surfaces are indented to catch individual grains of wheat but reject larger or smaller material. The blades push the wheat from one end of the machine to the other. The revolving disks discharge the wheat into a hopper or into the continuing stream. The wheat then moves into a scourer—a machine in which beaters attached to a central shaft throw the wheat against a surrounding drum. Scourers may be either horizontal or upright, with or without brushes, and adjusted for mild, medium, or hard scouring. Air currents carry off the dust and loosened particles of bran coating.

The stream of wheat next passes over a magnetic separator that pulls out ferrous materials. A washer–stoner may be the next piece of equipment. High speed rotors spin the wheat in a water bath. Excess water is thrown out by centrifugal force. Stones drop to the bottom and are removed. Lighter materials float off, leaving only the clean wheat. In the production lines of some mills, a dry stoner is also used. The wheat passes over an inclined, vibrating table that pushes stones and heavy material away from the lighter wheat, which is discharged separately.

The clean wheat is then tempered before the start of grinding. In the process, water is added to raise moisture content. This tempering ("conditioning") step aids the separation of the bran from the endosperm and helps provide a constant, controlled amount of moisture and temperature throughout the milling process. The percentage of moisture, length of conditioning, and temperature are the three important factors in tempering, with different requirements in soft, medium, and hard wheats (26).

The dampened wheat is held in a bin for a prescribed period, usually 8–24 h, depending on the type of wheat. The outer layers of the wheat berry tend to be brittle, and tempering toughens the bran coat for better separation of the endosperm. Within the kernel, tempering also mellows the endosperm so that the floury particles break more freely in milling. When the moisture content is properly dispersed in the wheat for efficient milling, up to approximately 16%, the grain is passed through an Entoleter scourer–aspirator as a final step in cleaning. Disks revolving at high speed in the scourer–aspirator throw the wheat against fingerlike pins. The impact cracks unsound kernels (including insect-damaged), which are rejected. The sound wheat flows to a grinding bin or hopper from which it is fed in a continuous metered stream into the mill itself.

7.3. The Milling Process. The first-break rolls of a mill are corrugated rather than smooth like the reduction rolls that reduce the particles of endosperm further along in the process. The rollers are paired and rotate inward against each other and at different speeds. The clearance between rollers, and the pressure as well as the speed of each separate roller, can be adjusted. At each breaking step, the miller selects the milling surface and the corrugations. The speed of and interrelation between the rollers depend on the type and condition of the wheat.

The next important step introduces the broken-ground particles of wheat and bran into a sifter where they are shaken through a series of bolting cloths or screens to separate the larger from the smaller particles. The fractions, and particles of endosperm graded by size are carried to purifiers. In a purifier, a controlled flow of air lifts off bran particles while bolting cloth at the same time separates and grades coarser fractions by size and quality.

Four or five additional break rolls, with successively finer corrugations (each being followed by a sifter) are usually used to rework the coarse stocks

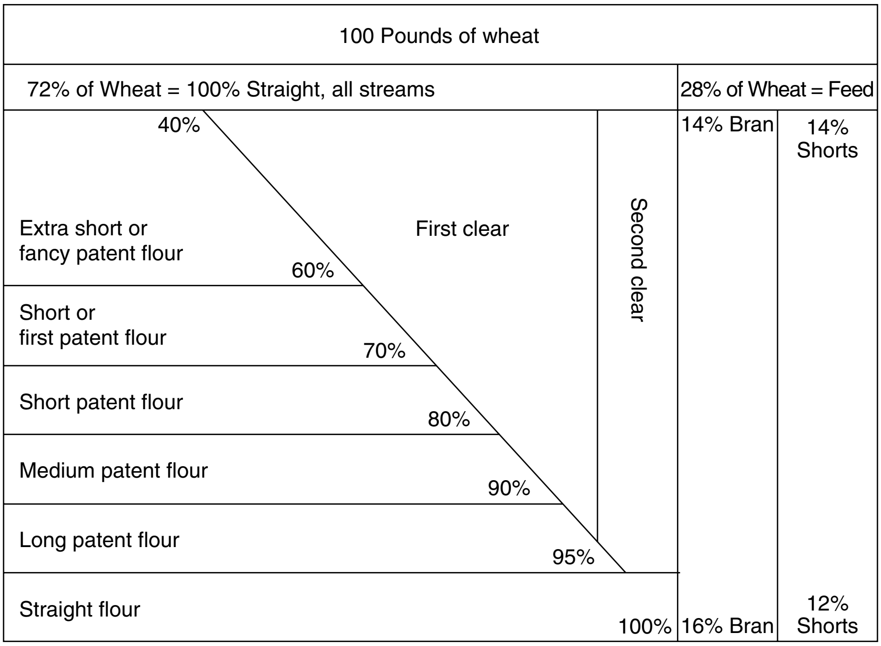

Fig. 15. Grades of wheat flour and 'offal' produced from 100 pounds of grain (29).

from the sifters and reduce the wheat particles to granular middlings as free from bran as possible. Germ particles, being somewhat plastic, are flattened by passage through the smooth reduction rolls and can be separated. The reduction rolls reduce the purified, granular middlings or farina to flour.

The process is repeated until the maximum amount of flour is separated, consisting of at least 72% of the wheat. Millers more often aim for a flour recovery of over 75%, but there are the limitations that the flour should be a bright and white, and have a low ash content (ie, low level of bran contamination). The resulting flour is made up of the various grades shown in Figure 15 (29). The remaining percentage of the wheat berry is classified as millfeed. The flour can be classified in several ways. Straight flour is all the flour produced, with various streams of flour mixed into one. Flour emerges at a number of points in the milling process, with the purified middlings yielding the extra-short or "patent" flour for bread manufacture. In hard wheat mills, as much as 75–80% may be run together as first clear or split into fancy clear and second clear.

In a soft wheat mill, 40–60% of the fancy patent may be taken off separately, leaving about 55% of the remaining flour to be classified as fancy clear. Figure 15 is a generalization rather than an exact description of the yield of a particular kind of wheat from a specific mill. It shows how the various streams of flour may be classified, starting with fancy patent, through short, medium, and long patent flours, leaving less and less to be classified as clear flour. The extra-short or fancy patent is the finest, with grades dropping down the scale to clears (26,30).

Toward the end of the millstream, the finished flour flows through a device that can release additives in measured amounts. If the flour is self-rising, a leavening agent and salt are also added. For bakery customers, the finished flour flows into hoppers for bulk storage, since most bakers add their own form of the enrichment formula to dough, eg, a combination of thiamine, niacin, riboflavin, and iron. For packing as grocery flour, the enrichment ingredients may be added in another mixing machine as the flour flows to the packing room.

In milling of durum wheat for pasta, special equipment is required, especially additional purifiers to separate the bran from the semolina, a coarse granulation of the endosperm (31). By regulation in many countries, semolina is prepared by grinding and bolting durum wheat, separating the bran and germ, to produce a granular product with no more than 3% fine flour. Durum millers also make granulars, or a coarse product with greater amounts of flour. Alternatively, they grind durum wheat into flour for special use in certain macaroni products.

7.4. Air Classification. In the early 1960s, it was found that wheat could be ground to a very fine flour by impact milling and that the product could be further separated ("air classified") into products varying widely in protein content. For these purposes, finished flour from a conventional roller mill may be further reduced in particle size in a high-speed grinder, an impact or pin mill. Disintegration of the flour particles takes place as they strike one another, the surface of the rotors, and the pins. The flour is fractured in granular form rather than pressed and broken as in a roller system. The reground flour contains a mixture of relatively coarse endosperm chunks, intermediate fragments, and fines.

The reground flour is channeled to a classifier, where swirling air funnels the larger particles down and away, while the smaller fines are lifted up and separated. Repeating the process permits 20–30% of the flour to be separated into a low-protein flour suitable for cakes and pastries, while 5–15% of the original flour makes up the fine fraction, containing 15–22% protein, and thus suitable for blending to raise the protein contant of other flours. Recombining some of the high-protein fraction with the coarse portions permits a miller to tailor a flour of protein value to a buyer's specifications.

Fine grinding and air classification offer the miller the flexibility to produce some cake flour from hard wheats, and some bread flour or high-protein fractions from soft wheats. Application of the process theoretically frees the miller from dependence on different wheats, either hard or soft, that change each crop year. Nevertheless, the problem remaining is how to market the larger volume of low-protein or starchy fractions at prices adequate to justify the installation and operation of the special equipment.

7.5. Flour Types. Hard-wheat flours are usually higher in protein than are soft-wheat flours. They may be milled from either winter or spring wheat varieties. Those with highest protein content, characterized by their capacity to develop the strongest gluten, are used in commercial bread production where doughs must withstand the rigors of machine handling. Other hard-wheat flours with more mellow gluten, easier to develop in kneading by hand, are packed as family flour, all-purpose flour and self-rising flour. The protein content of hard spring wheat flour runs from 11 to 16% and in hard winter wheat flour, the range is from 10 to 14%.

Soft-wheat flours are sold for general family use, as biscuit (cookie) or cake flours, and for the commercial production of crackers, pretzels, cakes, cookies, and pastry. The protein in soft wheat flour runs from 7 to 10%. There are differences in appearance, texture, and absorption capacity between hard- and soft-wheat flour subjected to the same milling procedures. Hard-wheat flour falls into separate particles if shaken in the hand whereas, soft-wheat flour tends to clump and hold its shape if pressed together. Hard-wheat flour feels slightly coarse and granular when rubbed between the fingers; soft-wheat flour feels soft and smooth. Hard-wheat flour absorbs more liquid than does soft-wheat flour, due to greater starch damage occurring during the milling of hard grain. Consequently, many recipes recommend a variable measure of either flour or liquid to achieve a desired consistency.

In whole-wheat flour, the presence of bran particles reduces gluten development. Consequently, baked products made from whole-wheat flour tend to be heavier and denser than those made from white flour. On the other hand, whole-wheat flour is richer in B-complex vitamins, vitamin E, fat, protein, and it contains more trace minerals and dietary fiber than does white flour. In most recipes, whole-wheat flour can be mixed half and half with white flour for a satisfactory product. Graham flour is synonymous with whole-wheat flour, named after a physician, Dr. Sylvester Graham, who advocated the use of whole-wheat flour in the first half of the nineteenth century.

All-purpose flours are designed for home baking of a wide range of products, namely, yeast breads, quick breads, cakes, cookies and pastries. Such flours may be made from low-protein hard wheat, from soft or intermediate wheats, or from blends of hard and soft wheat designed to achieve mellow gluten, such as a homemaker can manipulate by hand or in domestic kitchen equipment. Most recipes for home baking are designed for use with all-purpose flour.

Self-rising flours are all-purpose flours to which leavening agents and salt have been added. The leavening agents used are sodium bicarbonate and an acid-reacting substance, monocalcium phosphate, sodium acid pyrophosphate, sodium aluminum phosphate, or a combination of these acids. The sodium bicarbonate and the acid ingredient react in the presence of liquid (and heat) to release carbon dioxide. The leavening agent and salt are added in amounts sufficient to produce not less than 0.5% of their combined weight of carbon dioxide. Their combined weight must not exceed 4.5 parts per hundred parts of flour.

Phosphated flour is all-purpose flour to which the acid-reacting ingredient, monocalcium phosphate, has been added in a quantity of not more than 0.75% of the weight of the finished phosphated flour. It assists in stabilizing gluten and helps nourish yeast.

Cake flours are milled from low protein soft wheat especially suitable for baking cakes and pastries or from low-protein fractions derived in the milling process. Cake flours are usually not enriched, but are bleached. The sale of cake flours declined during the 1950s as packaged cake mixes became more popular. Instantized, instant blending, or “quick-mixing flour” is a granular or more dispersible type of product for home use. It is free-pouring like salt, and dust-free compared to regular flour. It eliminates the need for sifting, since it does not pack down in the package and since it pours right through a screen or sieve.

Granular flour instantly disperses in cold liquid rather than balling or lumping as does regular flour. The granular flour is produced by special processes of grinding and bolting, or from regular flour subjected to a controlled amount of finely dispersed moisture that causes the flour to clump or agglomerate. It is then dried to a normal moisture level.

Gluten flour is milled to have a high wheat gluten and a low starch content and is used primarily by bakers for dietetic breads, or mixing with other flours of a lower protein content.

Semolina is the coarsely ground endosperm of durum wheat. High in protein, it is used by manufacturers for high-quality pasta products, including macaroni and spaghetti. In Africa and Latin America, it is also used for a dish called "couscous".

Farina is the coarsely ground endosperm of hard wheats. It is the prime ingredient in many American breakfast cereals. It is also used by manufacturers for inexpensive pasta. Additional basic wheat products are wheat berry (kernel), bulgar, cracked wheat, wheat germ, bran, and commercial cereals.

8. Rice

Rice is the major food of about half of the world's population (18,32). There are two main races of rice – the tropical *indica* race and *japonica*, mainly grown in temperate regions. Overall, the span of rice growing is from 53° north to 40° south. In addition, there is the distinct genus and species, *Zizania aquatica*, known as wild rice, which has traditionally been grown in the lakes of North America (Table 1). In the world economy, rice is an extremely important food, second only to wheat in total world production. Its yield per hectare averages about 4 tons per hectare, generally exceeding that of wheat (compare data in Table 2). About 75% of the rice grown in the world is irrigated, a further 16% of production is rain-fed lowland (32). Additional areas are upland and flood-prone wet land.

About 90% of the world rice-growing area is in Asia. Rice, thus, accounts for up to half of the daily caloric intake in many Asian countries, as well as being their major source of protein. In many African and South American countries, rice is rapidly becoming the staple food for much of the population. Per capita consumption of milled rice in Asia averages about 86 kg per year, whereas the figure ranges from 4 to 30 kg on other continents. However, the rice-growing area is shrinking; thus, improved technologies must be employed to increase yields so that production levels can be maintained. An important part of these efforts is the intrduction of new and better genotypes. Most rice varieties grown in Asia are now improved semi-dwarf plant types, with semi-erect leaves.

The major rice-producing countries in recent years have been China, India, Indonesia, Bangladesh, Vietnam, and Thailand. There is additional significant production in the United States, Pakistan, the European Community, Burma, and Australia. Net exporters are Thailand, Vietnam, India, the United States, Italy and Spain as the main countries of the European Community, Pakistan, and Australia. Significant importing countries include Iran, Brazil, Nigeria, Philippines, Iraq, Saudi Arabia, Malaysia, and South Africa.

8.1. Processing of Rice. Tropical rice is generally harvested at over 20% moisture content, when grains reach optimum yield. In many regions, the harvesting involves cutting the rice panicle with enough stem below the grains to permit hand threshing, after drying in the sun. Delayed harvesting in rainy weather, or lodging (plants fallen over), may lead to grain sprouting in the panicle.

Rice processing involves harvesting, drying, storage, and milling. These operations vary considerably throughout the world. Broken rice is worth about one-half the value of head (whole grain) rice, so an important consideration during rice processing is prevention of breakage of the endosperm. Reduction of the grain moisture to below 14% is desirable for safe storage (32).

Practices for storing rice without losses due to microorganisms, insects, rats, mice, and birds are well developed in many countries, but good storage practice is not always followed. Estimates of storage losses range from 3% of production in the United States to as high as 30% in some developing countries (33).

The purpose of rice milling is to remove the hulls and bran from harvested, dried rough rice ("paddy"). Shelling refers to the removal of the outer hull or shell from rough rice. The operation is conducted in machines that have been known by different names such as shellers, hullers, huskers, dehuskers, and decorticators. Similarly, the shells are also known as hulls, husks and chaff. The term "hulling" in most parts of the United States has the same meaning as shelling. However in some areas, hulling also refers to the removal of both hulls and bran. After removal of the hulls, the rice is called brown rice.

The brown rice is milled to remove all or most of the bran, to produce white milled rice. Bran removal is sometimes called scouring or whitening. Traces of bran may remain on the rice after milling, so the process of polishing gives the milled rice a smoother finish. Total milled rice includes both the head rice and the broken rice. Head rice or head yield refers to the milled whole (unbroken) rice grains. The broken rice may be subdivided into three sizes: second heads, screenings, and brewer's rice.

In some rice-growing areas, rice milling is accomplished by very primitive methods, such as pounding the rough rice in a wooden mortar and pestle followed by winnowing. At the other extreme are very modern methods where milling is accomplished in large, highly automated plants. Thus, there is no typical rice mill. However, the modern processing of rice consists of essentially these steps:

- cleaning the incoming rough rice,
- shelling the rough rice,
- milling to remove the bran from the brown rice,
- grading the milled rice by length into whole grain and different sizes of brokens,
- mixing milled whole grain and brokens to meet specifications of buyers and
- packaging.

8.2. The Parboiling of Rice. The hydrothermic process of parboiling greatly improves the milling quality of rice, such that head yields approach total yields, ie, zero breakage. Kernel defects such as cracks, chalkiness, and incomplete grain filling are reported to be completely "healed" during the parboiling process (33). When properly dried, the rice kernels are resistant to mechanical breakage.

The milling quality of parboiled rough rice is determined largely by drying conditions following parboiling, rather than by the previous history or condition of the rice. Consequently, for rough rice that is to be parboiled, the optimum harvesting, drying, and storage conditions should be selected on some basis other than that of preserving the milling quality. For the same reasons, parboiling is an excellent means for salvaging rice whose milling quality has been inadvertently damaged by improper handling or processing. About 20% of rice is consumed world-wide as parboiled rice (32).

9. Corn

Corn is the common term for the species *Zea mays* (Table 1), but in some English-speaking countries, corn can be a generic term, to signify any type of grain. Thus, the term "maize" is a more specific descriptor in some regions (15). Maize is indigenous to the Americas, but it is grown world-wide. A crop of corn is always maturing somewhere in the world. It grows from north latitude 58° to south latitude 40° and from below sea level to altitudes of 4,000 meters. It is adapted to areas with fewer than 25 mm of rainfall and regions having more than 1,000 mm. Early varieties, that have been adapted to cold climates, mature in as little as 60 days. Late varieties, grown in the tropics, need nearly a year to reach maturity. Corn can grow to as little as 60 cm in height and as tall as 6.5 meters. Ears of corn can be as small as one's thumb for some popcorn varieties or as large as 60 cm as those grown in the Jala Valley of Mexico (34).

The cob of corn is a grain-delivery system that is distinct from that of any other cereal grain. The corn kernel is the largest of all cereal grains. Kernels are usually flattened, due to their position in the cob. The color of the grains vary from white to yellow to orange, but also to red-brown. Endosperm types range from soft and "floury" to hard and "flinty". The major uses for corn are industrial and as animal feed. Thus, corn enters our diet in indirect ways, for example, as sweetening agents in drinks, as ready-to-eat breakfast cereals, as snack foods and as meat products. The more obvious roles of corn in one's diet are as popcorn (involving genotypes with a special type of endosperm that suddenly expands on heating) and as the vegetable sweet corn (involving genotypes with unusually high sugar content, harvested immature to provide a juicy mouth feel).

The germ of the corn kernel, constituting about 10% of the kernel mass, is the largest germ of any cereal grain. It is rich in oil (about 33% of germ mass) and protein (about 20%). The protein content of the whole maize kernel is in the lower range for cereal grains, averaging 10% or less. The maize kernel is relatively sub-optimal in its lysine content, due to the high content of the main prolamin protein (zein) in the endsperm (15). However, maize genotypes have been developed with improved levels of lysine; these are the "opaque-2" and "floury-2" mutant types, with higher levels of the albumin classes of protein. The nutritional advantages of most of these genotypes are balanced by poorer grain yields.

Although corn was originally grown as food, the single largest use today is as feed for farm animals, especially in the United States, where a majority of domestic corn usage is for this purpose. Animal feeding (in volume use) is for swine, beef cattle, dairy cattle, and poultry. Corn is an important feed ingredient because it supplies the energy component and a large portion of the protein input to the animal's diet. Its high oil content makes a significant contribution to its energy value as a feed stuff.

Further uses of corn for animal feed come as co-products of the various industries that use corn to produce beverage alcohol, starch, corn sweeteners, corn oil, and dry milled products. These industries provide by-products with concentrated protein and vitamin content that are valuable feed ingredients. Corn gluten feed is a source of additional protein in feeds compounded for beef cattle and dairy herds. The fiber content is readily converted by these ruminants. The xanthophylls in corn gluten meal provide the coloration in chicken and eggs so desired by many consumers. The distilling industry provides distillers dried grain while dry millers produce high fiber, high calorie hominy feed.

9.1. Wet Milling. A century ago, all corn was harvested by hand and stored on the cob in drying cribs. Today, in the United States for example, one machine that picks and shells in the field can substutute for 50 workers in days long ago. After harvesting, kernels are dried to less than 15% moisture content to maintain grain quality and prevent long term storage spoilage. Drying must be done carefully to allow the use in wet milling (35,36).

Milling of the wet grain is a significant starting process for many industrial uses of maize. Shelled corn is shipped to wet millers by truck, rail, or barge. After cleaning to remove coarse material, ie, cobs and "fines" (broken corn, dust, etc), the corn is steeped in a sulfurous acid solution to soften the kernel and render the starch granules separable from the protein matrix that envelopes them. About 7% of the kernel's dry substance is leached out during this step, forming protein-rich steep-water, a valuable feed ingredient and fermentation adjunct.

The softened kernels are coarsely ground (first grind) to release the germ material. Because of its high oil content, the germ is lighter than the starch, protein, and fiber fractions, permitting the ready separation of the germ in hydrocyclones. This material is then washed free of the remaining starch, after which it is dried, and the valuable corn oil is removed by expelling, solvent extraction or a combination of both. The spent germ is a valuable feed ingredient.

The starch–protein–fiber slurry is subjected to more intense milling to release additional starch from the fiber. The fiber is then wet-screened from the starch–protein slurry, washed free of starch, and dried to form the major component of corn gluten feed. The best fiber can be additionally purified to become corn bran, a dietary fiber ingredient that has been shown to lower serum cholesterol and triglycerides (37). The starch-protein slurry is separated into its component parts, again taking advantage of the density difference between the heavier starch and the lighter protein (gluten) particles. Separation is usually done with combinations of disk-nozzle centrifuges and banks of hydrocyclones.

The protein fraction is filtered and dried to become corn-gluten meal of high protein content (about 60%). The starch slurry can be dewatered and dried to produce regular corn starch. Dry starch can be sold "as is" or heat treated in the presence of acid catalysts to produce dextrins. Furthermore, it is chemically modified before dewatering and drying to produce modified starches used in food and industrial applications. Lastly, it can be hydrolyzed to produce corn sweeteners.

9.2. Corn Starch. Corn starch is a principal ingredient in many food products, providing texture and consistency, as well as energy. More than half of the corn starch sold is used in industrial applications, primarily in paper, textile weaving, adhesives, and coatings. Starch is a polymer consisting of α-linked anhydroglucopyranose units. Two forms exist: amylose is an essentially linear molecule in which the anhydroglucopyranose units are linked almost exclusively via α-1,4 bonds. Amylopectin is a much larger, branched molecule (the molecular weight is about 1,000 times greater than that of amylose) (38). α-1,4 Linkages predominate but there is a significant number of α-1,6 linkages that result in the branched structure. Although the ratio of amylose to amylopectin is relatively consistent in normal corn varieties, it varies considerably when starch is obtained from either waxy or high amylose varieties.

When heated in the presence of water to 62–72°C, normal starch granules swell, forming high viscosity pastes or gels. This process is called gelatinization. Starch from normal corn genotypes form characteristic firm, opaque gels because of the amylose fraction. The linear molecules align on cooling after gelatinization in a process called retrogradation, forming a thick, rubbery mass. The bushy amylopectin molecules in waxy starch cannot align to form such a mass, resulting in softer, translucent gels. High-amylose starches are difficult to fully gelatinize and provide little viscosity unless cooked above the boiling point of water. These vastly different characteristics can be further enhanced by chemical or physical modification of the native granules, resulting in starches with a wide range of properties for industrial and food applications.

Corn Starch-Based Sweeteners. Acidic or enzymic hydrolysis can be used to break the linkages between the anhydroglucopyranose units in the starch molecule with the addition of a molecule of water at the break site. This process produces a variety of corn-based sweeteners. The first sweetener from starch (arrowroot, not corn) was produced in Japan in the ninth century. By the nineteenth century, starch sugars were being produced in Europe and the United States. Because glucose is not as sweet as sucrose, products made from corn syrups are not exceedingly sweet, allowing delicate flavors to reach the palate. However, enzymatic isomerization of glucose to fructose produces high-fructose corn syrups (HFCS) that are as sweet as sucrose syrups, thus allowing corn sweeteners to replace sugar in liquid applications (such as soft drinks).

To produce sweeteners from corn starch, the starch is gelatinized in the presence of a catalyst under conditions that promote hydrolysis. Acid is usually used to make slightly converted or low-dextrose equivalent (DE) syrups. Enzymatic conversion, using thermostable alpha-amylases (for liquefaction), beta-amylases (for maltose production), and glucoamylase (for high-glucose content) is widely practised to produce a full range of saccharide compositions.

After the desired degree of hydrolysis is achieved, insolubles are separated by centrifugation or filtration (or both). Soluble impurities are removed using activated carbon or ion exchange (either singly or in combination) before evaporation of the purified syrup to the desired solids concentration. Pure glucose is obtained by crystallization from highly converted starch syrups. Highly converted glucose syrups can also be enzymatically isomerized to 42% (dry basis) fructose content, significantly increasing their sweetness. Further increases in fructose content are possible using chromatographic enrichment (39). Pure fructose is produced by crystallization from syrups enriched to fructose contents above 90% (dry basis).

9.3. Corn Oil. The crude corn oil recovered from the germs consists of a mixture of triglycerides, free fatty acids, phospholipids, sterols, tocopherols, waxes, and pigments (40). Refining removes the substances that detract from the quality, resulting in a nearly pure (99%) triglyceride stream. The first refining step is degumming; 1–3% water is added and the dense, hydrated gums are removed by centrifugation. The degummed oil is then refined. Treatment with dilute NaOH (12–13%) forms water-soluble soaps of the free fatty acids, allowing centrifugal separation. An alternative physical refining process steam strips the volatile components, primarily free fatty acids.

Pigments are removed by sorption on bleaching clay that is then separated from the oil by filtration. The oil is then "winterized" by cooling it to about 4°C, precipitating the waxes that are then filtered from the oil. Winterization is not required if the oil is to be hydrogenated. Deodorization, a steam stripping process similar to physical refining, removes volatile impurities, resulting in an oil with lighter color and improved oxidative stability.

Corn oil has the important attributes of flavor, color, stability, retained clarity at refrigerator temperatures, polyunsaturated fatty acid composition, and vitamin E content; these qualities make it a premium vegetable oil. The major uses are frying or salad applications and margarine formulations.

10. Health and Safety Factors

10.1. The Nutritional Value of Cereal Grains. To compare the cost-effectiveness of the various sources of food in supplying one's dietary needs, a least-cost analysis (adapted from animal-feed formulation) was applied to supermarket products, based on the nutritional requirements of an adult. The aim was to determine what combination of food products would provide these nutritional needs most economically for one day. The "prize" for cost-effective nutrition went to the cereal grains, which provided about 80% of the protein requirement, half the energy, 90% of the iron, 80% of the niacin, 70% of the riboflavin, 70% of the thiamine and 36% of the calcium, but none of the Vitamin A or Vitamin C.

The rations selected in the final diet consisted of 76 g "Wheaties" (breakfast wheat biscuits), 312 g oatmeal, 28 g skim milk, 8 g liver, 193 g potatoes and 320 g sugar! The daily cost was only $2 or so, but it might be difficult to make this combination of rations into three palatable meals. In this case, the sugar contributed 40% of the energy, but no other nutrient. Skim milk contributed 60% of the calcium. Vitamin A came completely from the liver, and vitamin C came largely from the potatoes. The Wheaties and oatmeal were whole-grain products, enhancing their ability to contribute B vitamins.

The recommendation for more grain-based foods in the diet is a common factor in the various nutrition guidelines that have been developed in many countries (41). A food-guide pyramid was introduced in the U.S. in 1992. It showed whole-grain foods at its base, as the food that should be eaten in the largest proportion. A revised set of guidelines was recommended (42), suggesting the consumption of "healthy fats" and avoidance of refined carbohydrates, butter and red meat. Their revised pyramid retained whole-grain foods at the base, together with plant-derived oils, many of them from grains, eg, from corn (maize), canola, sunflower and peanut.

More recently, the U.S. Department of Agriculture has recommended a pyramid with the subtitle "One size doesn't fit all" (see the web site MyPyramid.gov) (43). This plan "can help you choose the foods and amounts that are right for you... to help you: make smart choices from every food group, find your balance between food and physical activity, and get the most nutrition out of your calories". Nevertheless, the whole grains and refined grains are given major accents in the food groups recommended in these new guidelines.

10.2. Celiac Disease. Despite the nutritional value of cereal grains to the vast majority of people, there is a minority who have intolerances to specific cereal species. Most thoroughly understood of these is celiac disease, a disturbance of the lower gastrointestinal tract. Celiac disease is a chronic condition characterized by loss of appetite and weight, depression and irritability, and diarrhea frequently followed by constipation (44–46). The disease may develop in childhood or later in life. Frequently, the patients who develop the disease in adulthood report having had some of the symptoms during childhood.

This disturbance was recognized shortly after World War II as being related to the ingestion of wheat. A group of physicians in the Netherlands was impressed by the fact that during the war, they saw many cases of celiac disease. During that time, wheat was the primary staple of the diet. However, at the end of the war, other foods again became available and the number of children who developed celiac disease decreased. One Dutch group of investigators had a seven-year-old female patient who displayed extreme fluctuations in her symptoms. These changes were shown to be associated with the presence or absence of bread in her diet. Using that patient as the test subject, the group soon learned that her symptoms worsened shortly after she consumed foods containing wheat gluten (47).

The primary therapy for celiac disease involves the elimination of gluten from the diet. In this case, the term "gluten" applies not only to the gluten of wheat, but also to the homologous storage proteins of closely related grain species, namely, triticale, rye, barley and possibly oats. Certain food products are specifically labeled as being free of gluten; this status is indicated by the gluten-free symbol (Fig. 16). Otherwise, it is difficult to be sure that a diet involving manufactured foods is free of the protein from these cereal species, because they are often used in food manufacture. To overcome this difficulty, a list has been prepared to indicate what ingredients may or may not be "safe" for a celiac diet (48). This list should thus assist in formulating a gluten-free diet through the use of ingredient labels on food products.

10.3. Deficiency Diseases. Apart from intolerance conditions such as celiac disease, the cereal grains made important contributions to improving our nutritional status, but they are also important dietary components of some groups of people who have shown specific nutritional deficiencies. Some pioneering studies of deficiency diseases led to the discovery of some vitamins. These deficiency cases have been associated with the use of rice, corn, and wheat.

Fig. 16. The gluten-free label for foods suitable for people with celiac disease.

Beriberi: Thiamine Deficiency. The early recognition of vitamins and their importance to human health came from the visit of Eijkman, a Dutch pathologist, to Java in an attempt to cure an epidemic of beriberi that had appeared in one of the hospitals. Eijkman kept a flock of chickens on the hospital grounds to assist in discovering the disease agent that he assumed was involved in the etiology of beriberi. These chickens were fed scraps from the plates of the hospital patients, primarily polished rice, the common food in that part of the world (49).

Although Eijkman recognized the condition in his polyneuritic chickens as the analog of beriberi, he misinterpreted its cause. He suggested, on the basis of bacteriological concepts then dominating the medical field, that beriberi resulted from the ingestion of a toxic substance associated with the starchy part of the rice. According to that theory, rice polishings contained an antitoxin, which neutralized the toxin present in the polished rice. It was Eijkman's successor who established that polished rice lacked some substance essential for normal physiological functioning, demonstrating that this substance occurred in rice polishings, beans, meat, and other foods (49). The critical ingredient is now known to be thiamine (vitamin B_1). The absence from the diet of similar substances is responsible for the development of scurvy, pellagra, rickets, etc (50).

Pellagra: Niacin Deficiency. It was 220 years after the first description of pellagra that nicotinic acid was discovered to be the cure for "Black Tongue" in dogs (51), a condition suggested by a veterinarian in North Carolina to be similar to human pellagra (52). The contrast was noted between a high incidence of pellagra among the inhabitants of the southeastern United States and its absence among the corn-eating people south of the Rio Grande. This puzzle continued for some years until it finally became evident that the lime water, in which the corn kernels were steeped prior to being made into tortillas, liberated nicotinic acid from its bound form (53).

Untreated kernels of corn contain nicotinic acid as a complex from which it cannot be made available by the human or animal digestive processes. However, a weak alkali, such as lime water, releases nicotinic acid from its complex and makes it available for absorption. Furthermore, the usual diet of the corn eaters south of the Rio Grande includes a large complement of beans. Beans are a rich source of tryptophan which can be converted to nicotinic acid by enzymes in the human body.

Zinc Deficiency. A nutritional problem associated with consumption of large amounts of whole wheat products is the unavailability of dietary zinc, first observed in a patient with immature development and dwarfism in southern Iran (54). The patient showed marked improvement when placed on a well-balanced, nutritious diet for a year. In 1962, similar patients were observed in Egyptian villages. A deficiency of zinc was identified as the primary reason for the development of this condition. This deficiency of zinc results from the binding of that metal by the phytates present in whole wheat (17). Even when an excess of zinc is present in the diet, if conditions are right, that zinc may be complexed with the phytate and thus rendered unavailable to the body. Thus, a zinc deficiency may develop when its dietary level appears adequate while the diet contains large amounts of a food, such as whole wheat, that has high levels of phytate.

Calcium Absorption. Phytates in cereal grains have also been reported to interfere with the absorption of calcium. However, a long-term study indicated a retention of calcium in subjects that consume large amounts of bread made with high extraction of flour (55).

11. Conclusion

The cereals can be seen as being responsible for leading humanity along the pathway to civilization, because it was the cultivation of the cereal grains that transformed the hunter-gatherer into the agriculturalist. The beginnings of civilization had their root in primitive people discovering the possibility of staying in one place where cereal seed, sown intentionally, would yield a reasonably reliable source of food. The consequences of a fixed dwelling place, near the cereal crops, were the construction of permanent housing, the domestication of animals (fed with the cereal grain), and the spare time to develop the many other characteristics of civilization.

Important contributions to these developments were the transition from merely chewing raw grain to grinding it between stones, soaking to make it easier to chew, and applying heat to further aid mastication and digestion. Further progression led from porridge to baked and leavened foods. From contributions to the origins of civilization, grain-crop cultivation and processing has contributed to the wider needs of good nutrition for mankind. Even today, one's diet is importantly reliant on foods made from the various cereal grains, which are recommended as essential components of balanced nutrition.

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