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Cereals

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INTRODUCTION

Cereal grains are the major food of humankind. In many of the less developed countries of the world, cereals provide two-thirds or more of the dietary calories (Deshpande and Damodaran 1990). Rice in Asia, corn (maize) in South America, sorghum in Africa, and wheat in the Middle East are recognized as the staple foods on whose yields famine or feast depends. Among the developed countries there are many, such as Russia and Japan, in which cereals still provide more than half the dietary calories. Although cereals make a smaller direct contribution to the diet of such developed countries as the United States and Canada, total cereal use per person is extremely high; however, most of the grain is fed to livestock and becomes an indirect component of human diets.

Rising standards of living in several parts of the world, especially traditional third world developing countries, are generally associated with higher consumption of meat and hence, indirectly, more grain. It takes an average cow 17 kg of vegetable protein to gain 1 kg of edible animal protein (Holmes 1971; Borlaug 1974). Thus, whereas in India the average per capita consumption of cereal grains is 158–170 kg per annum, in the United States it is 675 kg (Salunkhe, Chavan, and Kadam 1985; Pomeranz 1987). Japan is a classic example of the switch to a meat diet as prosperity increases. Between 1960 and 1972, annual meat consumption increased from 6.4 kg per person to 23.3 kg, an increase of 264% during a period when incomes increased by 204% (Allaby et al. 1975). It has been estimated that of every 30 metric tons (MT) average annual growth of world grain output, approximately 22 are absorbed by population growth and 8 by rises in per capita incomes (FAO 1988).

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D. K. Salunkhe et al. (eds.), *Foods of Plant Origin*

World production of cereals over the past thirty years has increased more rapidly than the world population, but with much more variation from year to year; for the world as a whole, increase in yield per unit area has contributed much more than the increase in the area under cereal crops (FAO 1988). This is particularly so in the developed countries; but in the less developed countries, the rather smaller increases in grain production have been due about equally to increases in yield and in area.

The world average yield of cereal grains is approximately 2.5 metric tons per hectare (MT/ha), two to three times greater than that of legume crops and oilseeds. Partly because of their higher yielding ability and greater economic returns, especially under subsistence farming, cereals are displacing pulses and legumes in many less developed countries, even though they complement one another both agronomically and nutritionally. Also, the rate of increase in yield, on a world scale, is much greater in the major cereals than in the legumes; consequently, cereals are becoming a progressively more predominant component of the total world food supply.

Given the restrictions on further increase in the area of land under cultivation, greater cereal yields are the key to increased food supplies. Improved agronomy, such as better weed control and more timely and effective fertilizer applications, has contributed greatly to the recent increases in cereal yields, as has better control of diseases and pests, whether by genetic or chemical means. Plant breeding has played a major role in three ways:

1. the selection of disease- and pest-resistant cultivars,
2. the development of shorter-statured varieties that do not lodge at high levels of fertilizer application, and
3. the selection of cultivars with greater yield potential that can respond to higher inputs.

All three plant-breeding approaches are essential and must be linked, so it is difficult to partition actual progress among them. At the lower yield levels, improved agronomy may be the major requirement for progress, as with corn in Africa (Evans and Wardlaw 1976). As fertilizer inputs increase, lodging resistance becomes more important, while in high-input systems increase in yield potential may be rate limiting.

Compared to developments in crop physiology, genetics, and agronomy, much less attention has been paid worldwide on reducing the tremendous losses that occur during the storage and handling of cereals. As much as 50% losses occur alone during the postharvest handling and processing of cereals, especially in the developing countries, where development infrastructure was too marginal or nonexistent to handle the tremendous yield increases achieved in cereal production during the recent decade.

Given the vast literature available on various aspects of cereal production and technology and the constraints of summarizing such information in one chapter, the present review is intended to be only a bird's-eye view of the recent developments in these areas. Although most aspects of cereal production and technology are briefly dealt with here, attention has been primarily focused on areas that need our attention in the coming years if we are to meet the increasing demands on our food supplies that would be made in the twenty-first century.

PRODUCTION AND DISTRIBUTION

According to Frey (1984), total world cereal production can be roughly divided into four groups: The first three are wheat, rice, and corn; the fourth includes barley, oats, rye, sorghum, various millets, and buckwheat. World cereal production in the recent past has shown variable trends (Table 1-1). Total production increased up to 1986 and then decreased slightly during 1987–8. In 1988, although rice production in the tropics increased, that of wheat, barley, and other coarse grains declined. This could be attributed to a decrease in cereal production in the United States and Canada, two of the largest cereal producers in the world, both of which recently experienced drought conditions (Table 1-2). The decrease of 31.5% in total U.S. cereal production in 1988 alone as compared to 1979–81 could also be attributed, in part, to land being taken out of cultivation as a part of government subsidy programs (FAO 1988).

Comparison of the 1960 and 1980 figures shows a large increase in the production of corn, wheat, rice, and barley, varying from a 75% increase in rice production to 92% for barley (Frey 1984). Sorghum and millet production in Africa and Asia increased nearly 66% and 100%, respectively, whereas Latin America has seen a spectacular sixfold increase in millet production. Total cereal grain output was about 1,800 million MT for 1986–8. The increase over 1969–71 was 22.6%, or a 22.3% increase per year (USDA 1989). Not only the production of cereal grains has increased during the past two decades; the cereal grain productivity (i.e., the yield per hectare) has also increased signifi-

Table 1-1. Worldwide Production[a] Trends of Cereal Grains, 1983–8.

	1983	1984	1985	1986	1987	1988
Total cereals	1642.7	1805.3	1844.5	1863.9	1803.1	1743.0
Wheat	494.0	517.3	505.9	536.7	517.2	509.9
Rice	451.2	470.4	472.6	472.5	464.5	483.5
Coarse grains	697.4	817.7	865.2	854.7	821.5	749.6
Corn	347.8	452.7	487.7	485.1	458.0	405.5
Barley	161.9	172.5	176.6	182.4	181.7	168.4
Other	197.7	192.5	200.9	187.2	181.8	175.7

Source: FAO (1988), courtesy Food and Agriculture Organization of the United Nations.
[a] In thousands of metric tons.

Table 1-2. Production of Total Cereals in Different Regions of the World.

Region	Production (10^6 MT) 1979–81[a]	1988	% change
World	1590.3	1743.0	+ 9.6
Africa	72.6	89.2	+ 22.9
N. America	369.5	269.3	− 27.1
USA	301.3	206.5	− 31.5
S. America	66.8	80.2	+ 20.0
Asia	640.0	797.2	+ 24.6
China	286.6	352.3	+ 22.9
India	138.2	175.6	+ 27.1
Europe	248.9	296.9	+ 19.3
Oceania	219.6	230.4	+ 4.9

Source: FAO (1988), courtesy Food and Agriculture Organization of the United Nations.
[a]Mean of three years.

Table 1-3. Grain Yield of Some Barley Cultivars Released during 1960–80 and Grown at the Plant Breeding Institute, Cambridge, England.

Cultivar	Year of Introduction	Grain Yield (kg/ha)
Vada	1960	5,700
Zephyr	1966	5,960
Golden Promise	1966	5,510
Julia	1968	6,200
Maris Mink	1973	5,930
Sundance	1976	6,320
Georgie	1976	6,300
Ark Royal	1976	6,350
Egmont	1980	6,930
Koru	1980	6,740
Triumph	1980	6,680

Source: Riggs et al. (1981).

cantly. The average yield for 1961–79 was highest for corn, followed by rice, barley, wheat, rye, oats, sorghum, and millet. It is, however, difficult to make valid comparison of yields of different cereals because of environmental conditions: The yield trend would vary depending on the cultivars and the year of introduction of the crop. For example, barley cultivars showed a large variation in grain yield (Table 1-3).

Total world production of the eight major cereals in recent years is sufficient to provide approximately 370–390 kg of cereal grains per person per annum, or slightly more than 1 kg/person/day, if shared equally among the entire world population. However, the average human consumption of cereals is only about one-third of this figure. This is largely due to a major proportion of cereal production being used for purposes other than human food—mainly as animal feed, industrial processing, and seed. In addition, there is considerable wastage of grains during storage and postharvest handling and processing of cereals.

The United States, Canada, Argentina, Australia, New Zealand, South Africa, and Thailand have been the net exporters of cereal grains (USDA 1989). Eighty percent of the total export came from the United States and Canada alone, despite the fact that their share of total world cereal grain production is only about 25%. It is quite apparent that world cereal production is not related geographically to food needs. Total per capita grain consumption varies from less than 200 kg per year in Pakistan, Philippines, Indonesia, India, and Nigeria to over 700 kg in the United States. Of the 700 kg consumed per person in the United States, about 100 kg is consumed directly as bread, pastries, and breakfast foods; the remaining 600 kg is fed to livestock (USDA 1989).

World agricultural production and population grew at an annual rate of 2.2% and 1.85%, respectively, from 1971 to 1980 (FAO 1981). If such production and population trends continue for the next twenty years, demand growth in the ninety developing countries (2.9%) will exceed projected agricultural production growth, according to projections by the FAO (1981, *Agriculture Towards 2000*). The imbalance will be greatest in Africa and West Asia. Self-sufficiency in cereals in developing countries would decline from 91% in 1979 to 83% in the year 2000, again with the situation being much worse in Africa and West Asia than in other regions. The ninety developing countries (including China) are projected to have a cereal deficit of 165 million MT by the year 2000. Most experts believe that the world is now probably producing enough to feed its people. However, because population distribution is not uniform worldwide, most experts predict that, by the year 2000, there will be an insufficient supply as well as inequitable distribution of food grains, primarily that of cereals.

ORIGIN AND BOTANICAL CLASSIFICATION

The term "cereal" is derived from *Cerealia munera,* the gifts of the goddess Ceres. It is commonly used to refer not only to the grain itself, and to the many foods manufactured from it (including flour, meals, bread, and flaked, shredded, or puffed breakfast cereals), but also to the cultivated grass plants (wheat, rice, corn, barley, oats, sorghum, rye, and millet) that yield the grain. All these grasses belong to the large monocotyledonous family Gramineae (Fig. 1-1).

At least two other species belonging to this family are economically important sources of food: sugarcane (*Saccharum* spp., Tribe Andropogoneae), the

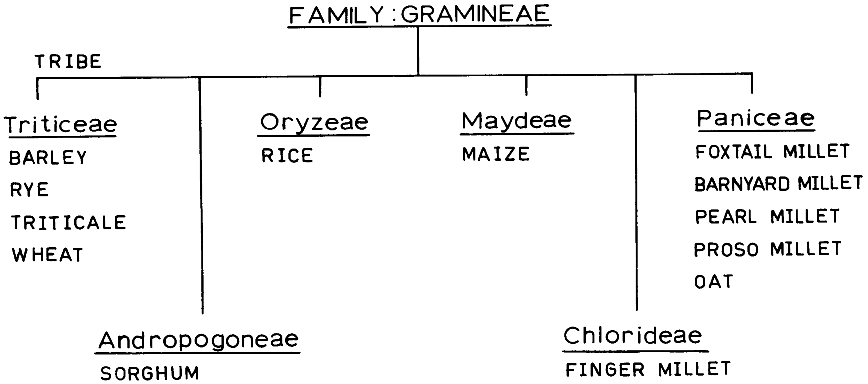


Fig. 1-1. Botanical classification of cereals.

principal source of sugar worldwide, and bamboo (*Arundinaria* spp., Tribe Bambuseae), whose young tender shoots are commonly consumed as vegetables in several East and Southeast Asian countries.

The cultivated grasses are cereals in the strictly botanical sense; but several other botanically different plants, often called "pseudocereals" (Brouk 1975), must be grouped with cereals because of the similarity of their use. Since most pseudocereals did not require cultivation but were simply gathered, it appears that many of these were used for human food long before grasses were successfully cultivated. Some pseudocereals, such as buckwheat, were cultivated in China and by Native Americans.

At present, the pseudocereals are a relatively insignificant group of crops. In contrast, the true cereals represent the world's most important source of food. In fact, if any one of the other commodity groups were to become unavailable, humankind could still survive and remain tolerably healthy; but a failure of the cereal crops would bring starvation and malnutrition to most parts of the world.

The cultivation of cereal crops, together with the domestication of animals and the invention of pottery, marked the beginning of the Neolithic period (Brouk 1975; Langer and Hill 1982). Except for corn, which originated in America, all the cereals are native to the Old World. The important characteristics of the cereals and pseudocereals are briefly described below.

Cereals

Wheat (**Triticum** *spp.*)

Wheat has been known since prehistoric times. The oldest grains, found in excavations of the Jarmo site in the upland of eastern Iraq, date from 6750 B.C. (Brouk 1975). It rapidly became the most important cereal, a position it still occupies in today's world.

The wild diploid progenitor of wheat occurs throughout the Fertile Crescent of the Middle East, where it was first domesticated about 10,000 years ago along with barley and several pulses (Harlan and Zohary 1966) by the selection of nonshattering, larger-seeded forms. Tetraploid wheats also developed in this area at about the same time. The final step in the evolution of wheat was the hybridization of the tetraploids with *Aegilops squarrosa* to give the hexaploid bread wheat *T. aestivum*. *A. squarrosa* occupies a wider range of environments than do the other wheat progenitors. As such it may have conferred on wheat not only the protein characteristics required for bread making but also a greatly increased adaptive range (Evans and Wardlaw 1976). Thus wheat became a crop of both subhumid and semiarid steppes, and adapted to more acidic soils (Zohary, Harlan, and Vardi 1969; Slootmaker 1974). This has led to its subsequent spread through central Europe to higher altitudes and more humid environments. In its original environment, wheat germinated with the onset of autumn rains, grew through the winter to flower in early spring and mature its grains before the summer drought, and was a vernalizable, long-day plant (Evans and Wardlaw 1976).

The members of the tribe Triticeae, wheat species can be grouped according to the *genomes* or sets of chromosomes their somatic cells contain (Table 1-4). "Einkorn" wheat has been known since the Stone Age and was developed from the wild wheat, *T. boeoticum,* that still grows wild in Asia Minor and southeastern Europe. It carries two A-genomes. The tetraploid wheats were derived from wild "emmer" wheat, *T. dicoccum,* still found in Syria and Palestine. They contain the two A-genomes of the einkorn parent plus the two B-genomes derived from a wild grass, *Aegilops speltoides,* and thus have the genotype AABB. Hexaploid wheats were then developed from a further crossing that occurred when the cultivated tetraploid wheat came into contact with the weed *A. squarrosa,* probably growing on the borders of the fields of the mid-European lake-dwellers of the Neolithic period (Brouk 1975). The hexaploid wheat contains two genomes contributed by the weed, so its genotype is AABBDD.

The einkorn wheats are no longer of any importance and are grown only rarely, primarily as a fodder plant in the mountain regions of Spain. The cultivation of emmer wheat also is limited, being now mainly restricted to the Soviet Union and parts of Germany. In contrast, the tetraploid wheat *T. durum* grows best in warmer regions and is an important source of semolina flour used for the manufacture of pasta products. However, the type of wheat most widespread throughout the world is hexaploid wheat, mainly *T. aestivum vulgare.* It is the choice wheat for bread making.

From the practical standpoint, wheat is differentiated into two main classes: hard and soft. Respectively, these yield the strong and weak flours known to bakers (Pomeranz 1987). The strong flour from hard wheat is of a coarse texture and is required for bread making. The weak flour from soft wheat, howev-

Table 1-4. Genomic Classification of Cultivated Wheat Species.

- *Einkorn group:* 7 pairs of chromosomes, diploid wheats
  - Wild form, fragile rachis, kernel in hull
    - *Triticum boeoticum*
  - Cultivated form, fragile rachis, kernel in hull
    - *T. monococcum* Einkorn
- *Emmer group:* 14 pairs of chromosomes, tetraploid wheats
  - Wild form, fragile rachis, kernel in hull
    - *T. dicoccoides*
  - Cultivated form, partly fragile rachis, kernel in hull
    - *T. dicoccum* Emmer (emmer wheat)
    - *T. timopheevi* (Timopheevi wheat)
  - Cultivated form, tough rachis, free kernel
    - *T. durum* (durum wheat)
    - *T. turgidum* (poulard or rivet wheat)
    - *T. polonicum* (Polish wheat)
    - *T. carthlicum* (= *persicum*) (Persian wheat)
    - *T. turanicum* (= *orientale*)
- *Vulgare group:* 21 pairs of chromosomes, hexaploid wheats
  - Wild form, none; synthetic type only
  - Cultivated form, partly fragile rachis, kernel in hull
    - *T. aestivum* subsp. *spelta* (spelt wheat)
    - *T. aestivum* subsp. *vavilovi* (Vavilov wheat)
    - *T. aestivum* subsp. *macha* (Macha wheat)
  - Cultivated form, tough rachis, free kernel
    - *T. aestivum* subsp. *vulgare* (common or bread wheat)
    - *T. aestivum* subsp. *compactum* (club wheat)
    - *T. aestivum* subsp. *sphaerococcum* (short wheat)

Source: Briggle and Reitz (1963).

er, is a fine powdery flour that, although of little use for bread making, is very good for biscuit manufacture. As will be described later (under "Processing Technology"), various grades of flours can be obtained from different kinds of wheats, or sometimes by blending strong and weak flours together.

Hard wheat is commonly grown in the United States and Canada as well as in the warmer parts of Europe; soft wheat is primarily grown in the United Kingdom and in northern and central Europe. Varieties described as "red" have a reddish-colored grain due to the presence of an anthocyanin pigment in the bran.

Bulgur, primarily used as a substitute for rice, is prepared from varieties of both common and durum wheat by parboiling, drying, cracking, and removing some of the bran.

Rice (Oryza *spp.*)

The rice species and their varieties (Tribe Oryzeae, Fig. 1-1) are certainly the main and often the only cereal used by several nations of the Far East and by Southeast Asian countries. According to ancient records, rice has been cultivated in China for 5,000 years, and Theophrastus mentions its cultivation in India (Langer and Hill 1982). It was first brought to Europe by Alexander the Great, but its cultivation started no earlier than the eighth century A.D. In A.D. 711, the Moors began to grow rice in Spain. The only European country producing rice in large quantities today, however, is Italy, where the plantations are situated in the north along the River Po.

Rice has two parallel series of species ranging from wild perennial to cultivated annual. One species, *Oryza glaberrima,* was domesticated in West Africa; the other, *O. sativa,* in Asia (Evans and Wardlaw 1976). It is predominantly a rain-fed crop, its most characteristic environment being the flooded fields of the tropics. As in other cereals of tropical origin, the response of rice to daylength has been considerably modified as the crop spread to higher latitudes. However, most wild forms and tropical cultivars are short-day plants and exhibit strong photoperiodism, although a few of the traditional upland rice varieties are relatively insensitive to daylength (Evans and Wardlaw 1976).

The commonest species of rice is *Oryza sativa.* Its varieties are subdivided into three subspecies: *japonica, javanica,* and *indica.* The *japonica* types are short-grained, the *javanica* of intermediate types, and the *indica* rices are long-grained. In general, *japonica* rices adapt to cooler temperatures and longer days better than the *indica* rices long ago selected in China, Japan, and elsewhere (Chang and Oka 1976). At higher latitudes, the cultivars become even less sensitive. There are over 2,400 varieties of cultivated rice; in India alone, about 1,100 of them are cultivated (Langer and Hill 1982; Brouk 1975; Pomeranz 1987).

Rice is the only cereal cultivated in flooded fields that remain flooded for the major part of the growing season and are normally drained a few weeks before harvest. Drainage of the fields creates favorable conditions for the grain to complete its development. There are, however, also varieties of rice that grow like other cereals in soils that are not flooded: These so-called dry, upland, or hill rices, although the oldest cultivated rice form, are today of no economic importance. The bulk of the rice consumed is produced from flooded fields and is called wet, aquatic, or lowland rice. The seedlings planted in the flooded fields are produced in nurseries that are also either wet or dry. In some countries, rice is sown directly in the flooded fields, but this method of cultivation is wasteful.

The so-called wild rice growing in Africa, Southeast Asia, and North America is in fact a plant of another genus, *Zizania,* but belongs to the same tribe, Oryzeae (Brouk 1975). *Z. aquatica* was an important cereal for Native Americans, although it is not a cultivated grass. Wild rice is also used in China, but more as a vegetable than as a cereal, the green parts and not the grain being eaten.

Corn (Zea mays)

Corn (maize) is the only cultivated cereal to originate from the American continent. The "discoverers" of America found the plant already in a state of cultivation, and there is ample evidence of its having been cultivated for at least 4,000 years, since the time of Mayas and Aztecs.

Corn is native to tropical Central America, the wild plant nearest to it being teosinte or *Zea (=Euchlaena) mexicana;* however, teosinte is not the true ancestor of cultivated corn. According to Brouk (1975), both plants had a common ancestor, now extinct, which by hybridization with another grass, *Tripsacum,* produced both corn and teosinte. Corn is intolerant to both shade and drought, and presumably originated in an area with alternately wet and dry seasons, where control of life cycle timing by daylength was very important (Evans and Wardlaw 1976). Many tropical races of corn are short-day plants, whereas modern temperate-zone cultivars appear to be almost wholly indifferent to daylength (Stevenson and Goodman 1972).

Corn also differs from other cereals in that its spikelets are unisexual, forming separate male and female inflorescences on the same individual. The staminate flowers form the terminal panicle, or so-called tassel, and the pistillate flowers in spikelets form the spadix, or cob, from which the grain develops. The cob arises laterally in the axil of the foliage leaf in which it is ensheathed.

There are many varieties of corn. *Zea mays* var. *saccharata* is the common sweet corn, mostly used as "corn on the cob" in the United States. *Z. m.* var. *everta* is a special variety from which popcorn is produced: Its small, hard seeds have a hard and glossy outer endosperm; the kernels burst when exposed to high temperatures, everting the soft palatable inner endosperm. Other varieties of corn normally cultivated include dent corn, *Z. m.* var *americana,* which is characterized by an indentation or depression on the top of the grain, caused by shrinkage of the soft endosperm. This is the typical corn of the American corn belt. Flint corn, *Z. m.* var. *praecox (=indurata),* with a hard endosperm and no indentation, is normally cultivated in Europe. Flour or soft corn, *Z. m.* var *amylacea,* is without the horny endosperm and is cultivated almost exclusively by Native Americans for their own use. Finally, waxy corn, although not regarded as a distinct variety, is valuable because its starch consists entirely of amylopectin. Other cornstarches normally have a 25 : 75 ratio of amylose to amylopectin.

Barley (Hordeum *spp.*)

The origin of barley has been dated as far back as 8000 B.C. (Brouk 1975; Langer and Hill 1982). Neolithic excavations at Fayum in Egypt have revealed that barley was grown by the ancient Egyptians. It was also known to the Greeks and Romans, and was cultivated in ancient China, whence it was introduced to Japan about 100 B.C. Barley thus appears to have been domesticated at the same time and place as wheat, and may have been even more important than wheat in the early stages of domestication. A wholly diploid crop, its history of change is similar to that of wheat, though it is not so well adapted to extreme cold. Today, as a cereal, barley plays only a minor role, the bulk of its production being used for brewing.

The commonest species, *H. distichum,* is a two-rowed barley type in which only the central spikelet is fertile and awned. In *H. vulgare* (=*hexastichum*), a six-rowed barley, all three spikelets are fertile and awned. Four-rowed barley in which all three spikelets are fertile but are asymmetrically arranged is also grown.

The cultivated varieties of barley were thought to be derived from the wild two-rowed barley, *H. spontaneum* of Southwest Asia. However, the more recent discovery of a wild six-rowed barley, *H. agriocrithon,* growing in Tibet has led to a reexamination of the theories of the origin of cultivated barley (Langer and Hill 1982; Brouk 1975). It appears likely that either *H. agriocrithon* gave rise to the cultivated species *H. vulgare,* and that *H. spontaneum* was the parent of *H. distichum,* or that a cross between *H. agriocrithon* and *H. spontaneum* produced the ancestors of both cultivated varieties.

Oats (Avena *spp.*)

Oats are of uncertain origin, although believed to be native to Asia. Oats may have appeared as weeds in wheat and barley fields in the Middle East. They became a secondary crop of increasing importance as the temperate cereals spread to higher latitudes and cooler, wetter climates (Evans and Wardlaw 1976). Oats derive from a polyploid series like wheat. The commonest cultivated species, the hexaploid *Avena sativa,* was derived from wild oats, *A. fatua,* whereas the cultivated red oat, *A. byzantina,* was believed to be descended from the wild red oat *A. sterilis.* However, recent genetic, physiological, and pathological studies have indicated that *A. sativa* is more likely to have been derived directly from *A. byzantina;* hence, *A. sterilis* is most probably the progenitor of all the other species of oats, including *A. byzantina, A. sativa, A. orientalis, A. fatua,* and *A. nuda* (Brouk 1975).

Although oats are a highly nutritive cereal, they are widely cultivated as an animal food plant, especially as fodder for horses in the colder parts of the temperate zone. In recent years, oat bran and fiber have become increasingly popular as breakfast cereal because of their alleged cholesterol-lowering effects in human nutrition.

Rye (Secale cereale)

Rye is one of the most recently domesticated cereals, being known to the ancient Greeks and Romans, but not to the ancient Egyptians. It is believed to have originated in Afghanistan and Turkey, where its wild ancestor, *S. montanum,* is still found (Lorenz 1982). Another wild form of rye, *S. anatolicum,* is also found in Syria and Iraq. Similar to oats, rye may have appeared as a weed crop in the ancient wheat and barley fields of the Middle East. Like barley, rye is a diploid with a notable winter hardiness and a capacity to grow on light and acid soils (Evans and Wardlaw 1976). There are only a few cultivated varieties of rye, and over 90% of the world production comes from Europe, where rye bread is preferred in countries such as Germany, Austria, Czechoslovakia, Poland, and the USSR. The Soviet Union is the largest producer of rye, since the crop is well adapted to colder climates with short summers.

Triticale

Triticale is the first man-made cereal and is a product of a cross between the genera *Triticum* and *Secale.* It was first described in the scientific literature in 1876 when A. S. Wilson reported the production of two sterile plants by crossing hexaploid wheat (*T. aestivum*) and diploid rye (*S. cereale*) (Skovmand, Fox, and Villareat 1984). The F_1 hybrids were very vigorous but sterile. Many years later in prerevolutionary Russia, spontaneous chromosome doubling apparently occurred in some wheat × rye F_1 hybrids, resulting in the first true-breeding diploid triticale.

Triticale is currently produced primarily in developed countries that are noted for their already high levels of small grain production. Spring triticale is commonly grown in Australia, Argentina, and Canada; the USSR, United States, France, and China are the largest producers of winter triticale.

Sorghum (Sorghum vulgare, S. bicolor)

A member of the tribe Andropogoneae (Fig. 1-1), sorghum was known as a cereal in ancient Egypt by 2200 B.C. It was probably domesticated in Africa, possibly 5,000 years ago (de Wet and Harlan 1971), in the savanna belt stretching from Lake Chad to the Sudan (Harlan 1971). From there it spread through Africa and India to China. Many tropical sorghums are strict short-day plants in which local adaptation of daylength response is very important (Evans and

Wardlaw 1976). The requirement for short days initially confined sorghum to the southern United States, but the selection of earlier maturing varieties and hybrids led to its cultivation at higher latitudes (Ross and Eastin 1972). Sorghum is not yet as well adapted to cool temperatures as is corn, but it is more drought resistant. The commonest species (which is often erroneously called millet) is *Sorghum vulgare*. The major cultivated varieties developed include *S. vulgare* var. *durra* (durra sorghum), *S. v.* var. *caffrorum* (kaffir sorghum of Africa), *S. v.* var. *rexburgii* (Indian sorghum, also known as *shallu*), and *S. v.* var. *nervosum* (Chinese sorghum, *kaoliang*). Sorghum is a tropical plant and grows only in warmer countries including those of the Mediterranean region and the U.S. South. It is an important human food in China, India, and Africa; elsewhere, the plant and grain are mainly used for fodder.

Millets

Finger Millet (*Eleusine coracana*)

This is the only millet that belongs to the tribe Chlorideae; all others belong to the tribe Paniceae. In various parts of the world, finger millet is also known as *ragi, nagli, telabun, marua, korakan,* bird's-foot millet, or African millet. The plant probably originated in India, and is now widely cultivated in India, Malaya, China, and the wetter parts of Central Africa.

Foxtail Millet (*Setaria italica*)

Depending on its country of origin, this millet is also known as Italian, German, Hungarian, or Siberian millet. In ancient times, foxtail millet was commonly used for human food in Europe; but today, because of higher economic standards, it is cultivated only for fodder. This plant is probably of Asiatic origin, and was being cultivated in China in the year 2700 B.C. (Brouk 1975). In Europe, it is known to have been grown by the lake-dwellers.

Japanese Barnyard Millet (*Echinochloa crusgalli* var. *frumentqacea*)

Japanese barnyard millet, also called *sanwa* millet, is used in Japan and Korea as human food, mostly prepared as a form of porridge. It is cultivated as a forage plant in the United States.

Pearl Millet (*Pennisetum typhoideum, P. glaucum*)

Pearl or bulrush millet was known in Asia and Europe in prehistoric times, but seems to have originated in tropical Africa. It is cultivated mainly in India and Africa, where it is ground into flour and made into bread or cooked as a porridge.

Proso Millet (*Panicum miliaceum*)

Proso millet (also known as hog or broom millet) is the true millet of the ancient Romans who called it *milium*. *Proso* is a Russian word for millet. The plant is generally believed to have originated in Egypt or Arabia and to have spread to the Soviet Union, India, China, and Japan, where it is mainly cultivated today. Some is also grown in the Mediterranean region.

Pseudocereals

All plants outside the Gramineae having fruits and seeds that can be ground into flour for making bread and similar products might be called *pseudocereals*. Although this group includes acorns, beechmast, sweet chestnuts, seeds of leguminous plants, and so on, these plants have today lost their importance as pseudocereals and have mainly acquired another function for human consumption (e.g., as nuts or pulses). Thus the true pseudocereals are nowadays mainly plants with small seeds used in the same way as cereals and also cultivated like cereals in fields. These include buckwheat, still sown in Asia and some parts of Europe and America; amaranth species, mainly of Central and South America, which were cultivated by the Aztecs; quinoa, the "cereal" of ancient Incas, still grown in Ecuador, Bolivia, and Peru; and the Mexican chia, another pseudocereal of the Aztecs (Brouk 1975). The only pseudocereal greatly dissimilar to cereals is the water chestnut, an annual aquatic plant bearing submerged large nuts. This was cultivated in Neolithic times in Europe but today it is grown only in China and the Far East.

In chemical composition, the seeds of pseudocereals are similar to those of the true cereals; unfortunately, figures are available only for buckwheat (described later under "Chemical Composition and Nutritional Quality"). Also, of all the pseudocereals, only buckwheat is mentioned in the world statistics of agricultural production of the Food and Agriculture Organization. Some of the economically important pseudocereals are briefly described below.

Amaranth (Amaranthus *spp.*)

The genus *Amaranthus* belongs to the family Amaranthaceae, which is very closely related to the family Chenopodiaceae. *Amaranthus leucocarpus* grows in the New World and is native to Central America. It is primarily cultivated in Mexico and Guatemala. In Mexico, it has been an important crop since 5000–3000 B.C., and the Aztec Emperor Montezuma received annual tribute from his subjects in amaranth grain (Brouk 1975). *A. cruentus* is cultivated in Guatemala and other parts of Central America, whereas *A. caudatus* is grown in the Andean region of Bolivia, Peru, and northern Argentina. *A. paniculatus* is a grain crop of Southeast Asia. Leaves from plants of this genus are also widely used as a vegetable on the Indian subcontinent.

Buckwheat (Fagopyrum *spp.*)

Buckwheat is a member of the dicotyledonous family Polygonaceae. As the name implies, it is cultivated much the same way as wheat, and its seeds are separated from the pericarp and ground into flour to be used in making porridge (i.e., Russian kasha) or pancakes. Sometimes the whole unmilled seed is consumed.

Buckwheat is a native of Central Asia, where it still grows wild. For several centuries, it has been cultivated in China, whence it was introduced into Europe at the end of the Middle Ages. It is still an important crop for human consumption in the USSR. In other European countries, however, it is grown mainly as a fodder plant.

There are three distinct species in the genus *Fagopyrum: F. esculentum* Moench (*F. sagittatum* Gilib, common buckwheat), *F. tartaricum* (tartary buckwheat), and *F. cymosum* (wild perennial buckwheat). Both diploid ($2n = 16$) and tetraploid ($2n = 32$) species are known to occur in common and perennial buckwheats, whereas tetraploids have not been reported in tartary buckwheat. Most species of the genus *Fagopyrum* are variable in plant habit and are markedly affected by habitat conditions, thus making them extremely difficult to differentiate from one another. The most consistent method of identifying these plants is on the basis of their fruit (achene) characteristics. The species of buckwheat most commonly grown in the North American continent is *F. esculentum,* whereas tartary buckwheat is cultivated for food purposes in the Himalayan regions of India and China (Pomeranz 1983).

Chia (Salvia columbarie)

Widely cultivated by the ancient Aztec civilization, chia and its related species belong to the same genus as sage (*S. officinalis*) and to the family Labiatae. Chia species are native to Mexico, whereas sage is of Mediterranean origin. Chia was a staple food of the Aztecs, along with corn, amaranth, and beans.

Quinoa (Chenopodium quinoa)

This is a member of the family Chenopodiaceae and a native of Peru, where it was used in large quantities by the ancient Incas. The seeds may be ground into flour from which bread and cakes are prepared, or the entire grain may be eaten in soups. Quinoa is still grown to a large extent in mountainous regions of Ecuador, Bolivia, and Peru, where corn cannot be cultivated. Excavation records of several settlements show that another species, *C. nuttalliae,* was grown in Mexico in pre-Columbian times, whereas in Iron Age Europe the species *C. album* was cultivated (Brouk 1975). Leaves of some species of quinoa are also used like spinach.

Table 1-5. Chromosome Numbers and Centers of Diversity of Commonly Grown Cereal Crops.

Cereal	Chromosome No. ($2n$)	Centers of Diversity[a]
Wheat		
Einkorn	14	NE
Emmer	28	NE, ES
Bread wheat	42	CJ, HI, CE
Club wheat	42	ES, NE, CE
Rice	24	CJ, II, HI
Wild rice	30	NA
Corn	20	MA, SA, CJ
Barley	14, 28	NE, ME, CJ
Oats	42, 48, 63	ME, NE, CJ
Sorghum	20	CJ, HI, ME
Rye	14–29	CE, NE, CJ
Millets		
Finger millet	36	HI, AF
Italian millet	18	CJ
Pearl millet	14	AF
Proso millet	36, 54, 72	CJ
Triticale	42, 56	NA, ES
Buckwheat	16, 32	NE

Adapted from: Jung (1978) and Hanson (1990).

[a] The possible center of origin is listed first. Abbreviations: AF, Africa; CE, Central Asia; CJ, China, Japan; ES, Euro-Siberian; HI, Hindustani (India); II, Indochina, Indonesia; MA, Middle America; ME, Mediterranean; NA, North America; NE, Near East; SA, South America.

Water Chestnut (Trapa *spp.*)

Water chestnut (*Trapa natans*) belongs to the family Onagraceae, and is an annual aquatic plant native to the territory marked by Persia, Egypt, and southern Europe. In Neolithic times it was a common food of most of the European peoples, and grew at that time in central and even northern Europe. Nowadays water chestnut is a rare plant found in Europe only in the warmer countries (e.g., in Italy). The water chestnut still consumed as grain in China, Korea, and Japan belongs to another species of *Trapa, T. bicornuta.* It is mainly used in the form of flour, and in pre-Communist China was one of the five most important "grains" (Brouk 1975). The third edible species, *T. bispinosa,* is a native of tropical Asia and is known as the *singhara* (horny) nut. It is mainly the food of people living by lakes in the northern Indian state of Kashmir, and is usually consumed in the form of a porridge.

Table 1-5 summarizes the chromosome numbers and primary and secondary centers of diversity of the commonly cultivated cereal crops.

ANATOMICAL STRUCTURES OF SEEDS

The grain or kernel of a cereal is a nutlike fruit, or *caryopsis*. The fruit contains only one seed and, as it ripens, the ovary wall (or *pericarp*) becomes rather firmly attached to the wall of the seed proper and forms the outer tissue of the bran. The monocotyledonous embryo that develops into a new plant upon germination occupies only a small part of the seed. The bulk of the seed is composed of the flour portion (the *endosperm*), which constitutes a food reservoir.

In the grass family, the floral envelopes (modified leaves), or chaffy parts, within which the caryopsis develops, persist to maturity. In some cereals such as rice and most varieties of oats and barley, some of the chaffy structures constitute the hull of such grains (which are said to be "covered"). In the common wheats, rye, hull-less barleys, and the common varieties of corn, the caryopsis readily separates from the floral envelopes on threshing; these grains are said to be "naked."

The anatomical structure of various cereal grains are quite similar and have been extensively studied. Although numerous reports are available on the topic, studies on kernel structure of wheat (MacMasters, Hinton, and Bradbury 1972), rice (Bechtel and Pomeranz 1980), corn (Wolf et al. 1952), and sorghum (Rooney and Miller 1982) are the most commonly referred to. Generally, in most cereals, the endosperm constitutes nearly 80% of the total seed weight and consists of highly packed starch granules embedded in a matrix of protein. The germ, bran, pericarp, and seed coat are the other important components of cereal grains. The germ is usually distinctly separated from other components, whereas the bran, pericarp, and seed coat are described in association with one another. Sometimes the pericarp, the testa, and the aleurone layers are collectively called the bran. Endosperm hardness, which is generally determined by the relative proportion of corneous to floury type within the grain, plays a very important role in determining the processing quality and industrial uses of cereal grains.

Wheat

The structure of the wheat kernel is shown in Fig. 1-2. The dorsal side of the grain is round; the ventral has a deep groove along the entire length of the kernel. At the apex end (small end), a brush of small hairs is present. Except for durum wheats, the grains are either red or white.

Wheat kernel consists of germ and endosperm enclosed in a seed coat. The seed coat or pericarp consists of four outer layers: epidermis, hypodermis, cross cells, and tube cells (Salunkhe, Chavan, and Kadam 1985). The pericarp with aleurone constitutes the bran, which is rich in protein, cellulose, hemicellulose, and minerals. The germ consists of plumule, radicle, and scutellum, while the

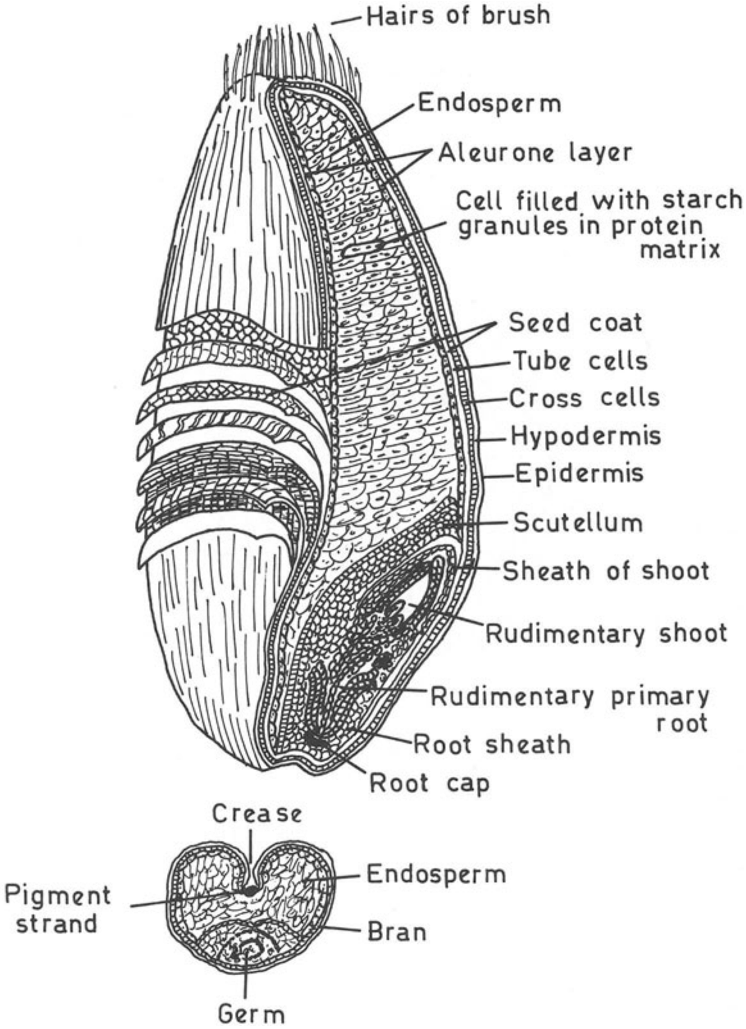


Fig. 1-2. Longitudinal and cross-section through a wheat kernel. *Source:* Wheat Flour Institute, Washington, D.C.

endosperm is highly packed starch grains in a matrix of protein. The outer portion of the endosperm is vitreous; the inner portion is floury. The durum wheats have a greater proportion of vitreous endosperm, whereas the soft red wheats have more floury endosperm. The relative proportions of the various constituents are as follows: 83% endosperm, 2.5% germ, and 14% bran.

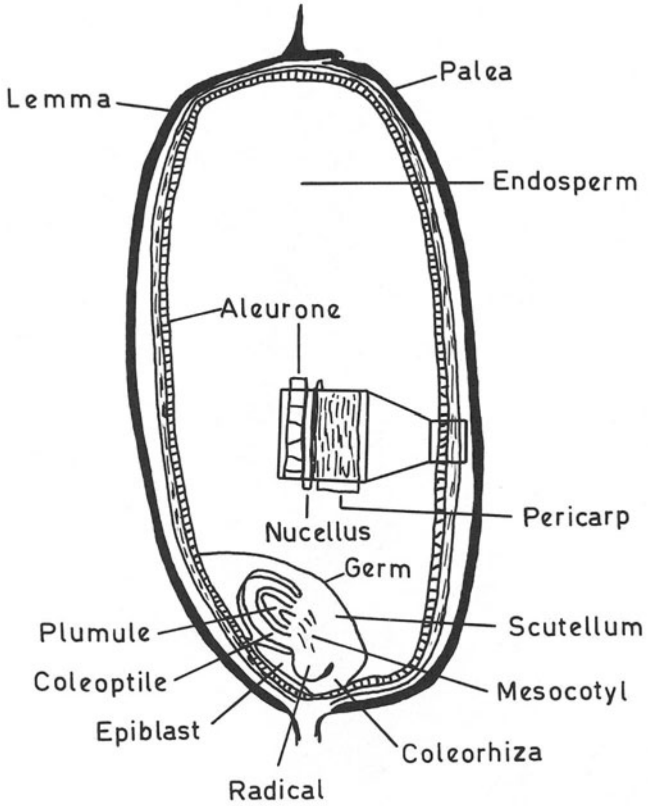


Fig. 1-3. Schematic diagram of a midlongitudinal section of rice caryopsis. *Source:* Pomeranz, Y., and Ory, R. L. 1982. In *Handbook of Processing and Utilization in Agriculture, vol. II, pt. 1, Plant Products,* ed. I. A. Wolff. CRC Press, Boca Raton, Fla., p. 139. Reprinted with permission.

Rice

Bechtel and Pomeranz (1980) described the fine structure of rice kernel in relation to its postharvest technology, storage, and nutritional and processing quality. Hull or husk, pericarp, seed coat (integument or testa), aleurone, endosperm, and germ are the principal components of rice seed (Fig. 1-3). In rice, the pericarp consists of outer pericarp, hypoderm, mesocarp, and cross cells; it constitutes about 4–5% of the kernel weight. The pericarp, along with the seed coat or testa, nucellus, and aleurone layer, forms the bran, which constitutes about 5–7% of the weight of the brown rice. The endosperm is predominantly made up of starch.

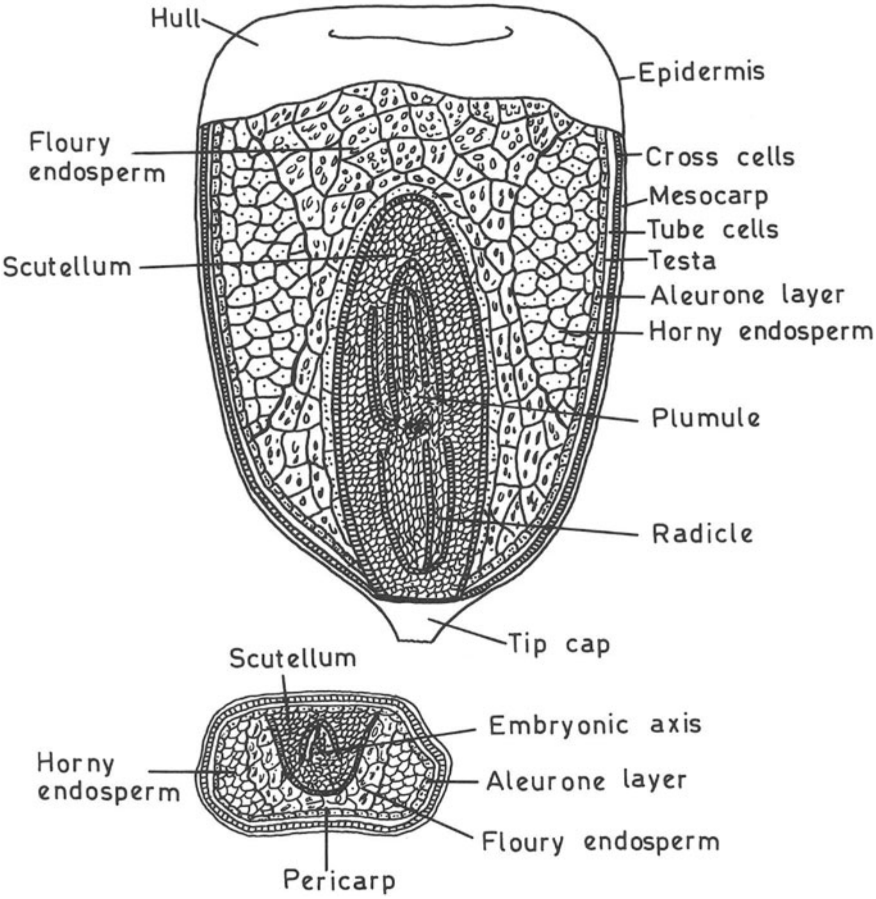


Fig. 1-4. Longitudinal and cross section through a corn kernel. *Source:* Wheat Flour Institute, Washington, D.C.

Corn

Studies on the structure of corn kernel have been recently reviewed (Salunkhe, Chavan, and Kadam 1985; Pomeranz 1987). Corn kernel is the largest of all the cereals. It is flattened, wedge-shaped, and broader at the apex end than at the point of attachment to the cob (Fig. 1-4). The size and weight (150–600 mg/kernel) of the kernel differs significantly from different types of plants and often even within the same ear. The color of the grain may be white, orange, yellow, cherry red, red, dark red, or brown. The pericarp and testa, endosperm, and the germ are the principal anatomical parts of the corn kernel. Their relative proportions vary considerably with grain type.

Corn pericarp consists of epidermis, mesocarp, and cross and tube cells, and constitutes 4–6% of the whole kernel. It mainly consists of insoluble non-starchy carbohydrates.

The endosperm consists of aleurone (2.2%), an outer two- or three-cell region (3.9%), and outer corneous (58.1%) and central floury (17.6%) portions (Salunkhe, Chavan, and Kadam 1985). The endosperm contributes about 80–85% of the kernel weight.

Corn kernel also has a relatively larger germ than other cereals. It is placed in the lower portion of the endosperm and contributes 10–14% of the kernel weight. Most of the oil (81–86%) and minerals (80%) are present in the germ. The higher proportion of protein and minerals also makes it susceptible to insect attacks, while the oil causes rancidity upon prolonged storage.

Barley

In barley grain, the husk, pericarp and testa, aleurone, endosperm, and germ are the important structures (Fig. 1-5). The husk accounts for about 10% of the dry weight of the grain. The pericarp, which is fused with the testa, is a mass of compressed cellulosic cells separated from the husk by a thin waxy layer; the testa is made up of two distinct bands containing fat and waxy material (Palmer and Bathgate 1976; Salunkhe, Chavan, and Kadam 1985). The aleurone is a distinct layer of cells between the testa and the endosperm. It secretes α-amylase, protease, and β-glucanase during malting (Palmer and Bathgate 1976; Pomeranz 1987). Similar to other cereal grains, barley endosperm is the major

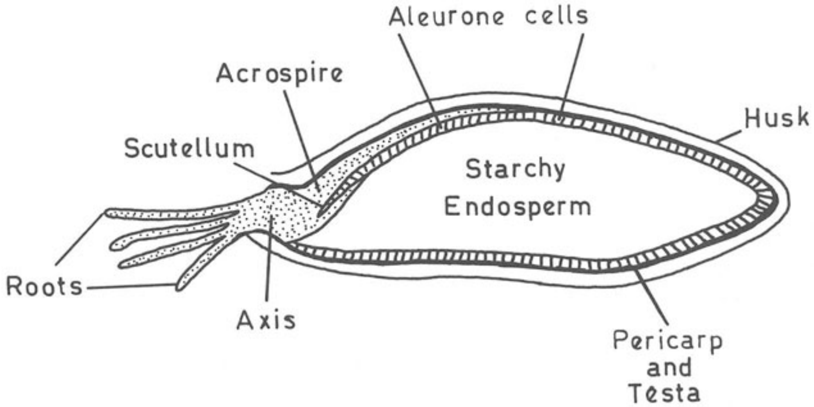


Fig. 1-5. Longitudinal section of a germinated barley kernel. *Source:* Burger, W. C. 1982. In *Handbook of Processing and Utilization in Agriculture, vol. II, pt. 1, Plant Products,* ed. I. A. Wolff. CRC Press, Boca Raton, Fla., p. 187. Reprinted with permission.

storage organ for protein bodies and starch granules. The embryo is partly embedded in the endosperm at the base of the kernel and is held at an oblique angle to the axis of the kernel. The literature on the structural and biochemical changes in embryo and endosperm of barley kernels during germination has been extensively reviewed (Palmer and Bathgate 1976; Pomeranz 1987).

Oats

With the exception of being covered with a fuzzy layer of trichomes or short hairs, the kernels (groats) of oats are similar in structure to the caryopsis of other cereal grains. In the common varieties of oats, the caryopsis is enveloped in a hull comprising certain of the floral envelopes; naked or hull-less varieties exist but are not extensively grown.

The hull content in oats varies with the test weight. In light, thin oats of low test weight, the hulls may comprise as much as 45% of the grain, but in very heavy or plump oats, they may represent only 20%. The dehulled kernels are called groats and contain 28–40% bran, 3% germ, and 55–68% endosperm.

Sorghum

Rooney and Miller (1982) have described the kernel structure of sorghum using light, fluorescence, and electron microscopy. The seed coat in sorghum is composed of pericarp and testa (Fig. 1-6). The pericarp comprises three to four layers: epicarp, mesocarp, cross-cell layer, and tuber-cell layer. The epicarp may be further subdivided into epidermis and hypodermis. The endosperm consists of the aleurone layer and peripheral corneous, intermediate, and floury portions. The aleurone is a single layer of blocklike rectangular cells beneath the testa. Sorghum germ contributes about 8–12% of the dry weight of the kernel and is made up of scutellum and the embryonic axis.

Rye

The mature rye kernels are more slender than those of wheat, and grayish-yellow, brown, or somewhat greenish in color. The crease or furrow extends the full length of the grain on the ventral side; the embryo is located at the base on the dorsal side. As in other cereal grains, the major components are pericarp, testa and aleurone, embryo and scutellum, and the endosperm. The mature kernels have a wrinkled pericarp, which gives them a rough appearance. The starchy endosperm represents the bulk of the kernel, and is composed of peripheral, prismatic, and central portions that differ in shape, size, and location within the kernels (Salunkhe, Chavan, and Kadam 1985; Pomeranz 1987). The embryo closely resembles that of wheat and is rich in oil and protein, whereas the aleurone layer is a major storage reserve of lipids.

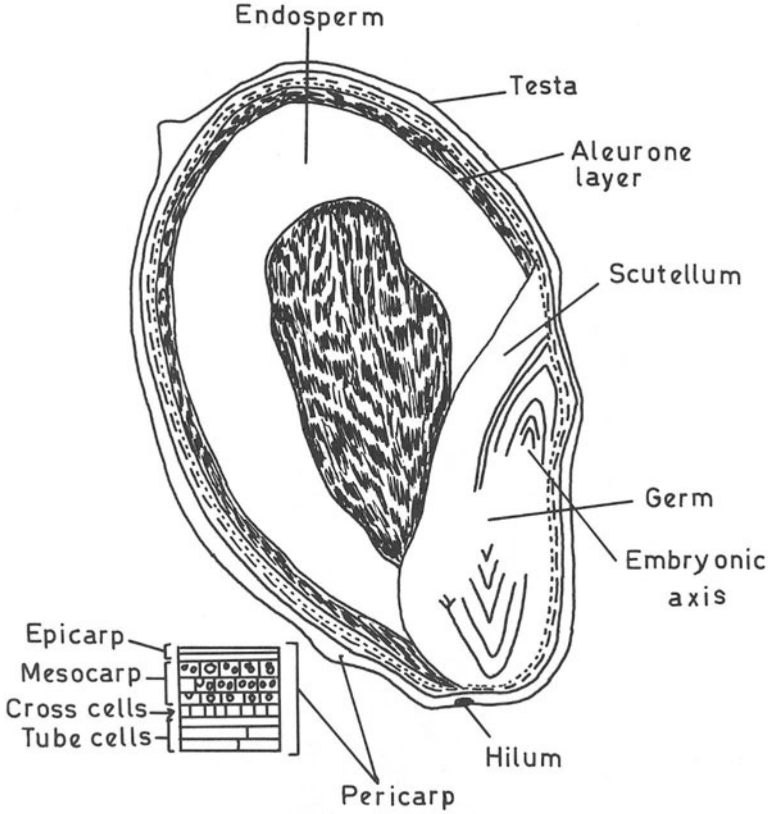


Fig. 1-6. Longitudinal section of a sorghum kernel. *Source:* Rooney, L. W., and Miller, F. R. 1982. *Proc. Int. Symp. Sorghum Grain Quality,* 28–31 October 1981. ICRISAT, Patancheru, India, p. 143.

Millets

Compared to other cereal grains, millets generally have smaller seeds. They also exhibit a wider range of size, shape, and color. For example, the pearl millet grain may be near white, pale yellow, brown, gray, slate blue, or purple in color, whereas finger millet grains may be white, orange-red, deep brown, purple, or almost black. In millets the pericarp, endosperm, and germ are the principal grain components. The aleurone is a single layer of blocklike cells extending around the periphery of the entire kernel. The starchy endosperm may be divided into peripheral, corneous, and floury regions. The grains of most minor millets also tend to be smaller than those of pearl millet, and have lemma and palea adhering to their pericarp. As a general rule, the seeds of common millets are flattened, oval, or smooth.

Table 1-6. Approximate Grain Size and Proportions of the Principal Parts Comprising the Mature Kernel of Different Cereals.

Cereal	Grain Wt. (mg)	Embryo (%)	Scutellum (%)	Pericarp (%)	Aleurone (%)	Endosperm (%)
Wheat						
Bread wheat	30–45	1.2	1.54	7.9	6.7–7.0	81–84
Durum wheat	34–46	1.6[a]		12.0		86.4[b]
Rice	23–27	2–3	1.5	1.5	4–6	89–94
Corn	150–600	1.15	7.25	5.5[b]		82
Barley	36–45	1.85	1.53	18.3		79.0[b]
Oats	15–23	1.6	2.13	28.7–41.4[b]		55.8–68.3
Sorghum	8–50	7.8–12.1[a]		7.3–9.3[b]		80–85
Rye	15–40	1.8	1.73	12.0		85.1[b]
Millets	7–14	2.3[a]		8.4–12.1		88–91[b]
Triticale	38–53	3.7[a]		14.4		81.9[b]

[a] Includes scutellum.

[b] Includes aleurone layer.

Adapted from: Simmonds (1978), which includes the original references.

Buckwheat

Buckwheat is not a true cereal. The fruit of a dicotyledonous plant, it is, however, classed in agriculture and commerce with the cereals. With the exception of the floral envelopes being absent, like the cereals, the grain of buckwheat is a dry fruit (achene). The kernels or achenes are triangular, either glossy, dull gray, dark brown, or black in color, and have a thick fibrous pericarp, which is not fused or cemented to the seed as in the true cereals.

The fruit in most varieties is 4–6 mm long, but 6–9 mm in Japanese types. It consists of hulls, spermoderm, endosperm, and embryo (Javornik and Kreft 1980). The kernels are easily dehulled. The hulls represent 17–26% (up to 33% in tartary buckwheat) of the kernel weight. The diploid varieties tend to have fewer hulls than the tetraploid. In common with the cereal grains, buckwheat has an aleurone layer of large, starch-free cells that surrounds the starchy endosperm (Marshall 1969; Pomeranz 1983). The embryo is dicotyledonous and is embedded in the white endosperm that forms the bulk of the seed. The embryo, however, is removed during the milling process.

Table 1-6 summarizes data on grain size and the proportions of the principal parts comprising the mature seed of different cereals.

NITROGEN FIXATION

The largest single industrial input into agricultural food production is nitrogen fertilizer. It accounts for 30–40% of total crop productivity (Wittwer 1980), but is energy intensive and demanding of nonrenewable energy resources. Natural gas equivalent to 300 × 10^6 barrels of oil is consumed annually for the synthesis of anhydrous ammonia by the Haber–Bosche process of nitrogen fertilizer production (Wittwer 1980). Nitrogen fertilizer now accounts for about one-third of all the energy going into agricultural production.

The alternative is biological nitrogen fixation, which constitutes approximately 70% of the total nitrogen fixed worldwide (Power and Papendick 1985). Next to photosynthesis, it is the second most important biochemical process on earth (Wittwer 1979). In fact, symbiotic nitrogen is the most efficient way of providing fixed nitrogen for plant growth (Deshpande and Damodaran 1990).

While legumes have the capacity of being at least partially self-sufficient through symbiotic N_2 fixation, the grain crops have relied mostly on commercial nitrogen sources of manures and fertilizers. In fact, increased use of nitrogen fertilizer is probably the most important single factor that has enabled cereal grain production to increase significantly in the past two decades. It is not surprising that increasing cereal grain production at the world level would require the use of increasing amounts of nitrogen fertilizer. However, in the less developed countries, the availability and the high prices of nitrogen fertilizer are limiting factors for its use on a large scale. In addition, in tropical regions considerable amounts of nitrogen, mostly in the form of NO_3, are lost from the soil by leaching (Neyra and Dobereiner 1977).

Although improved technologies of nitrogen fertilizer production and increased efficiency of fertilizer use by plants could make more nitrogen available for the plants, alternative technologies should be found to lessen the dependence of plants on nitrogen fertilizer. Developing nitrogen self-sufficiency in grain crops may constitute a major breakthrough in the years ahead. Efforts along these lines may include the incorporation of *nif* (nitrogen-fixing) genes into cells that normally do not fix N_2 (Brill 1975) or the development of already present plant-bacteria associations.

Some cereals, such as corn and sorghum, that are able to support significant nitrogenase activity possess the photosynthetic C-4 pathway. The amount of light required to saturate photosynthesis and the maximum photosynthetic rate attainable are much greater in C-4 than in C-3 plants (Chollet and Ogren 1975). At high light intensities and low temperatures, the rate of photosynthesis is essentially the same in C-3 and C-4 species, but at higher temperatures C-4 plants show higher photosynthetic rates. Furthermore, losses of carbon due to photorespiration are minimal in C-4 plants. This suggests that some cereals may be very efficient in harvesting light energy for nitrogen fixation. Maximization of N_2 fixation in cereal–bacteria associations and the elaboration of agronomic practices to enhance or promote N_2 fixation will depend on the identification of the various limiting factors controlling this process under field conditions.

High nitrogenase activities (up to 9,000 nmol C_2H_4/g roots per hour) have been reported on excised, preincubated corn and sorghum roots in lowland soil in Rio de Janeiro, Brazil (von Bulow and Dobereiner 1975). Other estimates by this method range between 100 and 2,000 nmol C_2H_4/g roots per hour. *Spirillum lipoferum* was found to be abundant in all N_2-fixing corn and sorghum roots examined. Field-grown corn plants in Wisconsin inoculated with strains of *S. lipoferum* isolated from *Digitaria* roots in Brazil showed establishment of the bacteria inside the roots (Dobereiner, Marriel, and Nery 1976). Inoculated plants showed higher nitrogenase activity than uninoculated ones, whereas nitrogen-fertilized plants had no activity.

There is little doubt as to the substantial contribution of biological N_2 fixation to the nitrogen economy of rice crop. For instance, a total of twenty-three rice crops, in an eleven-year experiment at the International Rice Research Institute in the Philippines, were obtained from a nonfertilized field with no apparent decline in the nitrogen fertility of the soil. About 45–60 kg N/ha per crop were removed through straw and grain (Watanabe and Kuk-Ki-Lee 1975). This represents a substantial amount of nitrogen that had to be replaced to maintain the fertility level of the soil. Blue-green algae and photosynthetic bacteria account for a large part of the N_2 in rice fields (Stewart 1975).

Bacterial counts indicate that *Beijerinckia* sp. and *Enterobacter cloacae* are the most common N_2-fixing bacteria in the rhizosphere of rice (Yoshida 1971; Neyra and Dobereiner 1977). However, most of the nitrogen fixation in the rice system has been attributed to rhizosphere soil rather than to the roots themselves. Higher numbers of aerobic than of anaerobic N_2-fixing bacteria in the rhizosphere of rice were also found by Watanabe and Kuk-Ki-Lee (1975). Methane-oxidizing bacteria, which are able to fix N_2, are also found in rice fields. The large amount of methane that can accumulate in these soils should not be overlooked as a potential carbon source for N_2 fixation (De Bont and Mulder 1976). However, oxygen diffusion seems to be a limiting factor for this system. De Bont and Mulder (1976) also reported very high numbers (up to 3.6×10^7) of N_2-fixing, methane-oxidizing organisms in the rice rhizosphere.

Nitrogen fixation in wheat fields has also been reported in the literature. A nitrogen balance study in the famous Broadbalk continuous wheat experiment carried out from 1843 to 1967 in England showed an average annual gain of 34 kg N/ha, of which 24 kg N/ha were removed with straw and grain (Jenkinson 1973). However, values extrapolated from the acetylene reduction assays on soil cores were much lower (2–3 kg N/ha per year). It was also shown that nitrogenase activity of soil cores containing wheat was significantly higher than in bare soils. Wheat cores assayed in Oregon have been calculated to fix 2 g N/ha/day (Barber, Tjepkema, and Evans 1976), whereas much higher nitrogenase activities have been observed in wheat cores assayed in Rio de Janeiro, Brazil (Neyra and Dobereiner 1977).

In the Broadbalk experiment, a large part of N_2 fixation was attributed to blue-green algae, whereas the root nitrogenase activity was attributed to anaerobic or facultative bacteria (Day, Neves, and Dobereiner 1975). Barber, Tjepkema, and Evans (1976) isolated N_2-fixing strains of *Enterobacter cloacae, Bacillus macerans,* and *B. polymyxa* from wheat roots in Oregon soils.

Larson and Neal (1976) described a highly specific association of a facultative *Bacillus* sp. with a disomic chromosome substitution line of wheat. The *Bacillus* was isolated from a soil where wheat had been growing for thirty years without nitrogen fertilizer. The rhizosphere of this wheat line contained also more nitrate-reducing bacteria and a lower total number of microorganisms. In monoxenic culture, the bacterium closely associated itself with the root surface. Abundant numbers of bacterial cells were found on the root surface as well as in the intercellular spaces between the cortical root cells.

The identification of the factors that limit nitrogenase activity and hence N_2 fixation under field conditions and in vivo is essential for any attempt to find agriculturally viable practice that may increase biological N_2 fixation in cereals. Some of the important factors in this regard, as described by Neyra and Dobereiner (1977), are briefly discussed below.

Seasonal and Diurnal Fluctuations

Nitrogenase activity fluctuates throughout the growth cycle of the plants. In general, maximal activities are found during reproductive growth of the plant. In field-grown corn, two peaks of nitrogenase activity, the first associated with silk emergence and the second with the onset of grain filling, are observed. Conversely, very little nitrogenase activity is observed before tasseling and after midgrain filling. Similarly, in sorghum maximal enzyme activities occur at flowering, and then decline linearly with the onset of grain filling. It is quite likely that competition for available photosynthate by the grain causes the observed decline of nitrogenase activity during the seed-filling stages.

Diurnal fluctuations also affect N_2 fixation in cereals. Peak enzyme activity is usually observed around midday, but in C-4 plants such as corn, sorghum, and millets, a second peak is observed at night. The latter peak is attributed to hydrolysis of carbon storage products accumulated during the day and their subsequent translocation and exudation in the rhizosphere. In general, most of the nitrogenase activity computed over a 24-h period occurs during the light period; this may reflect the dependence of nitrogenase activity in cereals upon the available photosynthate, as in the case of symbiotic systems of legume plants.

Plant Genotype

Nitrogenase activities vary widely with different genotypes of a given cereal species. Such effects have been shown for corn, millets, and wheat (Day, Neaves, and Dobereiner 1975; Larson and Neal 1976; Neyra and Dobereiner 1977). Crosses between higher-fixing versus lower-fixing cultivars show significant heterosis effects. This suggests the importance of plant genotype for optimal associations and the possibility of improvement of N_2-fixing associations by plant breeding.

Temperature

Soil temperatures below 22–25 °C are a major limiting factor in N_2 fixation in cereals. However, differences among plant species are expected to occur in relation to tolerance to relatively low temperatures.

Oxygen

Optimal nitrogenase activities are found at pO_2 far below that of air. The activity is almost completely inhibited in air. Most N_2-fixing organisms associated with cereals have very poor oxygen protection mechanisms for their nitrogenases (Abrantes, Day, and Dobereiner 1975).

Combined Nitrogen

High levels of combined nitrogen (NO_3, NO_2, and NH_4) in the soil, or the application of heavy nitrogen fertilization, reduce the potential for nitrogen fixation in cereals. It is quite likely that, at low levels of combined nitrogen in the soil, the simultaneous utilization of biological N_2 fixation and mineral nitrogen fertilizer may be possible. On the other hand, in areas receiving continuously high doses of N fertilizer, the potential for N_2 fixation may not be realized.

It is quite evident from the foregoing brief discussion that biological nitrogen fixation is possible in cereal crops, although not quite to the same extent as in legume–rhizobia symbiotic systems. Various nitrogen-fixing organisms associated with cereal crop systems are listed in Table 1-7. Although the cereal–bacteria associations contribute significantly to the overall nitrogen economy of the plants, the actual contribution of N_2 fixation in cereal crops is not known. The seasonal pattern of nitrogenase activity associated with plant life cycle and the genotypic differences observed with several species show that the physiology of the host can control the level of nitrogenase activity of the bacteria associated with their roots. While biological nitrogen fixation could be sufficient for the maintenance of cereals growing in their natural habitat, it is unlikely that it alone could satisfy all the nitrogen requirements of high-yielding agricultural cereal crops; therefore, studies on the interaction between combined nitrogen and biological N_2 assimilation should be ranked as a high research priority. Similarly, although good progress has been made in understanding the impor-

Table 1-7. Nitrogen-fixing Organisms Associated with Cereal Crops.

Organism	Reference
Azotobacter spp.	
A. paspali	Dobereiner (1970)
A. chroococcum	Watanabe (1975); Alexander (1985)
A. vinelandii	Neyra & Dobereiner (1977)
Beijerinckia spp.	Yoshida (1971)
B. indica	Dobereiner (1973)
B. fluminensis	Quispel (1974)
B. derxii	Alexander (1985)
Azospirillium spp.	Barber, Russel, & Evans (1979)
Spirillum lipoferum	Dobereiner, Marriel, & Nery (1976)
Rhodospirillum rubrum	Quispel (1974); Neyra & Dobereiner (1977)
Enterobacter cloacae	Yoshida (1971); Barber, Tjepkema, & Evans (1976); Neyra & Dobereiner (1977)
Pseudomonas spp.	Mendez-Castro & Alexander (1983)
Bacillus spp.	
B. macerans	Barber, Tjepkema, & Evans (1976)
B. polymyxa	Barber, Tjepkema, & Evans (1976); Larson & Neal (1976)
Clostridium pasteurianum	Neyra & Dobereiner (1977)
Klebsiella aerobacter	Neyra & Dobereiner (1977)
Blue-green algae	Stewart (1975); Alexander (1985)

tance of environmental and plant factors, the exact nature of cereal–bacteria association is still unclear. Until such information is made available, we may not be able to apply the modern biotechnological approaches for improving biological nitrogen fixation in cereals.

BREEDING APPROACHES

In a review dealing with the capacity of conventional plant breeding for crop yield improvement, Frey (1984) summarized data showing that, during this century, the yield potential of wheat and corn in the United States has increased by approximately 50% as a result of genetic improvement. It was estimated that 60% of the observed yield improvement in wheat could be attributed to genetic improvement, whereas for barley and oats the proportions attributable were 42% and 29%, respectively.

Cereal crop cultivars are homozygous and hence are genetically stable; that is, they can be grown year after year without losing their genetic identity. The most commonly used breeding approaches for cereal yield improvement are the pedigree method, the bulk method, backcrossing, and haploid breeding. These methods have been reviewed by Stoskopf (1985). There are several excellent examples of improving yield and quality of cereals by following suitable breeding methods: Hexaploid semidwarf wheat was utilized to transfer genes to durum wheat with continued backcrossing (Frey 1984), and hexaploid triticale was developed via crosses between *Triticum* and *Secale* for several years.

The gene pool concept for plant breeding of cereals was conceived by Harlan and de Wet (1971), who divided the genetic materials into primary, secondary, and tertiary genes. In case of primary genes, the progenitors of a crop species are used for increasing crop productivity. This approach has already been successful in improving the yields of oats and barley (Frey 1984). In a barley introgression study, matings among three barley cultivars and nine collections were backcrossed four times to the cultivated plants; the resulting lines had improved plant height, heading date, and harvest index (Frey 1984). Considerable gains in corn yield have been achieved using intrapopulation recurrent selection breeding techniques (Sprague and Eberthart 1977).

Breeding for specific traits, such as disease resistance and desirable quality characteristics in cereals, has made considerable progress over the past three decades. Several simultaneous backcrossing programs are required to recombine the various resistances with the background of the recurrent parent. An alternative method for achieving a combination of resistances in a crop, without the backcrossing requirement of multilines, is to blend existing varieties that differ in their resistance genes. The effectiveness of this approach in reducing yield losses from yellow rust and powdery mildew in barley has been demonstrated in field studies in the United Kingdom and Denmark (Walsh 1984).

Interspecific Gene Transfer

Deficiencies in crop cultivars for desirable characteristics (resistance to pests, diseases, drought, etc.) and their availability in wild relatives are now well documented in the agricultural literature. Although significant progress in conventional cereal breeding has been made in this regard in recent decades, such approaches are time consuming, and the natural barriers of cross incompatibility between species limit the possibilities of combining genomes and transferring desired traits from one species to another. Recent advances in gene manipulation and transfer have opened new vistas in agricultural research, generating considerable interest in interspecific breeding for effecting transfer of desirable genes from wild species into related cultivars (Stalker 1980; Stalker and Moss 1987; Singh, Moss, and Smartt 1990). When the donor and the recipient species are closely related, there is generally no genetic barrier in the production of a hybrid with a satisfactory level of chromosome pairing. In such cases, gene transfer can be and has been accomplished by conventional methods such as hybridization and backcrossing. Unfortunately, a majority of wild relatives of crop species have developed reproductive isolating mechanisms that may limit interspecific hybridization or inhibit genetic introgression through inadequate chromosomal meiotic pairing (Fehar and Hadley 1980; Sastry 1984; Gupta and Bahl 1985). Even where pairing occurs, linkage may restrict recombination between desirable and undesirable genes, thus preventing production of lines with desired agronomic characteristics.

Barriers to interspecific hybridization occur as a result of either sexual incompatibility or hybrid breakdown. Sexual incompatibility is caused by disharmonious pollen–pistil interaction resulting in a failure of the egg to form a viable zygote. In contrast, hybrid breakdown, hybrid weakness, and hybrid sterility are the main crossability barriers to interspecific hybridization. These may be caused by arrested embryo development, endosperm disintegration, abnormal development of ovular tissue, or chromosomal or genetic instability (Singh, Moss, and Smartt 1990). The two main requirements of interspecific hybridization to incorporate alien genetic variation therefore are

1. the initial production and establishment of viable hybrids, and
2. the subsequent integration of desirable genomic segment(s) from the donor species into the genome of the cultivated species.

In this regard, polyploidy has been particularly helpful in the production and propagation of many interspecific hybrid combinations with subsequent genome duplication. The most successful examples of using ploidy level and chromosome manipulations for introducing alien genetic variation are from *Triticum aestivum,* bread wheat. Sears (1956) was first to demonstrate the role of an integrated set of manipulations in the transfer of genes conferring resistance to leaf rust (*Puccinia recondita*) from *Aegilops umbellulata* to *T. aestivum.* Some of the other studies in this regard are summarized in Table 1-8. Some of the studies using more recent genetic engineering techniques, such as DNA transfer to protoplasts of barley, rice, wheat, and corn, are summarized in Table 1-9.

Direct gene transfer offers new possibilities for combining genomes and genes that so far could not be brought together by conventional means. Such approaches as microinjection of DNA into cells, injection of genetic material directly into plants, the use of pollen or embryos for DNA uptake, and the use of vector systems based on *Agrobacterium* or viruses have been suggested as alternative gene transfer methods applicable to cereals (Gobel and Lorz 1988). Excellent progress has been made toward cloning the genes of major storage proteins of wheat , corn, and barley (Table 1-10). Several genetic engineering approaches and their potential in cloning seed proteins have been reviewed by Croy and Gatehouse (1985).

Recently, there has been growing interest in crop improvement by exploiting exotic germ plasm. The most important characteristics of interest are resistances unavailable in crop species to diseases and pests that are major constraints in

Table 1-8. Ploidy Manipulations for Interspecific Hybridization and Gene Transfer in Wheat and Oats.

Species	Nature of Manipulation	Objectives Achieved	Reference
Wheat (*Triticum aestivum*)			
Triticum × *Triticum*, *Triticum* × *Aegilops*	Interploid hybrid, backcrossing	Genetic introgression	Vardi (1974)
		Herbicide resistance	Gill, Multani, & Dhaliwal (1986)
		Resistance to stem rust to 6*x* via 4*x*	Kerber & Dyck (1969)
		Direct gene transfer 2*x* to 6*x*	Gill & Raupp (1987)
	Amphiploidy	Resistance to leaf rust	Dyck & Kerber (1970)
	Amphiploidy	Addition line	Sears (1956)
	Amphiploidy, aneuploidy	Homologous pairing, resistance to yellow rust	Riley, Chapman, & Johnson (1968)
	Aneuploidy	Homologous pairing	Sears (1973)
Triticum × *Agropyron*	Interploid hybrid, backcrossing, amphiploidy	Hybrid establishment, genetic introgression	Cauderon (1978)
	Amphiploidy, aneuploidy	Resistance to wheat rust	Cauderon (1978)
	Aneuploidy	Resistance to stem rust	Knott (1961)
Agropyron × *Agropyron*	Autoploidy	Overcoming incompatibility	Dewey (1977)
Oats (*Avena sativa*)	Interploid hybrid	Addition line, genetic introgression	Thomas, Haki, & Arangzeb (1980)
	Amphiploidy	Resistance to powdery mildew	Kummer (1984)
	Amphiploidy, aneuploidy	Homologous pairing, resistance to powdery mildew	Thomas, Powell, & Aung (1980)

crop production. However, interspecific gene transfer has been devised in only a few cereal crops, such as wheat, rice, and oats, for which there has been a large research effort and for which genome structure and cytogenetic affinities between related species are very well understood and documented. Such studies for other important cereal crops, such as the millets, are lacking. Although existing cytogenetic methods of genetic manipulation will continue to be the principal means of effecting interspecific gene transfer for the foreseeable future, novel techniques for transformation at the cellular and/or molecular levels provide enormous opportunities for extending the range of gene introductions.

Table 1-9. Direct Gene Transfer and Vector-Dependent DNA Transfer to Cereals.

Transfer Type and Crop	Reference
Direct gene transfer	
(a) DNA transfer to protoplasts	
Wheat	Lorz, Baker, & Schell (1985)
Rice	Ou-Lee, Turgeon, & Wu (1986)
Corn	Rhodes et al. (1988); Junker et al. (1987); Gordonkamm et al. (1990)
Barley	Junker et al. (1987)
Sorghum	Ou-Lee, Turgeon, & Wu (1986)
(b) Injection of DNA into floral tillers	
Rye	De La Pena, Lorz, & Schell (1987)
(c) Pollen-mediated transformation	
Corn	de Wet et al. (1985)
Vector-dependent DNA transfer	
Agrobacterium as a vector	
Corn	Grimsley et al. (1987)

Table 1-10. Examples of Cloning and Isolation of cDNAs Encoding Cereal Proteins.

mRNA source	Vector	Seed Protein Encoded	Reference
Wheat endosperm poly(A) RNA	pBR 322/Pst-I	Gliadins	Bartles & Thompson (1983)
Corn endosperm poly(A) polysomal RNA	pBR 322/Pst-I	Zeins	Weinand, Bruschke, & Feix (1979)
Corn endosperm protein bodies poly(A) RNA	pMB 9/Eco-RI	Zeins	Burr et al. (1982)
Barley endosperm poly(A) RNA from membrane-bound polysomes	pBR 322/Hind-III	Hordeins	Brandt (1979)
Barley endosperm poly(A) RNA from membrane-bound polysomes	pBR 322/Pst-I	Hordeins	Forde et al. (1981)

Nevertheless, much work is still required to perfect the techniques of chromosome engineering in many cereal crops, which could reduce the size of the alien chromosome segment that can be transferred. Since wheat has provided such scope for improvement using these techniques, it is quite likely that, given serious research efforts, other cereal crops would respond to these approaches in the near future.

Breeding for Drought Resistance

The ability of a crop to grow satisfactorily in areas subjected to water deficits has been termed its "drought resistance"; its structural and functional modification to increase its probability of survival and reproduction in a particular environment is termed an "adaptation" (Turner and Kramer 1980; Turner 1986). Adaptations can be heritable or nonheritable, constitutive or facultative. Plants, for example, adapt their photosynthetic rate to moisture and temperature depending on habitat, and additionally acclimate photosynthetically to the seasonal changes in these two factors in their habitat.

In the past two decades there has been considerable effort devoted to breeding for improved drought resistance in cereals. While the benefit of this research by the development of new cultivars has yet to be realized on a large scale, it does point the way to future crop breeding methodologies for water-limited environments.

Four basic approaches to breeding for drought resistance have emerged (Turner 1986; Ludlow and Muchow 1990). The first is to breed for high yields under optimal conditions—that is, to breed for yield potential—and then to assume that this will provide a yield advantage under suboptimal conditions. Fischer and Maurer (1978), working with a wide range (up to 53) of bread wheats, durum wheats, triticales, and barleys, found that a high yield potential gave improved yields when the crops were stressed with drought. However, even in the severely stressed crops, grain yields were 2,000 kg/ha compared to 5000 kg/ha in the well-irrigated crops. Clearly yields were high compared with those in severely water-limited environments, where grain yields can be an order of magnitude lower.

The second approach to breeding for drought resistance is to breed for maximum yield in the target environment. However, water-limited environments are notably variable from year to year, so the environmental selection indices and pressures on the breeders' populations change drastically from generation to generation. Compounded with the low heritabilities for yield and yield components (Roy and Murty 1970; Turner 1986), this makes for slow breeding progress and a costly breeding program, and accounts for the low yield increases observed from breeding programs in water-limited environments compared to environments with optimal rainfall (Turner and Begg 1981).

Hence, some breeders developing cultivars for water-limited environments have suggested the selection and incorporation of physiological and morphological mechanisms of drought resistance into traditional breeding programs. This third approach requires the identification of the characters in each generation. To this end, considerable progress in rapid screening methods has been made (Mussell and Staples 1979; IRRI 1982; Ludlow and Muchow 1990). Having identified a range of characters with putatively useful qualities in conferring some measure of drought resistance, Ludlow and Muchow (1990) recommended selection for these characters at the F_5 and F_6 generations in an established program for selection for agronomic types, yield, and yield components under optimal environmental conditions.

Rather than utilizing multiple physiological selection criteria, an alternative, fourth approach to breeding under water-limited conditions aims to prove beyond doubt that a single drought-resistance character will benefit yield under water-limited conditions, and then to incorporate that character into an existing yield breeding program. A ten-year breeding program to incorporate a high hydraulic root resistance into wheat has provided results suggesting that lines with narrow xylem vessels in the seminal roots outyield lines with large vessels by 5–10% in water-limited environments (Passioura 1986). Likewise, selection for lines of wheat with high endogenous levels of abscisic acid have increased yields by 16% and 10% at two sites, the higher improvement being at the drier site (Quarrie 1985).

It thus appears, because of the variability in amount and temporal distribution of available moisture from year to year, breeding improved genotypes for the arid and semiarid tropics by selecting solely for grain yield is difficult. The genotypic variance in yield is low under these conditions. It is therefore essential to understand how plants survive drought and how traits influence yield by enhancing the determinants of survival. To survive periods of water deficit, higher plants may use one of two main strategies: drought escape and drought resistance (Table 1-11). Desert ephemerals and short-season annuals have such a short life cycle that they germinate (after rain), grow rapidly, flower, and set seed before the soil water is exhausted in arid environments with low and variable rainfall. These plants are said to "escape" drought or water deficits in their tissues. The cost of such a strategy, however, is lost opportunity and low yield in better-than-average seasons (Ludlow and Muchow 1990).

Longer-season annuals and perennials survive water stress by one of two drought-resistance strategies (Table 1-11). The first involves the avoidance of water deficits in tissues—despite the absence of rainfall and the presence of hot, dry atmospheres—by maintaining cell turgor and cell volume. This is achieved by maintaining water uptake, reducing water loss, and changing tissue characteristics (e.g., osmotic adjustment or increased tissue elasticity). The second strategy relies on tissues that are able to tolerate dehydration, usually because of superior protoplasmic tolerance of desiccation. Putative traits that improve yield per unit of precipitation by enhancing plant survival must act through one or more of the determinants given in Table 1-11.

Not all the mechanisms listed in the table are without metabolic cost to productive processes. Turner (1982, 1986) considered the influence of the adaptive mechanisms on crop productivity and concluded that only those mechanisms that aided in drought escape, maintenance of water uptake, and maintenance of turgor pressure did not reduce photosynthesis, crop growth, and yield (Table

Table 1-11. Mechanisms of Adaptation to Water Deficits and Their Influence on Productive Processes.

Mechanism	Productive Processes Reduced?
Drought escape	
Rapid phenological development	No
Developmental plasticity	No
Drought resistance	
Dehydration avoidance/postponement	
Maintenance of turgor	
Increased root density and depth	No
Increased liquid-phase conductance	No
Maintenance of volume	
Increase in elasticity	No
Reduction of water loss	
Reduction of leaf area	Yes
Increase in stomatal and cuticular resistance	Yes
Reduction in radiation absorbed	Yes
Osmotic adjustment	No
Changes in tissue characteristics	Yes
Dehydration tolerance	
Protoplasmic tolerance	Yes

Compiled from: Levitt (1980), Turner (1986), and Ludlow and Muchow (1990).

1-11). While it is relatively easy to decide whether a particular adaptive mechanism affects a short-term process such as the instantaneous rate of photosynthesis, it is much more difficult to determine whether it has long-term consequences. For example, maintenance of water uptake by the development of deep roots into a wet profile will maintain the assimilation rate of leaves, but the diversion of carbon from new leaves to new roots and the maintenance of a deep root system will ultimately reduce the aboveground productive capacity of the plant relative to one with an adequate supply of water (Turner 1986).

Many traits have been proposed for improving the performance of drought-affected crops; these are summarized in Table 1-12. (For details on the role of these traits in breeding drought-resistant cereal crops, see Begg and Turner [1976], IRRI [1983], Turner [1986], and Ludlow and Muchow [1990].) These traits may differ in priority when breeding drought-resistant varieties of different cereal crops. The recommendations of Ludlow and Muchow (1990) for breeding for drought-resistant sorghum in intermittent and terminal stress environments in both modern and subsistence agriculture systems are summarized in Table 1-13 as an example. It is quite likely that similar approaches may be successful in breeding other drought-resistant cereal crops.

Table 1-12. Traits That Control Drought Resistance of Cereal Cultivars.

1. Matching phenology to the water supply
2. Photoperiod sensitivity
3. Developmental plasticity
4. Mobilization of preanthesis assimilate to grain
5. Rooting depth and density
6. Root hydraulic conductance
7. Early vigor
8. Leaf area maintenance
9. Osmotic adjustment
10. Low lethal water status
11. Reduced stomatal conductance
12. Leaf movements
13. Leaf reflectance
14. Epidermal conductance
15. Transpiration efficiency
16. High-temperature tolerance

Compiled from: Begg and Turner (1976), IRRI (1983), Turner (1986), and Ludlow and Muchow (1990).

PHYSIOLOGICAL CONSIDERATIONS

Carbon Metabolism

The cultivated cereal crop species exhibit significant differences in their carbon metabolism pathway. Some of these aspects and their influence on certain parameters associated with their yield potential are briefly described below.

Two basic pathways of carbon metabolism operate in cereal crops: the Calvin cycle (Benson–Calvin–Bassham cycle) and the Hatch–Slack pathway (Hatch, Osmond, and Slatyer 1971; Evans and Wardlaw 1976; Tootill 1984). These are shown in Figs. 1-7(a) and 1-7(b), respectively, and are differentiated based on whether the first product generated during the photosynthesis process is a three- or four-carbon compound.

Any plant that produces the three-carbon compound phosphoglyceric acid as the first step in photosynthesis is termed a C-3 plant. Most plants of temperate regions are C-3 plants; among cereals, wheat, oats, rye, and rice are examples. Generally, C-3 plants exhibit photorespiration and are relatively inefficient photosynthetically as compared to C-4 plants. They also have lower CO_2-fixation rates and higher compensation points than C-4 plants.

C-4 plants produce, as the first step in photosynthesis, either oxaloacetic acid, maleic acid, or aspartic acid, which all contain four carbon atoms (Moss and Musgrave 1971). Over 100 species of C-4 plant have been identified, most

Table 1-13. Recommended Traits, in Order of Priority, for Grain Sorghum Grown in Intermittent and Terminal Stress Environments in Both Modern (Opportunistic) and Subsistence (Conservative) Agriculture.

Modern Agriculture[a]		Subsistence Agriculture[a]	
Intermittent Stress	Terminal Stress[b]	Intermittent Stress	Terminal Stress[b]
1. Matching phenology to water supply	1. Matching phenology to water supply	1. Matching phenology to water supply	1. Matching phenology to water supply
2. Osmotic adjustment of shoots and roots	2. Osmotic adjustment of shoots and roots	2. Osmotic adjustment of shoots and roots	2. Mobilization of preanthesis dry matter
3. Rooting depth and density	3. Rooting depth and density	3. Rooting depth and density	3. Increased leaf reflectance[c]
4. Early vigor	4. Increased leaf reflectance	4. Increased leaf reflectance	4. Photoperiod sensitivity[c]
5. Leaf area maintenance	5. Early vigor	5. Low lethal water stress	
6. Increased leaf reflectance[d]	6. Mobilization of preanthesis dry matter[c]	6. Leaf movements	
7. Low lethal water stress		7. Low epidermal conductance	
		8. Early vigor	
		9. Leaf area maintenance	
		10. Photoperiod sensitivity	

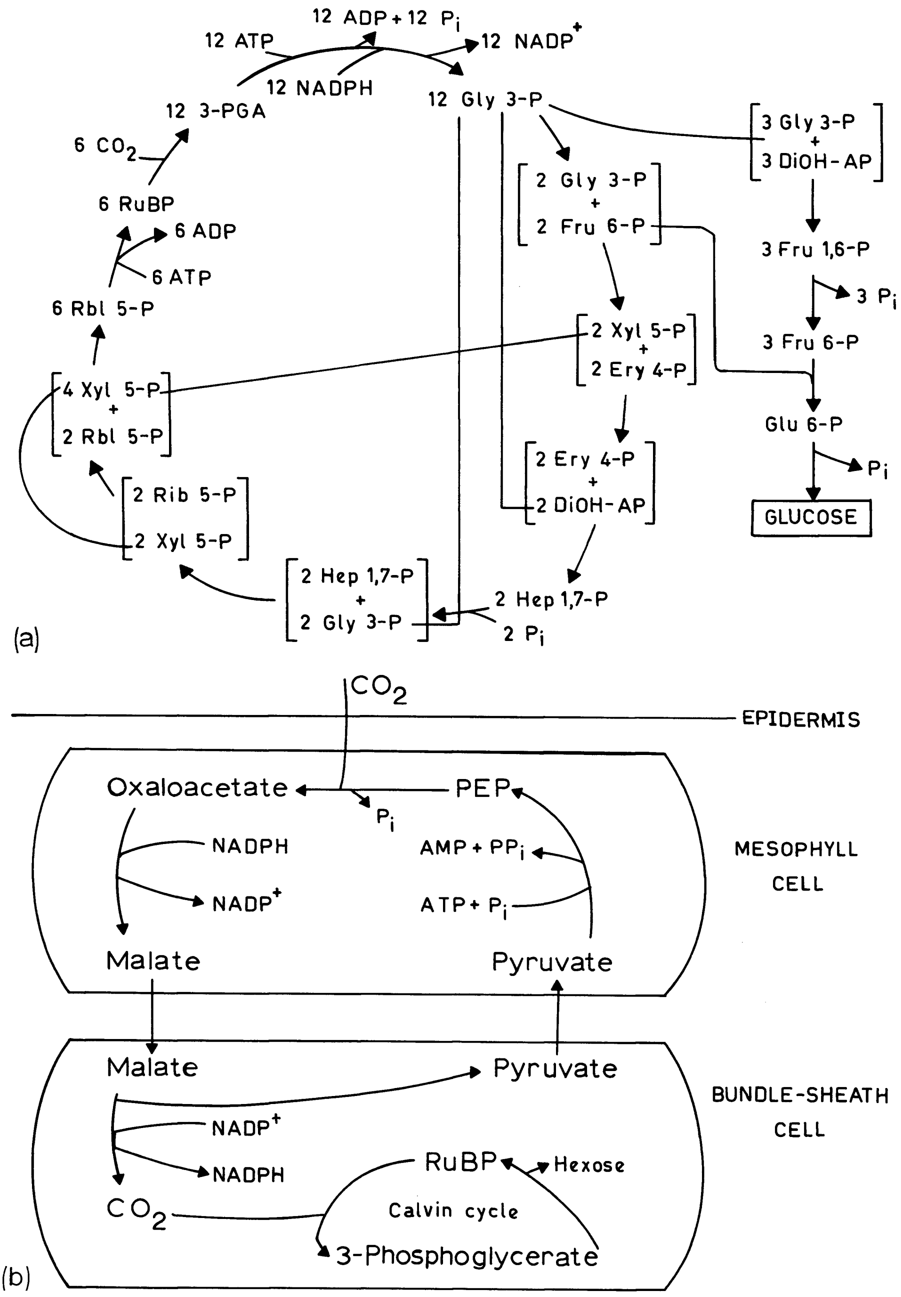
Source: Ludlow and Muchow (1990).

[a] Seedling tolerance of high temperature is an important trait in environments where soil surface temperature at emergence exceeds 50 °C.

[b] When lodging of grain sorghum is a problem in a particular environment, any trait that is shown to reduce lodging is desirable. It remains to be shown whether stay-green is such a trait without a yield penalty.

[c] Could be disadvantageous for grain sorghum in some environments if it promotes lodging.

[d] The scope for improvement may be small if current varieties are glaucous or bloomed.


12 ADP + 12 P_i
12 ATP
12 $NADP^+$
12 NADPH
12 3-PGA
12 Gly 3-P
6 CO_2
6 RuBP
6 ADP
6 ATP
6 Rbl 5-P
3 Gly 3-P + 3 DiOH-AP
2 Gly 3-P + 2 Fru 6-P
3 Fru 1,6-P
3 P_i
3 Fru 6-P
2 Xyl 5-P + 2 Ery 4-P
4 Xyl 5-P + 2 Rbl 5-P
Glu 6-P
P_i
GLUCOSE
2 Ery 4-P + 2 DiOH-AP
2 Rib 5-P
2 Xyl 5-P
2 Hep 1,7-P + 2 Gly 3-P
2 Hep 1,7-P
2 P_i
(a)
CO_2
EPIDERMIS
Oxaloacetate
PEP
P_i
NADPH
$NADP^+$
AMP + PP_i
ATP + P_i
Malate
Pyruvate
MESOPHYLL CELL
Malate
Pyruvate
BUNDLE-SHEATH CELL
$NADP^+$
NADPH
RuBP
Hexose
Calvin cycle
CO_2
3-Phosphoglycerate
(b)

of which are tropical. Examples include corn, sorghum, millets, sugarcane, Bermuda grass, and many desert plants. C-4 plants require thirty molecules of ATP and twenty-four molecules of water to synthesize a molecule of glucose, whereas C-3 plants need only eighteen molecules of ATP and twelve molecules of water (Tootill 1984). However, C-4 plants produce more glucose for a given leaf area than do C-3 plants, and consequently grow more quickly. They can also continue to photosynthesize at high light intensities and low CO_2 concentrations, and, most significantly, do not exhibit photorespiration.

Photorespiration occurs in plants in light. It differs from dark respiration in that it does not occur in the mitochondria and is not coupled to oxidative phosphorylation. The rate of CO_2 release by photorespiration in C-3 plants can be three to five times greater than that of dark respiration (Tootill 1984). Since the process does not generate ATP, it appears to be extremely wasteful. It has been estimated that the photosynthetic efficiency could be improved by 50% if photorespiration were inhibited (Evans and Wardlaw 1976). In C-4 plants photorespiration is hardly detectable, possibly because the synthesis of glycolic acid,

Fig. 1-7 (*facing*). **(A)** Calvin cycle (Benson–Calvin–Bassham cycle), which produces a three-carbon compound, phosphoglyceric acid, as the first step in photosynthesis in C-3 type plants. The sequence of reactions constitutes the dark or light-independent reactions of photosynthesis in which CO_2 is reduced to glucose using ATP and NADPH derived from the light-dependent reactions. The overall series of reactions is as follows:

$$\begin{aligned}&6\text{ Ribulose 1,5-biphosphate} + 6\,CO_2 + 18\text{ ATP} + 12\text{ NADPH} + 12\,H^+ + 12\,H_2O\\ &\rightarrow 6\text{ Ribulose 1,5-biphosphate} + \text{glucose} + 18\,P_i + 18\text{ ADP} + 12\text{ NADP}^+\end{aligned}$$

The glucose is subsequently converted to starch, cellulose, and other polysaccharides. *Abbreviations:* Gly 3-P, glyceraldehyde 3-phosphate; DiOH-AP, dihydroxyacetone phosphate; Fru 6-P, fructose 6-phosphate; Fru 1,6-P, fructose 1,6-biphosphate; Glu 6-P, glucose 6-phosphate; Xyl 5-P, xylulose 5-phosphate; Ery 4-P, erythrose 4-phosphate; Hep 1,7-P, sedoheptulose 1,7-biphosphate; Rib 5-P, ribose 5-phosphate; Rbl 5-P, ribulose 5-phosphate; RuBP, ribulose 1,5-biphosphate; 3-PGA, 3-phosphoglyceric acid. **(B)** Hatch–Slack pathway of alternative form of CO_2 fixation in C-4 plants. The first product of photosynthesis is a four-carbon compound, oxaloacetate, which is formed by the carboxylation of phosphoenolpyruvate (PEP) by PEP carboxylase. Oxaloacetate is then either reduced to malate or transaminated to yield aspartate. All these reactions take place in the cells of the mesophyll. The malate or aspartate is then transported to bundle-sheath cells and decarboxylated to form CO_2 and pyruvate. The CO_2 released reacts with ribulose 1,5-biphosphate to yield two molecules of phosphoglyceric acid. The normal Calvin cycle then commences to yield glucose. The pyruvate is then returned to the mesophyll cells, where it is converted back to PEP. Because of this last reaction, which uses two high-energy phosphate bonds (ATP to AMP), C-4 plants require thirty molecules of ATP for each molecule of glucose synthesized, compared to eighteen molecules in C-3 plants. *Source:* E. Tootill (ed.), *The Penguin Dictionary of Botany*. London: Penguin, pp. 54–5, 170. © Market House Books Ltd., 1984. Reproduced by permission of Penguin Books Ltd.

the substrate for photorespiration, is much lower in C-4 plants (about 10% of that of C-3 plants). This may be due to the high concentration of CO_2 in the bundle sheath cells that prevents the oxidation (instead of carboxylation) of ribulose biphosphate.

Another major difference between C-3 and C-4 plants is related to their *compensation points,* defined as the lowest steady-state CO_2 concentrations achievable in a closed system containing a photosynthesizing plant. These points are higher for the C-3 than for the C-4 plants (Tootill 1984). When the minimum level is reached, the photosynthetic uptake of CO_2 is exactly balanced by its respiratory release, indicating that the rate of synthesis of organic material equals the rate of breakdown by respiration. Low compensation points are indicative of photosynthetic efficiency, as the plant is then using the maximum amount of available CO_2.

Yet another form of photosynthesis, first observed in the family Crassulaceae and since found in many other succulent plants, is the crassulacean acid metabolism (CAM) pathway (Tootill 1984). CAM plants keep their stomata closed during the day to reduce water loss by transpiration. Carbon dioxide can therefore only enter at night, when, instead of combining with ribulose biphosphate (as in conventional C-3 plants) it combines with the three-carbon compound phosphoenol pyruvate to give the four-carbon oxaloacetate. This is then converted to malic acid, which can be stored in the cell vacuoles until daylight, when it is transferred to the cytoplasm. Here it is broken down to release CO_2, which is then fixed in the normal manner. This adaptation allows such plants to flourish in arid habitats, but their growth rate is slow. CAM can be induced in certain C-3 plants by water shortage.

The differences between C-3 and C-4 plants are reflected in their photosynthetic rates. McCree (1974) found the action spectrum for photosynthesis by leaves to be closely similar in wheat, oats, barley, triticale, rice, corn, and sorghum. As mentioned above, rice and the temperate small-grain cereals, such as wheat, barley, oats, and rye, depend entirely on the Calvin cycle; in corn, sorghum, and millets, however, the Calvin cycle is preceded by CO_2 fixation in the C-4 dicarboxylic acids. The Michaelis–Menten constant for the carboxylating enzyme in C-3 plants (RuBP carboxylase) is not much greater than that of PEP carboxylase, which mediates the primary carboxylation in C-4 plants (Evans and Wardlaw 1976). More important, refixation of CO_2 by RuDP carboxylase in the bundle-sheath cells of C-4 cereals, after transfer and decarboxylation of malate or aspartate from the mesophyll, probably takes place at a much higher CO_2 concentration, and is therefore less susceptible to photorespiratory decarboxylation. Consequently, the minimum values for mesophyll (or residual) resistance (r_m) to CO_2 uptake by leaves appear to be substantially lower in the C-4 cereals than in the Calvin cycle species. For example, r_m values of 0.7–0.9 $s\,cm^{-1}$ (Gifford and Musgrave 1973) and 1.0 $s\,cm^{-1}$ (El Sharkawy and Hesketh 1965) for corn are to be compared with minimum values of 4.1 s cm^{-1} for oats (El Sharkawy and Hesketh 1965) and 2.7–3.1 s cm^{-1} for a range of wheat species (Dunstone, Gifford, and Evans 1973).

The smaller r_m of the leaves of C-4 compared with C-3 cereals tends to be associated with a greater stomatal resistance r_s; hence the greater efficiency of the C-4 cereals in dry-matter production per unit of water transpired (discussed later in this section). Stomatal opening in the C-4 cereals increases up to very high flux densities of light, as in corn (Hatch, Osmond, and Slatyer 1971). Consequently, whereas photosynthesis by single leaves of the C-3 cereals tends to reach light saturation at 33–50% of full sunlight, that of the C-4 cereals increases with increasing intensity up to full sunlight (Hesketh and Musgrave 1962; Hesketh 1963). Even so, the minimum recorded gas phase resistances to CO_2 uptake tend to be rather lower in the C-3 cereals (e.g., 0.7–0.8 s cm^{-1} in wheat [Dunstone, Gifford, and Evans 1973] compared with 1.5 s cm^{-1} in corn [El Sharkawy and Hesketh 1965]).

The maximum photosynthetic rates achieved by the C-4 cereals are distinctly greater than those of the C-3 cereals. Rates up to 240–280 ng CO_2 cm^{-2} s^{-1} have been recorded in corn, sorghum (Downes 1971), and pearl millet (McPherson and Slatyer 1973), compared with up to 120 ng cm^{-2} s^{-1} in wheat cultivars at atmospheric CO_2 levels. However, rates up to 200 ng cm^{-2} s^{-1} have been measured in the wild diploid wheats (Evans and Dunstone 1970).

The greater rates of photosynthesis in C-4 plants, associated with their reduced photorespiratory losses and other characteristics mentioned above, have led to them being called "efficient" plants, and to a search for nonphotorespiring forms among the temperate cereals such as oats and wheat (Moss and Musgrave 1971), but without success. Other characteristics of the C-4 pathway in cereals should be considered, however. Although their greater photosynthetic rate may be of advantage at high light intensities, especially in view of their more efficient use of water, at low light intensities (such as overcast weather or for leaves deep in the canopy) their photosynthetic rate may be lower than that of C-3 plants (Evans and Wardlaw 1976). This is particularly true when cooler temperatures are associated with low light, the conditions under which the temperate cereals usually make their early growth. For example, the tropical C-4 grasses show poor photosynthetic performance at cool temperatures (around 10 °C) relative to temperate C-3 grasses and cereals such as barley and wheat (Evans 1975). At high temperatures, in contrast, photosynthesis by the C-3 cereals falls off rapidly at temperatures above 30 °C, as in wheat (Milthorpe and Ivins 1966), whereas photosynthesis by the C-4 cereals may reach its peak at temperatures of 30–40 °C as in corn, sorghum, and pearl millet (El Sharkawy and Hesketh 1964; Hofstra and Hesketh 1969; McPherson and Slatyer 1973). Although rice is a crop of tropical origin, its photosynthetic response to temperature resembles that of the other C-3 cereals in having a broad optimum (Murata

1961) with a rapid fall in the rate at high temperatures. Cool temperatures, however, have a more adverse effect on photosynthesis in rice than in the temperate cereals, particularly on the *indica* varieties (Evans and Wardlaw 1976).

The differences among C-3, C-4, and CAM plants are also reflected in their water-use efficiency, perhaps the most critical component of crop production. The transpiration ratio R_T, which is the loss of water by evaporation from a plant surface, is generally much lower for the C-4 metabolism plants (<400 with a mean of 320 ± 43) compared to that for C-3 metabolism plants (640 ± 165) (Stanhill 1986). These values are even lower for CAM plants, such as pineapple, with mean values ranging from 103 ± 41 (Ting 1976). The lower transpiration ratio found in C-4 plants can be attributed to their ability to continue photosynthesis at CO_2 concentrations that are one-third to one-fifteenth of those needed to sustain the process in C-3 plants (Stanhill 1986). This leads to an increased CO_2 gradient and hence flux, and is associated with a specialized leaf anatomy that enhances CO_2 but not H_2O gas exchange.

The marked yield improvements achieved in modern crop production are largely ascribable to the greater proportion of the crop's total dry-matter production harvested as yield, rather than to increases in dry matter production per se: Where total dry matter production has been increased, this has nearly always been achieved via larger and longer-lasting photosynthetic apparatuses (i.e., leaf canopies) rather than by a greater photosynthetic efficiency per unit leaf area (Gifford and Evans 1981).

Larger crop canopies and longer cropping seasons imply an increase in transpiration, which suggests that significant decreases in R_T are not to be expected when expressed on a dry matter rather than yield basis. However, the adoption of new varieties and improved fertilizer, irrigation, and plant protection practices continues to increase yields. Similarly, the larger and longer-lasting crop canopies resulting from these changes can be expected to reduce evaporation losses from bare soil, shaded to a greater degree by larger crop canopies.

An important exception to the strong coupling between dry-matter production and transpiration is the previously noted difference in the R_T values of plants with C-4, C-3, and CAM metabolisms. If the carbon metabolism responsible for the high net dry-matter production rates of C-4 plants could be transferred to C-3 crop species, a major increase in yields could be achieved without necessitating any increase in transpiration. In arid regions, the transfer of CAM metabolism to C-3 or C-4 plants would allow crop production at transpiration rates below those currently capable of supporting economic crop production.

The feasibility of transferring the different photosynthetic pathways from one species to another has been demonstrated, although not, to date, in crop plants. One major problem is that many of the first-generation hybrids between species of different metabolisms are not fertile. However, fertile hybrids have been produced between C-3 and C-4 *Atriplex* species from the same subgenus (Nobs 1976), and from a number of other genera, some between C-3 and intermediate

C-3 : C-4 species (Powell 1978; Brown et al. 1985; Holaday, Talkmitt, and Doohan 1985).

The prospects for achieving metabolism transfer selectively through genetic engineering rather than by plant breeding are distant. This is because each system of carbon metabolism involves a major complex of enzymatic, organelle, and cellular specializations, each of which in turn involves many groups of gene sequences. Even after the sites of all of the controlling genes have been identified, there are formidable difficulties involved in their transfer. One major problem is that of handling the large number of genes concerned. Another is the fact that one of the relevant genes for the large subunit of the central rubisco enzyme (ribulose-biphosphate carboxylase) is coded by DNA in the chloroplast genome (Stanhill 1986); as yet there is no transfer system available for gene manipulation within the chloroplast.

The possibility of incorporating the even lower values of R_T common to plants with CAM metabolism into other crop species is even more problematic. The fact that a number of C-3 plants utilize the CAM carbon pathway only under conditions of water stress shows that there is no fundamental incompatibility between these two metabolisms. However, the very energy-demanding nature of this metabolism reduces the absolute levels of dry-matter production by CAM plants to levels that are too low for economic crop production. An exception could be for high-value seed crops produced at the end of a wetter growing season. This same water-conserving strategy achieved by shifting from C-3 to CAM metabolism during the final reproductive growth phase has been reported for a plant growing in an arid Mediterranean habitat (Turner and Kramer 1980).

To incorporate the CAM metabolism into crop species by genetic engineering requires the same progress needed for the transfer of C-4 metabolism to C-3 plants: the identification of the controlling gene sequences and the development within the chloroplast genome of a transfer system capable of dealing with the large number of genes involved. Nevertheless, the practical benefits to be derived from progress in this field suggest that such research is worthy of our greater attention in years to come.

Vernalization

Vernalization may be defined as the promotion of flowering by exposure of young plants to a cold treatment. For example, the winter varieties of wheat, barley, oats, and rye will normally flower in early summer if they were sown before the onset of winter. However, in areas experiencing very harsh winters, this may not be possible; therefore, the plants are given an artificial cold treatment and are planted in the spring.

Russian researcher T. D. Lysenko was the first deliberately to chill seeds of winter wheats and demonstrate that this treatment hastened development when they were planted in spring (Salisbury 1963; Flood and Halloran 1986). Hence, winter wheats were made to act like spring wheats, for which Lysenko coined the term "jarovization" (Russian: *jarovizacija*). Vernalization (from the Latin *vernalis,* pertaining to spring) has now come to embrace other physiological processes unrelated to its original meaning—for example, the breaking of dormancy in bulb crops. This section focuses on vernalization in wheat.

Vernalization in wheat is generally considered to be affected by temperatures ≤10 °C, although the upper limit has not been critically established, and temperatures as high as 11–15 °C have been reported as being vernalizing (Vavilov 1951; Salisbury 1963; Flood and Halloran 1986). It is an unusual biological process in that it generally appears to have a negative Q_{10} value; that is, the lower the temperature, the faster it proceeds (Bidwell 1979). Ahrens and Loomis (1963) found that 1 °C had a vernalizing effect in winter wheat although there was no vernalization at –2 °C. The possibility of an optimum vernalization temperature was supported by Trione and Metzger (1970), who found that rate of vernalization was maximal at 7 °C but much lower at both 9° and 3 °C.

Since low temperatures influence the rates of both growth and development, the most effective vernalizing temperature for early induction of flowering cereal is not yet resolved. It is generally considered, however, that the weaker the vernalization response, the higher the vernalizing temperature needed for maximum rate of vernalization. As a corollary, the higher the optimum temperature for vernalization, the shorter the vernalization period. Citing the pioneering work of a Russian researcher by the name of Dolgusin, Flood and Halloran (1986) summarized the optimal temperature–time treatments for vernalization in a range of wheats as shown in Table 1-14.

As constant temperatures are not experienced in the field, vernalization in these situations must be considered in the context of the vernalizing component of diurnal temperature fluctuation and the possible influence of higher (nonvernalizing) day temperatures on this process. Gregory and Purvis (1948) were the first to demonstrate reversal of vernalization with the rye variety Petkus by imposing a temperature of 35 °C for three days on vernalized seed. They also found that the longer the period of cold treatment, the less reversible was the

Table 1-14. Optimal Temperature–Time Treatments for Vernalization in Wheat.

Varieties	Temperature–Time Treatment	
Early spring varieties	8–15 °C	for 5–8 days
Late spring varieties	3–6 °C	for 10–15 days
Intermediate varieties	2–5 °C	for 20–25 days
Winter wheats	1–4 °C	for 30–35 days
Extreme winter wheats	0–3 °C	for 30–45 days

Source: Flood and Halloran (1986).

vernalized condition. This was the trend up to a certain period of cold, beyond which the vernalized condition was irreversible.

Summarizing the available literature, Flood and Halloran (1986) suggest that vernalization could be satisfied at three stages in the life cycle of the wheat plant: (1) during germination, (2) during plant growth, and (3) during seed formation and ripening. These researchers also found that the vernalization response in wheat is controlled by one to four genes, and that some varieties may display polygenic control of this process.

Vernalization has the adaptive value of delaying the initiation of floral development. Under the moderately long photoperiods and warm temperatures subsequent to sowing in many autumn-sown wheat areas of the world, it ensures against precocious photoperiod induction of reproductive development before the onset of winter cold. In prolonging vegetative development, it minimizes or prevents the damaging effects of winter freezing temperatures on the differential head during the period from apex initiation to flowering. By delaying the initiation of reproductive development, it can ensure closer-to-optimum fitness, as higher reproductive potential, of the species in particular environments.

Physiology of Grain Yield

Crop yield is an agroindustrial concept; thus it does not necessarily relate to natural selection or to crop evolution, but rather is expressed by the nonbiological criterion of weight of product per unit area. In some crops a vegetative part is harvested; in others, a reproductive organ. Yet whatever plant part is used, natural crop evolution on the one hand and trends in crop yields on the other must be recognized as separate, if interrelated, phenomena. Increased understanding of the factors governing crop photosynthesis and respiration, distribution of assimilates, and seed growth permits us to compare and contrast the performance of annual seed crops such as cereals and legumes in terms of their branching, leafiness, light profile, photosynthesis, biomass, flowering, seed setting, grain filling, harvest index, and yield, and/or in terms of agronomic factors such as soil fertility, plant density, and plant arrangement. The prime need for farmers has always been the quantity of seed in the bag or basket—the crop yield per unit area of land—rather than the size of the individual seed or the seed yield per plant. A cereal breeder may therefore gain leverage in producing higher-yielding plants by selecting types capable of producing a higher proportion of grain to straw. Since over 90% of the dry weight of a plant is the product of photosynthesis, and since a plant is limited by time in the amount of assimilate it can produce, a better distribution of assimilates (i.e., the photosynthates) into grain and less into straw should produce a more efficient plant. Here literature pertaining to grain-yield physiology in major cereal crops is reviewed.

Partitioning of photosynthate—the differential distribution and deposition of assimilate among the organs, tissues, and cells plants—is an important component of economic yield. *Partitioning efficiency* is then defined as the amount of product produced per unit of resource used (Snyder and Carlson 1984). In modern cropping systems, it is the ratio of the amount of food, feed, or fiber energy produced per unit or radiant energy absorbed. Synthesis, translocation, partitioning, and accumulation of the photosynthetic products within the plants are controlled genetically, influenced by the environmental factors, and involve a number of complex physiological processes (Donald and Hamblin 1976, 1983; Evans and Wardlaw 1976; Snyder and Carlson 1984).

"Source" and "sink" are the two terms often used in conjunction with partitioning. Leaves and other green tissues and organs of plants that produce photosynthate are called *sources,* as are organs or tissues that receive products, temporarily store them, and later release them to other sites. All sites within the plant that utilize the photosynthetically derived products, either in situ or after receiving the products, are called *sinks* (Cooper 1975; Donald and Hamblin 1983). There is a close relationship between net photosynthesis and crop yield as well as the need for improved translocation and larger sink capacity.

Environmental factors significantly influence the partitioning of photosynthates and the subsequent dry-matter accumulation. For example, the optimum temperature for growth of roots and shoots differs in many species. Although shading and other practices may modify temperature within the crop canopy and the soil, for crops grown in the field, it is generally not possible to control temperature. Therefore, the greatest opportunity for manipulating temperature effects on partitioning lies in changing the plant genotype itself.

Light also affects dry-matter production and partitioning in a number of ways. More light (by either increased duration or intensity) increases the biomass and, therefore, the proportion of root weight and economic yield of many crops (Donald and Hamblin 1983). As irradiance levels increase, the capacity of sources to produce assimilates also increases.

Deficiencies in water and mineral nutrients result in a smaller source, lower photosynthetic rates, and altered partitioning. Water and nitrogen deficits tend to increase the proportion of root to total biomass as well as of root to shoot (Caloin, Khodre, and Atry 1980). The effect of water stress on dry-matter accumulation by the cereal grains depends upon the time and intensity of stress during grain development (Donald and Hamblin 1976, 1983).

Snyder and Carlson (1984), reviewing the literature on the effects of CO_2 and O_2 concentrations on growth and distribution in a number of crop plants, reported that high CO_2 promoted some increases in height and leaf area. C-4 plants are generally less responsive than C-3 plants. High CO_2 promotes tillering in barley and rice, and rice partitions relatively more dry matter to roots than to leaves when exposed to relatively higher CO_2 (Donald and Hamblin 1983; Snyder and Carlson 1984). In contrast, the growth of corn, a C-4 plant, is promoted less by high CO_2 and suppressed less by low CO_2.

Plant stand densities can also be selected to complement environmental factors that will produce the greatest economic yield per hectare (Donald and Hamblin 1976, 1983; Snyder and Carlson 1984). Generally, the yield of aboveground biomass is greater for high-density than for low-density stands. Cereal crops such as wheat, oats, and rice tiller less at high density than at low density; thus the partitioning response to stand density in the vegetative state compensates to quite a degree, and tends to lessen differences in economic yields caused by differences in stand density (Donald and Hamblin 1976, 1983). However, when water or nutrient stress occurs, the economic yield may be greater at somewhat lower stand densities than at higher densities. In general, the optimum stand density for cereals tends to be more variable because of their capacity to tiller as compared to that for root crops (Snyder and Carlson 1984).

The efficiency of partitioning of photosynthates is further reflected in the biological yield (BY), harvest index (HI), and grain yield (GY) of cereal crops. Donald and Hamblin (1976) defined the BY of a cereal crop as the total yield of plant material, and HI as the ratio GY : BY. The relationships between BY and GY in cereal crops display some important differences.

The BY of cereals increases with density until it reaches a plateau (Donald 1963; Donald and Hamblin 1983). This is maintained up to very high densities unless crop failure occurs from lodging or the advent of disease or pests among the attenuated plants. The GY increases to a maximum at a density approximating the minimum density giving the full BY. To the extent that, when maximum seed yield is attained, there is a maximum exploitation of the environment in terms of BY, cereals are efficient in ensuring this prolificacy. Donald and Hamblin (1983) further speculated (Fig. 1-8) on future trends in the relationship be-

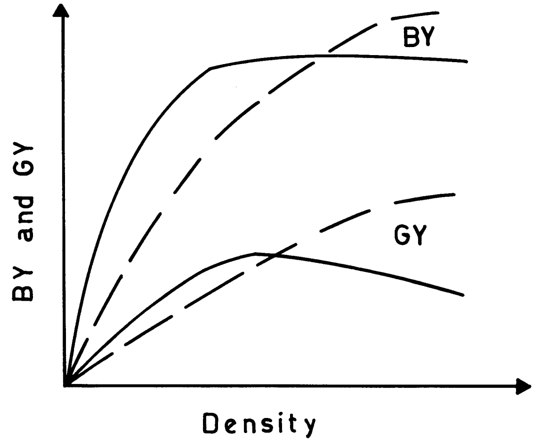


Fig. 1-8. Present relationship (solid lines) and possible future relationship (broken lines) between biological yield (BY) and grain yield (GY) as related to stand density under field conditions of cereal genotypes. *Source:* Donald and Hamblin (1983).

tween BY and GY of cereal crops. If nonbranched plants are used, the density (plants/ha) required to give the full BY will be greater. The main contribution to potential yield will then be an improved HI, perhaps 0.35–0.40 or 0.50 in cereals, representing an increase of about 25% in GY of modern cultivars. Donald and Hamblin (1983) also suggested that an increase of 10% in BY and 25% in HI would increase the GY by 37%.

The HI is correlated positively with GY and negatively with BY in barley (Singh and Stoskopf 1971), oats (Takeda, Frey, and Bailey 1980), rye (Singh and Stoskopf 1971), and wheat (Singh and Stoskopf 1971; Luthra and Dawari 1979). Based on these and several other studies, Snyder and Carlson (1984) suggested that selecting for higher HI should increase the GY in most cereals, particularly where BY is relatively stable.

Donald and Hamblin (1976) studied various models and actual relationships between BY and GY within a series of genotypes or agronomic treatments; these are summarized in Fig. 1-9. Model 1A depicts a situation in which a number of varieties all have precisely the same BY but different GY; in model 1B, these genotypes are ranked in order of increasing GY. In both these cases, the GY is proportional to HI and their correlation is 1.0 (Table 1-15), whereas the BY and HI are unrelated.

In some situations, the GY shows dependence on the BY. As shown in model 2, the GY is strictly proportional to the BY with a correlation of 1.0. Similar relationships may be observed in relation to responses to water and nitrogen fertilizers (models 3 and 4, respectively). However, in a complex case where water is deficient, the BY shows a negative correlation with HI and GY with increasing application of nitrogen. This relationship is shown in model 5. In fact, models 3–5 are in effect variations of model 2, where GY is proportional to BY. Each of these relationships has been reported frequently in agronomic studies, and each is also feasible in comparisons of genotypes. With an increase in BY, the GY may rise more than proportionately (model 3), rise less than proportionately (model 4), or decline (model 5).

Cereal crops suffering from water stress not only have lower BY and GY, but also lower HI (Donald and Hamblin 1976). Citing the results of Poostchi, Rovhani, and Razmi (1972) of supplementary spring irrigation of wheat under semiarid conditions in southern Iran, they found a characteristic response pattern that was remarkably consistent for each of the three years of the experiment (Fig. 1-10). As the water supply was increased, the BY rose from 9.5 to 15.8 MT, the GY from 1.6 to 3.6 MT, and the HI from 0.172 to 0.229.

The application of nitrogen to cereals also tends to influence the BY with a concurrent decrease in HI. This relationship was demonstrated at the Rothamsted Experimental Station in England as early as last century by the application of nitrogen to wheat for the period 1852–63 (Fig. 1-11). The increase in BY (3.4–8.5 MT) greatly exceeded the decline in HI (0.36–0.30) such that the GY rose from 1.2 to 2.6 MT with 192 kg N/ha.

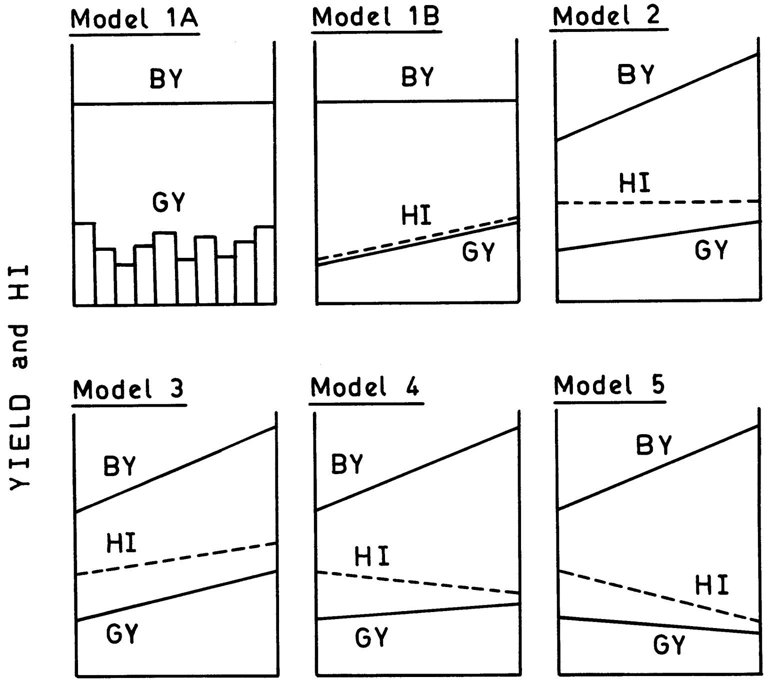


Fig. 1-9. Models of relationships between biological yield (BY), grain yield (GY), and harvest index (HI). BY is shown as constant or as increasing from left to right; however, the graphs can also be considered in mirror image. In model IA the varieties are unranked; in 1B they are ranked. In both cases, GY is directly proportional to HI. Model 2 represents tendency of genotypes in mixtures where, as BY increases, GY increases proportionately. Model 3 is typical of responses to water where, as BY increases, GY increases more than proportionately. Responses to nitrogen are shown in Model 4 where, as BY increases, GY increases less than proportionately. Model 5 depicts an inverse relationship between BY and GY and is characteristic of responses to nitrogen when water is deficient. *Source:* Donald and Hamblin (1976).

Table 1-15. Correlation Coefficients Showing Interrelationships among the Biological Yield (BY), Grain Yield (GY), and Harvest Index (HI), as Shown in Fig. 1-9.

Model	GY vs. BY	GY vs. HI	BY vs. HI
1A, 1B	0	1	0
2	1	0	0
3	1	1	1
4	1	–1	–1
5	–1	1	–1

Adapted from: Donald and Hamblin (1976).

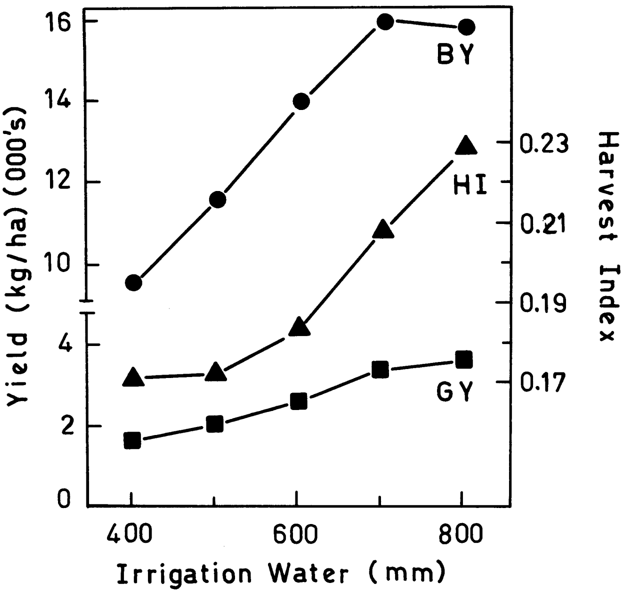


Fig. 1-10. The responses of wheat to irrigation in southern Iran. The data shown are means of three seasons. *Abbreviations:* BY, biological yield; HI, harvest index; GY, grain yield. *Source:* Adapted from the data of Poostchi, Rovhani, and Razmi (1972).

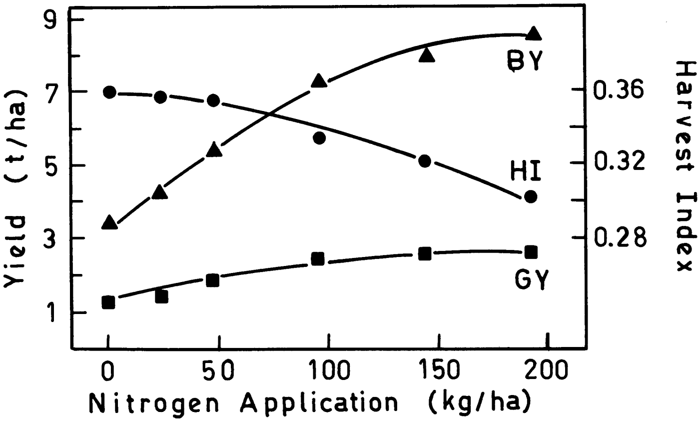


Fig. 1-11. The influence of nitrogen on biological yield (BY), grain yield (GY), and harvest index (HI). The experiments were conducted at the Rothamsted Experimental Station in England and represent means of twelve years (1852–63). The data were taken from Russell and Watson (1940) as reported by Donald and Hamblin (1976). This was the first classic experiment on the influence of nitrogen fertilizers on yields of field crops. Subsequently, similar relationships were shown by several researchers worldwide for different cereal crops.

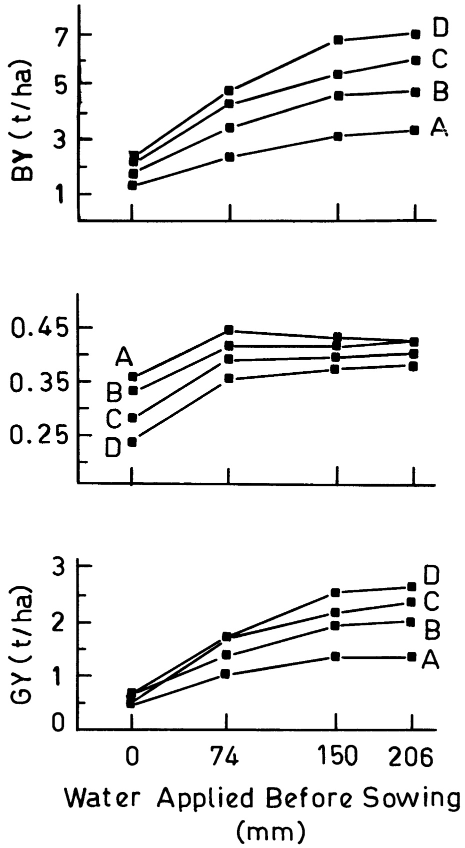


Fig. 1-12. The interaction of nitrogen and water on the biological (BY) and grain (GY) yields and harvest index (HI) of wheat at North Platte, Nebraska. Nitrogen application rates: (A) 0, (B) 20, (C) 40, and (D) 80 lbs/acre. *Source:* Ramig and Rhoades (1963); redrawn from Donald and Hamblin (1976).

When water is in limited supply, as generally is the case for a considerable part of the world's cereal growing regions, the fall in HI associated with applied nitrogen may be more marked than the increase in BY and the decline in GY. Ramig and Rhoades (1963) made a factorial study of the interaction of nitrogen and water on wheat at North Platte, Nebraska. The natural rainfall (mean 328 mm, October 1–June 30) was supplemented with several levels of water supply prior to sowing during the three years of study. Nitrogen and water each gave increased BY (grain + straw) with a strong positive correlation (Fig. 1-12). However, nitrogen severely lowered the HI at low water (0.36 at N_0 to 0.24 at N_{80}), and to an appreciable though lesser extent at high water (from 0.41 to 0.38). The outcome was a modest absolute increase in GY with a small nitro-

Table 1-16. Harvest Indices (HI) of Some Commonly Cultivated Cereal Crops.

Crop	HI	Reference
Wheat		
3 semidwarf winter vars.		Vogel, Allan, & Peterson (1963)
Medium fertility level	0.385	
High fertility level	0.385	
5 standard height vars.		Vogel, Allan, & Peterson (1963)
Medium fertility level	0.305	
High fertility level	0.276	
Standard wheat	0.40	Spiertz & van der Haar (1978)
Semidwarf wheat	0.47	
Tall wheats (86 cm)	0.38	Singh & Stoskopf (1971)
Medium wheats (78 cm)	0.40	
Dwarf wheats (58 cm)	0.42	
6 Australian and 1 German vars. (all normal height) and 2 Mexican semidwarf vars.	0.243–0.396	Syme (1970)
Plant density (000/ha)		Puckridge & Donald (1967)
14	0.364	
70	0.358	
350	0.304	
1540	0.262	
4470	0.251	
Nitrogen application (kg/ha)		Barley & Naidu (1964)
0	0.36	
67	0.28	
134	0.27	
Rice		
Soil saturation level		Enyi (1968)
Upland variety		
60%	0.17	
80%	0.19	
100%	0.21	
Flooded	0.16	
Swamp rice		
60%	0.13	
80%	0.13	
100%	0.21	
Flooded	0.26	
Growth type		Jeanings & de Jesus (1968)
Short, erect, compact	0.53–0.56	
Intermediate	0.48	
Tall, leafy, spreading	0.39–0.42	
Corn		
11 hybrid maize vars.		Hanway & Russell (1969)
Low-density planting	0.44	
High-density planting	0.40	

Table 1-16. (*Continued*)

Crop	HI	Reference
Plant density (000/ha)		
20	0.475	Scarsbrook & Doss (1973)
40	0.420	
80	0.389	
21	0.494	Fairbourn, Kemper, & Gardner (1970)
32	0.494	
37	0.474	
42	0.373	
Water stress		Downey (1971)
No stress	0.28	
Early stress	0.42	
Late stress	0.21	
Barley		
Plant height		Hayes (1968)
Very tall variety	0.401	
Tall variety	0.487	
3 medium vars.	0.535–0.571	
Nitrogen application (kg/ha)		Luebs & Laag (1969)
0	0.45	
45	0.37	
90	0.13	
Sorghum		
Plant density (000/ha)		Gerakis & Tsangarakis (1969)
80	0.169	
120	0.141	
160	0.141	
200	0.125	
Percent daylight		Fischer & Wilson (1975)
100	0.49	
72	0.46	
48	0.42	
35	0.39	
N and P (kg/ha) application		Roy & Wright (1973)
0/0	0.37	
60/0	0.42	
120/0	0.43	
0/26	0.43	
60/26	0.50	
120/26	0.49	

gen dressing at low water (470 kg/ha at N_0 and 538 kg/ha at N_{20}) and a GY strongly related to BY at high water.

The HI thus has been used extensively both for measuring the partitioning of photosynthates in cereal crops and in selecting for increased economic yields. The HI values for major cereals are shown in Table 1-16.

Table 1-17. Principal Characteristics of an Ideal Cereal Ideotype.

1. Strictly annual habit
2. Erect growth form
3. Dwarf structure
4. Strong stems
5. Unbranched or nontillered habit
6. Reduced foliage (smaller, shorter, narrower or fewer leaves)
7. Erect leaf disposition
8. Determinate habit
9. High harvest index
10. Nonphotoperiodic for most but not all situations
11. Early flowering for most but not all situations
12. High population density
13. Narrow rows or square planted

Source: Donald and Hamblin (1983).

Based on the various interactions among plant genotypes and characteristics, water, nitrogen application, and their interrelationships with HI, BY, and GY, Donald and Hamblin (1976, 1983) have proposed several characteristics for an ideal cereal "ideotype" (i.e., a biological model that is expected to perform and behave in a predictable manner within a defined environment). They further suggest that these characteristics be considered in breeding future cereal cultivars. The principal characteristics of the ideotype proposed for all cereal and other annual seed crops and their cultures are summarized in Table 1-17. Based on these, they have further postulated other useful features and practices for annual seed crops (Table 1-18).

The various studies described above suggest the need for considerable additional information of the physiological mechanisms that control growth and ultimate size of the individual plant and its potential for economic yield, if more rapid progress in increasing crop yields is to be achieved. In addition, information is needed on the role of specific genes and the heritability of morphological and physiological traits to help breeders operate more efficiently. Interdisciplinary research teams are needed to understand the complex interrelationships among the mechanisms controlling growth, development, and partitioning, and to develop techniques and guidelines for improving management practices and for selecting for increased economic yield of cereal crops.

Table 1-18. The Features of a Common Ideotype for All Cereal Crops, Together with Associated Cultural Practices.

Feature of Crop	Features of Ideotype
Pure culture sown at high density	Good plant performance among like neighbors sown at high density, hence communal plants needed; plant yield in isolation or in competition with other genotypes of no relevance
Strictly annual habit	Determinate growth; plant death at seed ripeness; loss of residual features of perenniality (i.e., of vegetative branching, tillering or vegetative storage organs)
Crop must not lodge or collapse	Plants of sound physical structure; short stature, strong or flexible stems, nonbranching, nontillering, nonleafy
Effective form and disposition of foliage for light utilization	Deep light penetration within the leafy canopy; small, narrow or divided, erect leaves
High seed yield sought	High biological yield, attainable through high sowing rate, rapid emergence, rapid attainment of optimum leaf area index, high net assimilation rate High harvest index, involving annual habit, no excessive use of resources on plant framework, short stature, light stems, nonbranching, nonleafy Large sink for photosynthates, many seeds per unit of biological yield, long interval flowering to maturity, no sterility at high plant density
Minimal competition between plants	Absence of those features associated with strong competitive ability (i.e., absence of tallness, large or horizontally disposed leaves, branching or widely ramifying root system)
Plant density and plant arrangement to be appropriate to the communal plant form	High plant density to compensate for lack of branching and lack of leafiness; close approach to uniform spacing through use of narrow rows
Effective response to high nutrient levels	Limited increase in competition between plants as fertility is raised; absence of plant responses giving increased competitive ability, especially minimal increase in height, leafiness, or branching
Wide climatic adaptation	As appropriate to the climatic region but commonly including nonphotoperiodicity; earliness of flowering to avoid early or late frosts, cold soil or cold irrigation water early in the season, drought, or wet or wintery conditions at harvest; wide temperature tolerance

Source: Donald and Hamblin (1983).

AGRONOMY

Agronomic practices for the cultivation of different cereal crops vary not only from one geographical location to another, but often also from one location to another within the same geographical area. They are a function of several variables, differing significantly with variety, cultivar, and genotype. More intensive cultivation practices are required for high-yielding genotypes than for cultivars grown under traditional subsistence farming, where any grain and fodder yield is preferable and desired. The high-yielding genotypes require significant inputs of irrigation, fertilizers, and pesticides at timely intervals if their full potential is to be realized. Cereal cultivation in the developing countries is still labor intensive where land preparation, seeding, cultural operations, harvesting, and threshing are done manually; fortunately, these countries also enjoy the benefits of cheap and abundant farm labor throughout the year.

The effects of the green revolution, as well as the increasing awareness among farmers of the potential benefits and economic rewards of resorting to high-yielding modern cereal genotypes, are quite evident throughout the developing countries. The characteristics of these genotypes (especially of rice and wheat) and of their use include the following:

higher, often doubled yield of grain per unit land area, combined with a similar protein content (thus giving the possibility of doubled yield of protein);
larger return of grain per unit of fertilizer applied and per person-hour of labor expended;
higher yield of protein per unit of irrigation water;
early maturation;
less sensitivity to daylength, thus allowing greater flexibility in planting time and the possibility of two or even three crops per year; and
shortness of height, making them resistant to lodging under the windy conditions prevalent in the tropics and subtropics, which include most of the world's developing countries.

It is neither intended nor feasible to cover here in detail the various agronomic practices employed in cereal cultivation worldwide. Moreover, production systems are not fixed packages to be used year after year. For example, the correct seeding rate depends on the area of production, the cultivar, the intended end use of the crop, and soil fertility. For any given genotype, where moisture is plentiful throughout the growing season, a higher seeding rate may be used than in areas of limited rainfall. The planting date may be varied if a particular disease or pest is known to invade a given locality or geographical area during a certain time of year. Similarly, the crop may be harvested early if bad weather conditions that may ruin the entire crop are forecasted. Fixed guidelines are therefore practically impossible when dealing with a system so dependent upon the vagaries of the surrounding environment and of nature itself.

Some of the textbooks and monographs available on various topics covering the broad area of cereal agronomy, including individual cereal crops, include the following: Inglett (1970, 1979), Pomeranz (1971), Chandler (1979), Esmay, Soemangat, and Phillips (1979), Yamazaki and Greenwood (1981), Gallagher (1982), Lorenz (1982), Kent (1983), Stoskopf (1985), DuPont and Osman (1987), ICAR (1988), and Palmer (1989). Readers are also referred to *Advances in Agronomy,* an excellent series of continually updated reviews on various production aspects of cereals. Information on newly developed genotypes and cultivars of various cereals and their cultural requirements is also published annually by the various national agricultural agencies of different countries, as well as by such international research institutions as CIMMYT in Mexico, IRRI in Philippines, and ICRISAT in India. Therefore, only the salient features of cultivation of some of the important cereal crops, mostly taken from the above references, are described below.

Wheat

The cultural practices for wheat depend on the type of wheat grown. The hard red spring (HRS) wheat is grown in the northcentral United States, mostly where the winters are too severe for the production of winter wheat. HRS wheats are also grown in Canada, Poland, and the USSR. Durum wheat is also commonly grown in these countries. The hard red winter (HRW) wheats are adapted to the central and southern Great Plains, where the annual rainfall is <35 in.; they are also grown extensively in Europe, Argentina, and the southern USSR. The soft red winter (SRW) wheats are grown principally in the eastern United States, where the average annual rainfall is <30 in., but also in Western Europe. White wheats are grown in the far western U.S. states and the rest of Europe, as well as in Australia, South Africa, western South America, and Asia.

Wheat, a cold-weather crop, prefers soils with pH in the range 4.5–8.6 for bread wheat and 5.3–8.3 for durum wheat types, and an average temperature of 5–27 °C and 7–20 °C during the growing season for bread and durum wheats, respectively. The crop is generally sown in drills at a depth of 1.5–3 in. in well-prepared seedbeds. Seed rates for bread wheat are in the range 30–120 lb/acre, and for durum types, 60–90 lb/acre. The time of seeding varies with geographical location. In the semiarid Great Plains of the United States and Canada, the optimum date for winter wheat seeding is generally at the beginning of September, becoming progressively later to the south. Spring wheats are also grown from fall or winter sowing in China, India, southern Europe, Africa, and parts of Latin America. Early seeding of the spring wheats usually results in the highest yields, since the crop is most likely to escape injury from drought, heat, and diseases that become more prevalent as the season advances.

The crop is harvested with combines in developed countries, whereas both harvesting and subsequent threshing are still largely manual operations in developing countries.

Rice

Rice is unique among the cereals in being able to germinate and thrive in water. Without oxygen, a condition associated with wet or flooded soil conditions, most cereal crop plants turn yellow, wilt, and eventually die. Oxygen-deprived cereal plants show restricted shoot and root growth. Under normal, aerobic soil conditions, water and air fill the porous structure from which roots obtain the oxygen necessary to function. Lowland rice does not rely on soilborne oxygen for its survival and is thus able to grow under submerged conditions. There are three main adaptive mechanisms that enable rice to grow under these conditions (Martin and Leonard 1967; Gallagher 1982):

1. A highly developed system of anaerobic respiration, especially during early growth stages, allows the plant to tolerate oxygen-deprived conditions.
2. An ability to transport oxygen from leaves to roots through tubelike structures ("aerenchyma" cells in leaves, stems, and roots) permits air to move from the leaves to root surfaces. This supplies the submerged roots with sufficient oxygen for normal respiration, subsequent growth, and nutrient absorption.
3. A special system of very fine, abundantly branched, negatively geotropic roots on the soil surface (developed at the time of panicle initiation) supplies oxygen to the roots when stem elongation temporarily disrupts the downward internal flow of oxygen.

Rice is grown in the tropics and subtropics where both rain and sunshine are abundant. It is also grown in the temperate regions of the world. *Indica* rices predominate in the tropical rice-growing areas, whereas *japonica* types are suited to the temperate regions. Although typically a swamp cereal, rice can be grown either on dry land (upland rices) or underwater (lowland cultivation). Yields under dry upland conditions, however, are much lower than those for submersion.

The best soils for rice are slightly acidic to neutral, but the crop can be grown on soils in the pH range 4.3–8.3. Heavy soils with an impervious underlying subsoil 1.5–5 ft from the surface are required to minimize water drainage. The common practice of flooding the paddies has been adopted both as a means of irrigation and also to control weeds.

The crop is sown either broadcast or with grain drills. Seed rates may vary from 67 to 160 lb/acre depending upon the variety. In many oriental countries, the seeds are first grown in rice nurseries and transplanted after four to eight weeks to the main fields. Transplanting offers the advantages of better land use (growing two different crops per year), savings on irrigation water, and better weed control. In hand transplanting, the rows are spaced for convenient weeding, harvesting, and fertilizer application, all of which are done manually. The seed is generally sown in beds while the fields are still occupied by other crops.

Rice is a highly mechanized crop in the United States, where planting, fertilizer treatment, and weeding are all carried out on a large scale by means of aircraft, and the crop is harvested by combine harvesters. In contrast, over 90% of the world crop is managed entirely without mechanization.

In order to produce maximum yields of high milling quality, rice should be harvested when the moisture content of the grain of standing rice has dropped to 23–28%. At this stage, the kernels in the lower portion of the heads are in the hard-dough stage while those in the upper portion are fully ripe. Increased shattering occurs in some varieties if the harvest is delayed beyond this stage. When grown as a lowland crop, the fields are drained about two to three weeks before harvest. The harvest is then dried to about 14% moisture content prior to threshing.

Rice yields become stabilized at low yield levels when grown continuously on the same land. In the southern and western United States, rice is usually grown on the same land for two or three years, which is then seeded to pasture crops. Crops frequently grown in rotation with rice on well-drained soils include safflower, sorghum, wheat, and barley.

Corn

Corn has a remarkable diversity of vegetative types and is grown in a wide range of environmental conditions. From latitude 58° N in Canada, corn cultivation passes without interruption through the tropical regions and on to the frontiers of agriculture in the Southern Hemisphere (35°–45° S latitude). Corn is cultivated in regions that experience periods of at least ninety days of frost-free conditions. The annual rainfall where it is grown ranges from 10 in. in the semiarid plains of the USSR to >200 in. in tropical India. Suitable types are available for these varying conditions.

Corn requires an abundance of readily available plant nutrients and soils with pH ranging from 5.5 to 8.0 for the best production. Fertile, well-drained loam soils found in the North American prairie region are best suited for corn cultivation.

The crop is usually planted 2–3 in. deep in rows 36–44 in. apart. Seed rates vary depending upon the end use of the crop, rates of 6–18 lb/acre commonly being used for grain production, 8–18 lb/acre for silage, 3–6 lb/acre for popcorn, and 12–18 lb/acre for sweet corn types. It is harvested for grain with a corn picker, picker-sheller, or corn combine. In the developing countries, the cobs are manually picked, dehusked, and shelled.

Almost the entire U.S. corn crop is planted to hybrid corn varieties, which normally outyield by 15–20%, and sometimes up to 50%, those of inbred lines.

Barley

Barley is grown throughout the more temperate regions of the world, mainly as a spring crop, and has a geographic distribution generally similar to that of wheat. It withstands more heat under semiarid than under humid conditions. In the warmer climates, barley is sown in the fall or winter.

The best barley soils appear to be well-drained loams, which need not be as fertile as those required by wheat. It produces a poor crop of low grain quality on heavy, poorly drained soils in regions of frequent rains. Light sandy soils are unsuitable since crop growth is often erratic and ripening may be premature. In spite of the stringent requirements to produce a crop of high grain quality, especially for the brewing industry, barley is one of the most dependable cereal crops under extreme conditions of salinity, frost, or drought (Martin and Leonard 1967).

Where moisture is plentiful throughout the growing season, a higher seeding rate may be used than in areas of limited rainfall. Large-seeded, two-row barley cultivars should be seeded at a slightly higher rate than average-sized, six-row cultivars. Seeding rates for barley in western Canada vary 35 to 90 lb/acre (40–100 kg/ha) (Gallagher 1982). The crop is usually planted in drills. In general, most cultural operations, including harvesting and threshing of barley, are similar to those used in wheat production.

Oats

Common oats are best adapted to cooler, more temperate regions, where the annual rainfall is ≥30 in., or where the land is irrigated. Thus they are more successful than wheat or barley in wet climates. Oats are a major crop in the Pacific Northwest and in valleys of the Rocky Mountain regions of the United States, as well as in northern Europe and Canada. Because of drought and heat, the crop often fails in the Great Plains.

Oats produce a satisfactory crop on a wide range of soil types, provided the soil is well drained and reasonably fertile. In general, loam soils, especially silt and clay loams, are best suited for oat cultivation. Heavy, poorly drained clays are likely to cause the crop to lodge. Oats generally follow corn or some other row crop; consequently, the seedbed often is prepared by disking and harrowing without plowing. The crop is seeded at 50–130 lb/acre as early in the spring as a seedbed can be prepared, but after the prolonged cold weather is past.

In the United States and Canada, over 95% of the crop for grain is threshed with a combine. Sometimes the crop is harvested with a binder in order to save more of the straw. Nearly 40% of the crop is windrowed before combining, in order to avoid losses from lodging and shattering of the grain.

Sorghum

Sorghum crop is grown in latitudes below 45° on all continents, in warm or hot regions that have summer rainfall as well as in hot, irrigated areas. The most favorable mean temperature for the crop is 27 °C (80°F). Sorghum withstands extensive heat better than other crops, but extremely high temperatures during the fruiting period reduce the seed yield.

Sorghums are well adapted to summer rainfall regions where the average annual rainfall is only 17–25 in. The plants remain practically dormant during periods of drought but resume growth as soon as there is sufficient rain to wet the soil. Sorghum is grown successfully on all types of soil. In rainy seasons, the highest yields are obtained on heavy soils, but in dry seasons, it does best on sandy soils. Sorghum also tolerates considerable salinity. The crop is not troubled by serious pests and diseases, and has the added advantage that it can be sown late, if other crops fail.

A warm, mellow seedbed is essential to good seed germination for sorghum. High temperatures of 23 °C at planting depth favor rapid germination; therefore, the crop must be planted after the soil is sufficiently warm. In general, sorghum planting may extend from midspring or early March to about the beginning of July in areas with an extended growing season. The seed is best planted in rows 30–42 in. apart and about 1 in. deep in moist soil, or at 2 in. depth in dry warm soil. Shallow seeding depths are generally recommended in the cooler regions. Seed rates for grain crop vary from 2 to 5 lb/acre. The crop is harvested with a combine, or manually in the developing countries of the world.

Rye

Winter rye is the hardiest of all cereals (Martin and Leonard 1967). On good soils, it is a less profitable crop than wheat. The highest yields are usually obtained on rich, well-drained loam soils. It is more productive than other grains on infertile, sandy, or acidic soils, and is the only small grain crop that succeeds on coarse, sandy soils.

Winter rye can be seeded at almost any time during the late summer or early fall, but early seeding produces the most fall pasture. In contrast, spring rye, like other spring small grains, should be sown as early as is feasible. The seed is generally planted in drills at a rate of about 30–110 lb/acre. Most other cultural operations are similar to those used in wheat and barley production.

Millets

Millets are grown throughout the drier parts of tropics and in drier areas of Africa, India, and China. In recent years, they are being increasingly cultivated in the United States, Australia, and South Africa. As a general rule, they are well adapted to drought conditions, well suited to arid tropics with high temperatures, and have good yields under low rainfall. In areas receiving <45 cm annual rainfall, they are not usually grown as a dryland crop, and often require irrigation. Millets are susceptible to frost during the growing period, and plants may be killed if the temperatures are sufficiently low. Optimum temperatures for millet cultivation are in the range 16–40 °C. Early frosts also cause premature ripening of grain; the seeds may mature badly frostbitten and shriveled.

Millets are adapted to a wide range of soil types varying from light loams to heavy clays, but light soils are generally preferred. They thrive best on free-working soils of high fertility. Millets are often the most productive grain crops in extremely dry and infertile soils of India and Africa.

Generally, millets require firmly prepared seedbeds due to their small seed size. It is essential to control weeds thoroughly up to the time of sowing because millet seedlings are small and compete poorly with weeds until they have attained some size. The crop is planted when the soil is warm and after the danger of frost is passed. They are seeded, with an ordinary grain drill, 2–5 cm deep and 5–10 cm apart; closer spacings help the crop suppress weeds. Seed rates vary with soil type, species, variety, and the availability of irrigation water during the growing season.

Millets respond well to nitrogen and phosphorus fertilizers. Under dry conditions, weekly irrigations are usually necessary for good yields. In tropics, two to four cultivations are usually necessary to control weeds. For seed, the crop is usually harvested with a binder and allowed to stand in the field until the seed can be rubbed from the head. The crop may be windrowed to be threshed later with a combine with pickup attachment. Direct combining is less successful because part of the seeds shatter before the later seeds are ripe. In tropical countries the heads are cut by hand and dried in heaps on the ground or on the threshing floor. For proper storage, millet seeds should be dried down to 12–13% moisture.

Buckwheat

Although cultivated primarily to produce seed for human consumption, buckwheat is often used as a green manure crop, as a smother crop to suppress weeds, and as a source of buckwheat honey. Buckwheat grows best in a cool, moist climate. It is extremely susceptible to frost and can be severely damaged by late spring or early fall frost. Seeding, therefore, is generally delayed until the danger of spring frost is past. The crop is also sensitive to high temperatures and hot, dry winds, especially when moisture is scarce. These conditions during flowering can cause flower blasting, which reduces seed set and yield.

Buckwheat is adapted to a wide range of soil types and has high tolerance to soil acidity. It grows best on well-drained sand or silt loam soils. Although it grows well on hastily prepared land, careful plowing and seedbed preparation give higher yields. Seeds are either broadcast or drilled 2.5–5 cm apart in rows 15–40 cm wide. Seed rates generally vary between 25 and 40 kg/ha.

On poor soils, buckwheat responds well to fertilizers. Phosphorus application is generally beneficial. In contrast, excess nitrogen encourages vegetative growth and increased tendency to lodge, thereby reducing seed yields. Serious losses due to diseases and pests are rare in buckwheat.

Because of its indeterminate growth habit, ripening in buckwheat is rarely uniform. The crop is normally harvested after ten weeks, when seeds at the base of the plants are fully ripe. Buckwheat is usually swathed and then harvested with a combine after the plants and seeds have dried. To reduce losses due to shattering, the crop is usually cut early in the morning or in dull weather when the plants are moist; it is then combined when the seed in the swath contains $<16\%$ moisture. Average seed yields range from 800 to 1,000 kg/ha, although yields of up to 2,000 kg/ha are produced under favorable conditions in the Prairie Provinces of Canada.

Some of the relevant agronomic data on various cereals are summarized in Tables 1-19, 1-20, and 1-21. Although the values for soil pH, annual precipitation, and temperature shown in Table 1-19 are extreme ranges, best yields are generally obtained in the middle of the ranges given. The cold weather crops—spring wheat, barley, and oats—show the highest resistance to frost, whereas rice and corn are quite susceptible to these conditions, especially during the fruiting season (Table 1-20). Data on the nutrient uptake from soils by the high-yielding genotypes of various cereals (Table 1-21) could be used as a rough index for the application of fertilizers; actual levels will, of course, be determined by the nutrient analyses of the soil and the previous crop grown on the same piece of land. In general, C-4 crops such as corn and sorghum are nutrient demanding as compared to C-3 crops, and thus should not be grown continuously on the same land.

The advantages of cereal–legume intercropping systems, especially under the subsistence farming systems, as well as the technology of drying and storage of grains, are described at great length in Chapter 2, and hence will not be discussed here.

Table 1-19. Some Agronomic Requirements of Various Cereal Crops.

Cereal	Growth Type[a]	Soil pH	Rainfall (dm/yr)	Annual Temp. (°C)[b]	Seed Rate (lb/acre)		Germination Time (days)	Temp. Type[c]
					Drills	Rows		
Wheat								
Bread	A,G	4.5–8.6	3–25	5–27	30–120		7	C
Club	A,G	5.8–8.3	3–16	6–16	60–90		7	C
Durum	A,G	5.3–8.3	3–16	7–19	60–90		10	C
Rice	A,G	4.3–8.3	5–42	9–29	67–100		14	W
Wild	A,G	5.8–7.8	4–13	7–19				
Corn	A,G	4.3–8.3	3–40		5–29	6–18	7	W
Barley	A,G	4.5–8.3	5–25	5–24	72–96		7	C
Oats	A,G	4.5–8.6	2–21	5–26	48–128		10	C
Sorghum	A,G	4.3–8.7	4–41	8–27		2–5	10	W
Rye	A,G	4.5–8.3	3–17	5–21	28–112		7	C
Millets								
Finger millet	A,G	4.3–8.4	3–42	12–27	12–20	5–10	7	W
Italian millet	A,G	5.0–8.3	3–42	6–27	20–30		10	W
Pearl millet	A,G	4.5–8.3	2–26	12–27	16–20	4–6	7	W
Proso millet	A,G	4.8–8.5	3–42	6–27	15–35		7	W
Triticale	A,G	5.3–7.5	4–25	6–26	30–90		8	C
Buckwheat	A,H	4.8–8.2	4–13	6–25	36–60		6	W

Compiled from: Jung (1978), Gallagher (1982), Kent (1983), Stoskopf (1985), and Hanson (1990).

[a] Growth type: A, annual; H, herb; G, grass.

[b] Average of monthly means with values below 0 °C treated as 0.

[c] Temperature type: C, cold weather crop; W, warm weather crop.

Table 1-20. Resistance of Cereals to Frost in Different Developmental Phases.

Frost Resistance	Temperature (°C) Harmful to Plant in the Phases of: Germination	Flowering	Fruiting
High			
Spring wheat	–9, –10	–1, –2	–2, –4
Oats	–8, –9	–1, –2	–2, –4
Barley	–7, –8	–1, –2	–2, –4
Medium			
Italian millet	–3, –4	–1, –2	–2, –3
Low			
Corn	–2, –3	–1, –2	–2, –3
Millet	–2, –3	–1, –2	–2, –3
Sorghum	–2, –3	–1, –2	–2, –3
None			
Buckwheat	–1, –2	–1, –2	–0.5, –2
Rice	–0.5, –1	–0.5, –1	–0.5, –1

Adapted from: Chang (1968).

Table 1-21. Uptake of Nutrients (kg/ha) by the High-Yielding Varieties of Cereals.

Cereal	Yield/ha, Plant Part	N	P_2O_5	K_2O	Mg	S
Wheat	5,376 kg grain	106	49	30	13	6
	Straw	47	11	151	13	17
	Total	153	60	181	26	23
Rice	7,840 kg grain	86	52	31	9	6
	Straw	39	16	134	7	8
	Total	125	68	165	16	14
Corn	12,544 kg grain	168	97	64	20	17
	Stover	130	30	234	53	20
	Total	298	127	298	73	37
Barley	5,376 kg grain	123	45	39	9	11
	Straw	45	17	129	10	11
	Total	168	62	168	19	22
Oats	3,584 kg grain	90	28	22	6	9
	Straw	39	17	140	17	12
	Total	129	45	162	23	21
Sorghum	8,960 kg grain	134	67	34	16	25
	Stover	146	34	190	34	18
	Total	280	101	224	50	43
Buckwheat	1,613 kg grain	34	17	11	—	6
	Straw	13	6	28	—	3
	Total	47	23	39	—	9

Source: Courtesy Potash and Phosphate Institute, Atlanta, Georgia.

DISEASES AND PESTS

The three most important constraints in the production of field crops are water, nitrogen fertilizers, and pests and diseases. World crop losses to the three major pest groups—insects, pathogens, and weeds—are currently estimated at about 35% (Pimentel 1981; Davidson and Lyon 1987). Mammal and bird losses appear to be more severe in the tropics and subtropics than in the temperate region, but still are low compared with losses to these three pest groups. Representative data on losses in world cereal crops from insects and pathogens are summarized in Table 1-22; data on losses due to various arthropod pests of selected cereals are shown in Table 1-23.

Losses to pests have been intensified by the use of the intensive crop production technology introduced with the green revolution. The new high-yielding cereal cultivars in use today are often more susceptible to pests than were their old counterparts. Before the green revolution, farmers usually selected seeds from individual plants that survived and yielded best under the native cultural conditions. These plants contained genes resistant to insects and pathogens, and competed successfully with weeds (Pimentel 1981).

Table 1-22. Estimated Losses (%) in World Cereal Crops from Insects and Diseases.

Cereal	Insects	Diseases	Total
Wheat	5	9	14
Rice	27	9	36
Corn	12	9	21
Barley	4	8	12
Oats	8	9	17
Sorghum and millets	10	11	21
Rye	2	3	5

Source: McEwen (1978).

Table 1-23. Losses of Various Cereal Crops Caused by Arthropod Pests.

	Calculated Yield Loss (%)	
Crop and Pest	Without Control	With Control
Wheat, oats, rye, & millets		
Banks grass mite	61	18
Brown wheat mite	100	21
Cutworms	54.7 ± 12.4	7.7 ± 3.2
Rice		
Leafhoppers	42	9
Rice water weevil	5.2 ± 4.6	1.5 ± 1.5
Corn (field)		
Corn field ant	20	3
Corn rootworms	15.7 ± 4.6	5.0 ± 1.3
Garden symphalid	14	7
Leafhoppers	74.7 ± 15.7	38.3 ± 14.8
Southwestern corn borer	34.4 ± 10.4	9.9 ± 2.7
White grubs	43	11
Wireworms[a]	48.3	18.4
Cutworms	22	7
European corn borer	4.3 ± 4.3	0.3 ± 0.3
Fall armyworm	67.5 ± 1.5	27.0 ± 1.0
Rootworms	45.5 ± 45.5	0.0 ± 0.0
Barley		
Greenbug	84	7
Sorghum		
Fall armyworm	19.4 ± 7.2	0.0 ± 0.0
Sorghum midge	5.0 ± 5.0	0.2 ± 0.2
Sorghum webworm	3	0
Southwestern corn borer	24	4
White grubs	39.0 ± 26.3	9.3 ±4.7

[a] For sweet corn: 29.0 ± 19.0 without control, 4.0 ± 2.0 with control.
Source: Schwartz and Klassen (1981).

Worldwide postharvest losses of food plants to pests are estimated to range from 10% to 20% (Salunkhe, Chavan, and Kadam 1985). The major pests of harvested foods are microorganisms, insects, and rodents. When these losses are added to preharvest losses, worldwide food losses due to pests amount to a staggering 45% of total crop production. This significant loss of valuable food occurs in spite of all of the methods used to control pests.

Pimentel (1981) estimated U.S. preharvest losses of food plants to pests to be about 37% even with the use of modern pest control technology. Insects account for 13% of these losses, plant pathogens 12%, and weeds 12%. U.S. postharvest food losses are estimated to be about 9%. Thus, total losses to pests in the United States alone are estimated to be more than 40%. It is quite possible that such losses would be even higher in the developing countries where the advanced pest control technology is neither available nor economically feasible.

Diseases

Major diseases of economic importance in cereal crops and their geographic distribution are summarized in Table 1-24. Fungi and bacteria are the major disease-causing agents, although in several places viruses, nematodes, and mycoplasmas are also important.

Bacteria

Bacteria are disseminated primarily by water, insects, seeds, plant parts, machinery, tools, or any method that can move soil from place to place. They are, however, infrequently disseminated by wind. Free water on the plant surface is necessary for motility of bacterial cells, which enter a plant through a natural opening or wounds. Once a cell enters a plant, it begins to multiply and establish an infection if environmental conditions are favorable. Survival, overwintering, or overseasoning is accomplished as survival spores directly in soil or in the dead tissue; in live infected perennial plants, insects, and on or in seed; and as saprophytes on plant residue (Jones and Clifford 1979; Nyvall 1989).

Symptoms of diseases caused by bacteria are varied. Infected below-ground plant parts may have galls on roots, discoloration only of xylem tissue or of other tissue, and decomposition typified by wet, slimy, and smelly rot. Aboveground plant parts may have wet-appearing or water-soaked spots as well as chlorotic or yellow spots, tan spots, or streaks with or without a chlorotic halo (Nyvall 1989). Stalks or stems may have a wet and smelly rot. The entire plant may wilt showing a grayish-green foliage and, often, a discoloration of seeds.

Fungi

Fungi are disseminated by wind, water, insects, seeds, plant parts, machinery, and tools. They enter plants by spores or propagules forming a germ tube that

Table 1-24. Major Diseases of Cereal Crops and Their Distribution.

Crop and Disease	Organism[a]	Distribution
Wheat		
Bacteria		
Bacterial leaf blight	*Pseudomonas syringae*	Northcentral USA
Bacterial mosaic	*Corynebacterium* spp.	Central USA
Basal glume rot	*Pseudomonas atrofaciens*	Worldwide
Black chaff	*Xanthomonas translucens*	Worldwide
Pink seed	*Erwinia rhapontici*	Canada, Europe
Spike blight	*Corynebacterium tritici*	Australia, Canada, China, Egypt, Ethiopia, India
Fungi		
Anthracnose	*Colletotrichum graminicola*	Worldwide
Ascochyta leaf spot	*Ascochyta tritici*	Europe, Japan, N. America
Cephalosporium stripe	*Cephalosporium gramineum*	England, Japan, N. America
Common bunt	*Tilletia caries*	Worldwide
Common root rot	*Helminthosporium sativum*	Worldwide
Downy mildew	*Sclerophthora macrospora*	Worldwide
Dwarf bunt	*Tilletia controversa*	Canada, Europe, USA
Ergot	*Claviceps purpurea*	Worldwide
Eyespot	*Pseudocercosporella herpotrichoides*	Worldwide
Flag smut	*Urocystis agropyri*	Australia, USA
Glume blotch	*Septoria nodorum*	Worldwide
Halo spot	*Selenophoma donacis*	England, northern Europe, USA
Leaf rust	*Puccinia recondita*	Worldwide
Leaf spot	*Ascochyta sorghi*	Eastern USA
Leaf spot	*Phaeoseptoria urvilleana*	England, USA
Leptosphaeria leaf spot	*Leptosphaeria herpotrichoides*	Canada, Europe, USA
Loose smut	*Ustilago tritici*	Worldwide
Phoma glume blotch	*Phoma insidiosa*	India
Pink snow mold	*Calonectria nivalis*	Canada, central and northern Europe, and USA
Platyspora leaf spot	*Platyspora pentamera*	Northcentral USA and Canada
Powdery mildew	*Erysiphe graminis*	Worldwide
Pythium root rot	*Pythium* spp.	Worldwide
Scab	*Gibberella zeae*	Worldwide
Sclerotinia snow mold	*Sclerotinia borealis*	Canada, Europe, Japan, Scandinavia, USSR
Septoria leaf blotch	*Septoria tritici*	Worldwide
Sharp eyespot	*Rhizoctonia solani*	Worldwide
Snow rot	*Pythium aristosporum*	Northwestern USA
Stem rust	*Puccinia graminis*	Worldwide
Stripe rust	*Puccinia striiformis*	N. and S. America, Asia, central Europe
Take all	*Gaeumannomyces graminis*	Worldwide
Twist	*Dilophospora alopecuri*	Canada, Europe, India, USA
Yellow leaf spot	*Pyrenophora trichostoma*	Worldwide
Mycoplasmas		
Aster yellows	Aster leafhoppers	Eastern Europe, Japan, N. America

Table 1-24. (*Continued*)

Crop and Disease	Organism[a]	Distribution
Nematodes		
Oat cyst	*Heterodera avenae*	Africa, Australia, southeastern Canada, Europe, Japan, USSR, USA
Root gall	*Subanguina radicicola*	Canada, Northern Europe
Root knot	*Meloidogyne* spp.	Worldwide
Root lesion	*Pratylenchus* spp.	Worldwide
Seed gall	*Anguina tritica*	E. Asia, Europe, India, southeastern USA
Stubby root	*Paratrichodorus* spp.	Worldwide
Stunt	*Merlineus brevidens*	Indigenous to most soils
Viruses		
American wheat striate mosaic	*Endria inimica, Elymana virescens*	Central USA, Canada
African cereal streak	*Toya catilina*	E. Africa
Barley stripe mosaic	Wind, hail, animals, and infected pollen	Australia, S. Asia, Europe, Japan, western N. America, USSR
Barley yellow dwarf	11 species of aphids	Worldwide
Eastern wheat striate	*Cicadulina mbila*	India
Soilborne wheat mosaic	*Polymyxa graminis*	Eastern and central USA
Tobacco mosaic	Soilborne	Central USA
Spindle streak mosaic	*Polymyxa graminis*	Northeastern USA, Canada
Wheat streak mosaic	*Aceria tulipae*	Eastern Europe, west-central USA
Rice		
Bacteria		
Bacterial blight	*Xanthomonas oryzae*	Africa, Asia, Caribbean, Central and S. America
Glume blotch	*Pseudomonas oryzicola*	Asia, Australia
Leaf streak	*Xanthomonas translucens* sp. *orizicola*	Tropical Asia
Fungi		
Bakanae disease	*Fusarium moniliforme*	Worldwide
Blast	*Pyricularia oryzae*	Worldwide
Brown bordered leaf and sheath spot	*Rhizoctonia oryzae*	Japan, USA, Vietnam
Brown leaf spot	*Helminthosporium oryzae*	Africa, Asia
Crown sheath rot	*Ophiobolus oryzinus*	Africa, India, Japan, USA
Downy mildew	*Sclerophthora macrospora*	Australia, China, India, Italy, Japan, USA
False smut	*Ustilaginoidea virens*	Worldwide
Kernel smut	*Tilletia barcclayana*	Worldwide
Leaf scald	*Rhynchosporium oryzae*	W. Africa, Central America, Southeast Asia, USA
Leaf spot	*Helminthosporium rostratum*	India
Leaf smut	*Entyloma oryzae*	Worldwide
Narrow brown leaf spot	*Cercospora oryzae*	Worldwide except Europe
Phoma seedling blight	*Phoma glomerata*	Ghana

Table 1-24. (*Continued*)

Crop and Disease	Organism[a]	Distribution
Fungi (*continued*)		
Pithomyces glume blotch	*Pithomyces chartarum*	India
Rust	*Puccinia graminis*	Worldwide
Seed and seedling blight	Several fungi	Temperate rice-growing areas
Sheath blight	*Rhizoctonia solani*	Worldwide
Sheath rot	*Acrocylindrium oryzae*	Southeast Asia, USA
Stackburn disease	*Alternaria padwickii*	Worldwide
Stem rot	*Leptosphaeria salvinii*	Asia, USA
Nematodes		
Stem nematode	*Ditylenchus angustus*	Southeast Asia, India, Egypt
White tip	*Aphelenchoides besseyi*	Southeast Asia, Australia, Cuba, Japan, USA
Viruses		
African cereal streak	Leafhopper	E. Africa
Grassy stunt	Brown planthopper	India, Malaysia, Philippines, Sri Lanka, Thailand
Hoja blanca	Leafhoppers	Western Hemisphere
Orange leaf	Zigzag leafhoppper	Malaysia, Philippines, Sri Lanka, Thailand
Ragged stunt	Brown leafhopper	Philippines, India, Indonesia, Sri Lanka
Yellow mottle	Mechanical transmission	Africa
Tungro	Green rice leafhopper	India, Bangladesh, Indonesia, Malaysia, Philippines, Thailand
Waika disease	Green rice leafhopper	Japan
Yellow dwarf	Leafhoppers	Tropical Asia
Corn		
Bacteria		
Bacterial leaf blight	*Pseudomonas avenae*	Southeastern USA
Bacterial stalk rot	*Erwinia* spp., *Pseudomonas* spp.	Worldwide
Bacterial stripe	*Pseudomonas andropogoni*	Eastern USA
Bacterial top rot	Unknown bacteria	Central USA
Chocolate spot	*Pseudomonas coronafaciens*	Central USA
Goss's bacterial wilt and blight	*Corynebacterium nebraskense*	Central USA
Holcus spot	*Pseudomonas syringae*	Eastern and midwestern USA
Stewart's wilt	*Erwinia stewartii*	Central America, China, Eastern and Southern Europe, eastern USA, USSR
Yellow leaf blotch	*Pseudomonas* spp.	W. Africa
Fungi		
Anthracnose	*Colletotrichum graminicola*	France, Germany, India, Philippines, eastern USA
Ascochyta leaf and sheat spots	*Ascochyta zeae*	USA
Aspergillus ear rot	*Aspergillus* spp.	Worldwide
Brown stripe downy mildew	*Sclerophthora rayssiae*	India

Table 1-24. (*Continued*)

Crop and Disease	Organism[a]	Distribution
Charcoal rot	*Macrophomina phaseoli*	Europe, N. America, S. Africa
Cladosporium rot	*Cladosporium herbarium*	Worldwide
Common rust	*Puccinia sorghi*	Worldwide
Common smut	*Ustilago maydis*	Worldwide
Corticium ear rot	*Corticium saskii*	India
Crazy top	*Sclerophthora macrospora*	Africa, N. and Central America, Asia, Europe
Curvularia leaf spots	*Curvularia* spp.	Warmer and milder climates
Diplodia ear and stalk rot	*Diplodia maydis*	Africa, Australia, Philippines, Romania, USA
Diplodia leaf spot	*Diplodia macrospora*	Central America
Downy mildew	*Sclerospora graminicola*	Worldwide
Ear and stalk rot	*Nigrospsora oryzae*	Worldwide
Ergot	*Claviceps gigantea*	Central Mexico
Eyespot	*Kabatiella zeae*	Northcentral USA and Ontario
False smut	*Ustilaginoidea virens*	Worldwide
Fusarium kernel and stalk rot, leaf spot	*Fusarium moniliforme*	Worldwide
Gibberella ear and stalk rot	*Gibberella roseum*	Worldwide
Gray ear rot	*Physalospora zeae*	Eastern USA
Gray leaf spot	*Cercospora zeae-maydis*	Africa, Southeast Asia, China, Europe, India, eastern USA
Head smut	*Sphacelotheca reiliana*	Australia, India, western Mexico, New Zealand, S. Africa, USSR, Yugoslavia, western and southeastern USA
Leaf disease	*Helminthosporium rostratum*	Worldwide
Leaf spot	*Helminthosporium carbonum*	Eastern and midwestern USA
Northern corn leaf blight	*Helminthosporium turcicum*	Worldwide
Northern leaf spot	*Helminthosporium* spp.	Northcentral USA
Penicillium rot	*Penicillium oxalicum*	Worldwide
Phomopsis seed rot	*Phomopsis* spp.	USA
Physoderma brown spot	*Physoderma maydis*	Southeastern and midwestern USA
Pythium root rot	*Pythium graminicola*	Worldwide
Pythium stalk rot	*Pythium aphanidermatum*	Worldwide
Red kernel disease	*Epicoccum nigrum*	USA
Sclerotium ear rot	*Sclerotium rolfsii*	India
Seed and seedling blight	*Pythium* spp., *Diplodia maydis, Gibberella zeae, Fusarium moniliforme, Rhizoctonia solani*	Worldwide Worldwide
Sorghum downy mildew	*Sclerospora sorghi*	Africa, Asia, India, USA
Southern corn leaf blight	*Helminthosporium maydis*	Worldwide
Southern rust	*Puccinia polysora*	Africa, Southeast Asia, Central and S. America, USA
Sugarcane downy mildew	*Sclerospora sacchari*	Southeast Asia
Tropical rust	*Physopella zeae*	Central and S. America, Caribbean

Table 1-24. (*Continued*)

Crop and Disease	Organism[a]	Distribution
Fungi (*continued*)		
Yellow leaf blight	*Phyllosticta maydis*	Africa, Asia, Brazil, Canada, Romania, USA
Zonate leaf spot	*Gloeocercospora sorghi*	Africa, S. America, USA
Mycoplasmas/Spiroplasmas		
Corn stunt	Leafhoppers	Southern and southeastern USA
Nematodes		
Root lesion nematodes	*Pratylenchus* spp.	Probably worldwide
Lance nematode	*Hoploaimus* spp.	Probably worldwide
Viruses		
American wheat striate mosaic	*Endria inimica, Elymana virescens*	Canada, northcentral USA
Corn lethal necrosis	Plant-sucking bugs	Central USA
Maize chlorotic dwarf	*Graminella nigrifrons*	Eastern USA
Maize chlorotic mottle	6 species of beetles	Peru, USA
Maize dwarf mosaic	*Rhopalosiphun maidis, Schizaphis graminun, Myzus persicae*	Australia, USA
Maize mosaic	*Peregrinus maidis*	Africa, Australia, Caribbean, Hawaii, India, N.–S. USA
Maize streak disease	*Cicadulina mbila, C. zeae, C. nicholsi*	Africa, Asia
Rayadofino (fine stripping)	*Dalbulus maidis*	Central America
Wheat streak mosaic	*Aceria tulipae*	Northern Africa, N. America, Europe
White leaf of corn	*Peregrinus maydis*	Venezuela
Barley		
Bacteria		
Bacterial stripe blight	*Pseudomonas striafaciens*	Australia, N. and S. America, Europe
Basal glume rot	*Pseudomonas atrofaciens*	Worldwide
Black chaff	*Xanthomonas translucens*	Worldwide
Fungi		
Anthracnose	*Colletotrichum graminicola*	Worldwide
Ascochyta leaf spot	*Ascochyta graminea*	Eastern USA
Aster yellows	*Macrosteles fascifrons*	Eastern Europe, Japan, N. America
Cephalosporium stripe	*Cephalosporium gramineum*	N. America, England, Japan
Common root rot	*Helminthosporium sativum*	Worldwide
Covered smut	*Ustilago hordei*	Worldwide
Downy mildew	*Sclerophthora macrospora*	Worldwide
Dwarf bunt	*Tilletia controversa*	Western USA
Ergot	*Claviceps purpurea*	Worldwide
Eyespot	*Pseudocercosporella herpotrichoides*	Worldwide
Glume blotch	*Septoria nodorum*	Worldwide
Halo spot	*Selenophoma donacis*	England, N. Europe, USA
Leaf rust	*Puccinia hordei*	Worldwide

Table 1-24. (*Continued*)

Crop and Disease	Organism[a]	Distribution
Leaf spot	*Leptosphaeria herpotrichoides*	Canada, Europe, USA
Loose smut	*Ustilago tritici*	Worldwide
Net blotch	*Helminthosporium teres*	Worldwide
Powdery mildew	*Erysiphe graminis*	Worldwide
Pythium root rot	*Pythium* spp.	Worldwide
Scab	*Gibberella zeae*	Worldwide
Scald	*Rhynchosporium secalis*	Worldwide
Seedling blight	*Gibberella zeae*	Worldwide
Semiloose smut	*Ustilago nigra*	Worldwide
Septoria leaf blotch	*Septoria avenae*	Worldwide
Sharp eyespot	*Rhizoctonia solani*	Worldwide
Spot blotch, associated seedling and crown rots	*Helminthosporium sativum*	Worldwide
Stem rust	*Puccinia graminis tritici*	Worldwide
Stripe disease	*Helminthosporium gramineum*	Worldwide on winter barley
Stripe rust	*Puccinia striiformis*	N. and S. America, mountain areas of Europe and Asia
Take all	*Gaeumannomyces graminis*	Worldwide
Nematodes		
Root gall	*Subanguina radicicola*	Canada, N. Europe
Root knot	*Meloidogyne* spp.	Worldwide
Root lesion	*Pratylenchus* spp.	Worldwide
Viruses		
African cereal streak	*Toya catilina*	E. Africa
American wheat striate mosaic	*Endria inimica*, *Elymana virescens*	Central USA, Canada
Barley stripe mosaic	Infected pollen	S. Asia, Australia, Europe, Japan, western N. America, USSR
Barley yellow dwarf	11 species of aphids	Worldwide
Eastern wheat striate	Plant hopper	India
Moderate barley dwarf	Leafhoppers	Canada, Europe, northcentral USA
Wheat soilborne mosaic	*Polymyxa graminis*	Argentina, Brazil, Egypt, Italy, Japan, eastern and central USA
Wheat streak mosaic	*Aceria tulipae*	Eastern Europe, western and central N. America, USSR
Rye		
Bacteria		
Blight	*Xanthomonas translucens*	Australia, N. America
Halo blight	*Pseudomonas coronafaciens*	Worldwide
Fungi		
Anthracnose	*Colletotrichum graminicola*	Worldwide
Cephalosporium stripe	*Cephalosporium gramineum*	England, Japan, N. America
Common bunt	*Tilletia caries*	Worldwide
Common root rot	*Helminthosporium sativum*	Worldwide
Downy mildew	*Sclerophthora macrospora*	Worldwide
Ergot	*Claviceps purpurea*	Worldwide

Table 1-24. (*Continued*)

Crop and Disease	Organism[a]	Distribution
Fungi (*continued*)		
Eyespot	*Pseudocercosporella herpotrichoides*	Worldwide
Glume blotch	*Septoria nodorum*	Worldwide
Leaf rust	*Puccinia rubigo-vera*	Worldwide
Leaf spot	*Leptosphaeria herpotrichoides*	Canada, Europe, USA
Loose smut	*Ustilago tritici*	Worldwide
Pink snow mold	*Calonectria nivalis*	Canada, USA, central and northern Europe
Platyspora leaf spot	*Platyspora pentamera*	Northcentral USA, Canada
Powdery mildew	*Erysiphe graminis* sp. *secalis*	Worldwide
Scald	*Rhynchosporium secalis*	Worldwide
Septoria leaf blotch	*Septoria secalis*	Worldwide
Sharp eyespot	*Rhizoctonia solani*	Worldwide
Speckled snow mold	*Typhula incarnata*	Canada, central and northern Europe, Japan, northwestern USA
Spot blotch, associated seedling/common rots	*Helminthosporium sativum*	Worldwide
Stalk smut	*Urocystis occulta*	Worldwide
Stem rust	*Puccinia graminis*	Worldwide
Stripe rust	*Puccinia striiformis*	N. and S. America, mountain areas of central Europe and Asia
Take all	*Gaeumannomyces graminis*	Worldwide
Yellow leaf spot	*Pyrenophora trichostoma*	Worldwide
Mycoplasmas		
Aster yellows	Aster leafhopper	Eastern Europe, Japan, USA
Nematodes		
Root gall	*Subanguina radicicola*	Canada, Northern Europe
Root lesion	*Pratylenchus* spp.	Worldwide
Seed gall	*Anguina tritici*	Eastern Asia, parts of Europe, India, southeastern USA
Stubby root	*Paratrichodorus* spp.	Worldwide
Viruses		
African cereal streak	Delphacid leafhopper	E. Africa
Wheat soilborne mosaic	Soilborne	Argentina, Brazil, Egypt, eastern and central Europe, Italy, Japan
Wheat streak mosaic	wheat curl mite	Eastern Europe, western and central N. America, USSR
Oats		
Bacteria		
Black chaff	*Xanthomonas translucens*	Worldwide
Halo/blade blight	*Pseudomonas coronafaciens*	Australia, Europe, N. and S. America
Stripe blight	*Pseudomonas striafaciens*	Australia, Europe, N. and S. America
Fungi		
Anthracnose	*Colletotrichum graminicola*	Worldwide
Cephalosporium stripe	*Cephalosporium gramineum*	England, Japan, N. America

Table 1-24. (*Continued*)

Crop and Disease	Organism[a]	Distribution
Covered smut	*Ustilago kolleri*	Worldwide
Crown rust	*Puccinia coronata*	Worldwide
Downy mildew	*Sclerospora macrospora*	Worldwide
Ergot	*Claviceps purpurea*	Worldwide
Eyespot	*Pseudocercosporella herpotrichoides*	Ireland
Foot rot	*Helminthosporium sativum*	Worldwide
Leaf blotch	*Scoleocotrichum graminis* var. *avenae*	Worldwide
Leaf blotch, seedling blight, crown and lower stem rot	*Helminthosporium avenae*	Worldwide
Loose smut	*Ustilago avenae*	Worldwide
Powdery mildew	*Erysiphe graminis* sp. *avenae*	Worldwide
Root rot	*Fusarium roseum*	Worldwide
Scab	*Gibberella zeae*	Worldwide
Seed and seedling rot	*Pythium debaryanum*	Worldwide
Septoria diseases	*Septoria avenae*	Africa, Australia, Europe, and N. America
Sharp eyespot	*Rhizoctonia solani*	Worldwide
Snow mold	*Fusarium nivale*	N. America, central and northern Europe
Stem rust	*Puccinia graminis* sp. *avenae*	Worldwide
White head	*Gaeumannomyces graminis*	Worldwide
Mycoplasmas		
Aster yellows	Leafhopper	Eastern Europe, Japan, N. America
Nematodes		
Cyst nematodes	*Heterodera latipons*, *H. avenae*, *Longidorus cohni*	Africa, Australia, Canada, Europe, Japan, USA, USSR
Root gall	*Subanguina radicicola*	Canada, Europe
Root lesions	*Pratylenchus* spp.	Worldwide
Stubby root	*Paratrichodorus* spp.	Worldwide
Viruses		
African cereal streak	Leafhoppers	E. Africa
Blue dwarf	Leafhoppers	Canada, Northcentral USA
Oat mosaic	Soilborne	Europe, N. America
Red leaf	Aphids	Worldwide
Streak mosaic	Wheat curl mite	Eastern Europe, western and central N. America, USSR
Wheat striate mosaic	Leafhoppers	Central USA, Canada
Sorghum		
Bacteria		
Bacterial spot	*Pseudomonas syringae*	Worldwide
Bacterial streak	*Xanthomonas holcicola*	Argentina, Australia, S. Africa, USA
Bacterial stripe	*Pseudomonas andropogoni*	Argentina, Australia, China, Nigeria, Taiwan, USA
Yellow leaf blotch	*Pseudomonas* spp.	W. Africa

Table 1-24. (*Continued*)

Crop and Disease	Organism[a]	Distribution
Fungi		
Anthracnose	*Colletotrichum graminicola*	Worldwide
Charcoal rot	*Macrophomina phaseoli*	Worldwide
Covered kernel smut	*Sphacelotheca sorghi*	Worldwide
Crazy top	*Sclerophthora macrospora*	Worldwide
Curvularia kernel rot	*Curvularia lunata*	Mexico
Downy mildew	*Sclerospora sorghi*	Africa, India, Southeast Asia, USA
Fusarium leaf blight, root and stalk rot	*Fusarium moniliforme*	Worldwide
Gray leaf spot	*Cercospora sorghi*	Worldwide
Green ear	*Sclerospora graminicola*	Worldwide
Head smut	*Sphacelotheca reiliana*	Worldwide
Leaf spot	*Helminthosporium rostratum*	Africa, USA
Long smut	*Tolyposporium ehrenbergii*	Africa, Asia
Loose kernel smut	*Spacelotheca crucenta*	Worldwide
Northern leaf blight, seed and seedling blight	*Helminthosporium turcicum*	Worldwide
Periconia root rot	*Periconia circinata*	Southern USA
Phoma leaf spot	*Phoma insidiosa*	Worldwide
Pokkah boeng	*Fusarium moniliforme*	Tropics and semitropics
Red rot	*Colletotrichum graminicola*	Worldwide
Rhizoctonia stalk rot	*Rhizoctonia solani*	Worldwide
Rough leaf spot	*Ascochyta sorghina*	Africa, Asia, southern Europe, USA
Rust	*Puccinia purpurea*	Worldwide
Seed and seedling blight	*Pythium* spp.	Worldwide
Sooty stripe	*Ramulispora sorghi*	Africa, Asia, S. America, USA
Southern leaf blight	*Helminthosporium maydis*	Worldwide
Southern sclerotial rot	*Sclerotium rolfsii*	Warmer sorghum-growing areas
Target leaf spot	*Helminthosporium sorghicola*	Cyprus, India, Israel, Sudan, USA
Zonate leaf spot	*Gloeocercospora sorghi*	Africa, Asia, Central and S. America, USA, West Indies
Nematodes		
Root knot	*Meloidogyne* spp.	Warmer sorghum-growing areas
Root lesion	*Pratylenchus* spp.	Warmer sorghum-growing areas
Stubby root	*Trichodorus* spp.	Warmer sorghum-growing areas
Sting nematodes	*Belonolaimus* spp.	Warmer sorghum-growing areas
Viruses		
Maize dwarf mosaic	Aphids	USA
Maize dwarf head blight	*Graminella nigrifrons*	Southern USA
Red stripe	Johnson grass	New South Wales (Australia)
Yellow sorghum stunt	Insects	USA
Millets		
Bacteria		
Bacterial blight	*Xanthomonas coracanae*	Africa, India
Bacterial stripe	*Xanthomonas panici*	USA
Yellow leaf blotch	*Pseudomonas* spp.	W. Africa

Table 1-24. (*Continued*)

Crop and Disease	Organism[a]	Distribution
Fungi		
Blast	*Pyricularia setariae*	India
Cercospora leaf spot	*Cercospora penniseti*	USA
Downy mildew	*Sclerophthora macrospora,* *S. graminicola*	Africa, India
Ergot	*Claviceps microcephala*	India
Foot rot	*Sclerotium rolfsii*	Africa, India
Head mold	Several fungii	Africa, India, USA
Head smut	*Sphacelotheca destruens*	Worldwide
Helminthosporiosis	*Helminthosporium nodulosum*	Africa, India
Kernel smuts	*Ustilago crameri*	Africa, Asia, USA
Leaf mold	*Curvularia* spp.	India, USA
Leaf spot	*Helminthosporium frumentacei*	India
Leaf spot	*Helminthosporium stenospilum*	USA
Long smut	*Ustilago penniseti*	Africa, Asia
Rhizoctonia blight	*Rhizoctonia solani*	USA
Rust	*Puccinia substriata*	Africa, India, USA
Smut	*Melanopsichium elesinis*	India
Viruses		
Bajra streak	Leafhoppers	India
Panicum mosaic	Mechanical transmission	USA
Buckwheat		
Fungi		
Chlorotic leaf spot and stipple spot	*Bipolaris sorokinione,* *Alternaria alternata*	Manitoba Province (Canada)
Downy mildew	*Peronospora ducometi*	Canada, Europe, Japan

Compiled from: Jones and Clifford (1979), Lucas, Campbell, and Lucas (1985), and Nyvall (1989).

[a]Includes the vectors of mycoplasmas and viral agents.

penetrates the plant directly or grows through a natural opening or wound (Davidson and Lyon 1987; Nyvall 1989). They survive by saprophytic growth on plant residues, or through survival spores in soil or infected plants, reproductive structures on infected plants, and mycelia in perennial plants, insects, seeds, or plant residue.

Symptoms of plant diseases caused by fungi are also varied and may resemble those caused by bacteria (Nyvall 1989). Below-ground plant parts, including seeds, emerging seedlings, and roots, become discolored and rotted to various degrees. Aboveground plant parts display spots of various shapes and sizes that can occur on any part of the plant from the cotyledonary leaves to the grain or fruit. Some cause pustules to form in which spores are produced, giving the plant a rusty appearance. Galls that become dusty when mature may be produced on any aboveground plant part. In some diseases, the seeds may be replaced by either dusty-appearing groups of spores of the fungus or a hard, almost rocklike appearing object called a "sclerotium." Soft rots on stems and fruits may become overgrown with fungus mycelia during moist conditions. Many fungal diseases also occur inside a stem, showing little outward evidence that the plant is diseased until it topples over or is harvested; the rotted stalk interior or discoloration inside a stem is then evident. An overall wilting of the plant may occur with some vascular wilt fungi (Nyvall 1989).

Mycoplasmas

Mycoplasmas somewhat resemble bacteria, but are usually smaller in size, lack rigid cell walls, and are variable in shape. They disseminate from plant to plant mainly by insects. Entrance into the plant is accomplished during feeding activities of the insect vector. Mycoplasmas overwinter in infected perennial plants and possibly in certain insect vectors. Usual symptoms of mycoplasma infection are distortion, yellowing, and proliferation of aboveground plant parts.

Nematodes

Nematodes infect the plants using their stylet to probe a plant cell. Fluids are injected into the plant through the stylet to soften or predigest plant tissue. Survival is by eggs in the soil or in cysts (the resistant body of a dead female) and by larvae in the soil.

Nematode symptoms are mostly confined to below-ground plant parts, although some are capable of infecting aboveground parts. Galls on roots, numerous short or short and stubby roots, lesions, and a poorly developed root system are the characteristic symptoms of nematode infection. Often, wounds caused by nematodes provide an entry for root rot and wilt organisms into the plant. The most common aboveground symptom is a general unthriftiness of the entire plant. Other symptoms include leaf distortion, discoloration, and formation of galls in seed.

Viruses

Viruses disseminate by several means, such as insects, nematodes, soil fungi, and seed. They enter plants through the feeding activity of a vector, and survive

Table 1-25. Major Insect Pests of Cereal Crops.

Family	Common Name	Scientific Name
Aphididae	Corn root aphid	*Anuraphis maidiradicis*
	Green bug	*Schizaphis graminum*
	Apple grain aphid	*Rhopalosiphum fitchii*
	Corn leaf aphid	*Rhopalosiphum maidis*
	English grain aphid	*Macrosiphum avenae*
	Cherry oat aphid	*Rhopalosiphum padi*
Carabidae	Slender seedcorn beetle	*Clivina impressifrons*
Cecidomyiidae	Sorghum midge	*Contarinia sorghicola*
	Hessian fly	*Mayetiola destructor*
	Wheat midge	*Sitodiplosis mosellana*
Cephidae	Wheat stem sawfly	*Cephus cinctus norton*
	Black grain stem sawfly	*Trachelus tabidus*
Chrysomelidae	Cereal leaf beetle	*Oulema melanopus*
	Corn rootworms	*Diabrotica* spp.
	Southern corn rootworm	*Diabrotica undecimpunctata howardi*
	Northern corn rootworm	*D. longicornis barberi*
	Western corn rootworm	*D. virgifera virgifera*
	Mexican corn rootworm	*D. virgifera zeae*
	Banded cucumber beetle	*D. balteata*
	Western spotted cucumber beetle	*D. undecimpunctata*
	Corn flea beetle	*Chaetocnema pulicaria*
	Toothed flea beetle	*C. denticulata*
	Desert corn flea beetle	*C. ectypa*
	Pale-striped flea beetle	*Systena blanda*
	Red-headed flea beetle	*S. frontalis*
	Western black flea beetle	*Phyllotreta pusilla*
Curculionidae	Maize billbug	*Sphenophorus maidis*
	Clay-colored billbug	*S. aequalis*
	Bluegrass billbug	*S. parvulus*
	Southern corn billbug	*S. callosus*
	Corn or timothy billbug	*S. zeae*
	Hunting billbug	*S. venatus vestitus*
	Nutgrass billbug	*S. cariosus*
	Rice water weevil	*Lissorhoptrus oryzophilus kuschel*
Eurytomidae	Wheat jointworm	*Tetramesa tritici*
	Wheat strawworm	*Tetramesa grandis*
	Wheat sheath jointworm	*Tetramesa vaginicola*
	Rye jointworm	*Tetramesa secale*
	Rye strawworm	*Tetramesa websteri*
	Barley jointworm	*Tetramesa hordei*
Lygaeidae	Chinch bugs	*Blissus leucopterus*
Noctuidae	Corn earworm	*Heliothis zea*
	Sorghum webworm	*Celama sorghiella*
	Rice worm	*Apamea apamiformis*
Pentatomidae	Rice stink bug	*Oebalus pugnax*
Pyralidae	European corn borer	*Ostrinia nubilalis*
	Southwestern corn borer	*Diatraea grandiosella*
	Southern cornstalk borer	*Diatraea crambidoides*
	Lesser cornstalk borer	*Elasmopalpus lignosellus*
	Rice stalkborer	*Chiloplejadellus zincken*

Compiled from: Hill (1983) and Davidson and Lyon (1987).

in perennial plants, seeds, and (sometimes) insect vectors. Viral symptoms are visible most commonly on the aboveground parts. Leaves, pods, and fruits may be malformed or have varying patterns of discoloration. Leaves or other tissues may proliferate, causing the plant to appear bushy. Streaks and spots of various colors and patterns may also be present, and stems may be cracked, pitted, or cankered (Nyvall 1989).

The methods for the control of plant diseases are discussed at length in Chapter 2, and hence will not be described here.

Pests

Major insect pests attacking various cereal crops are listed in Table 1-25. The characteristics of various insect pests of field crops and methods for their control are discussed in Chapter 2 with regard to legumes; similar approaches may be used for the control of cereal pests.

CHEMICAL COMPOSITION AND NUTRITIONAL QUALITY

The proximate composition of important cereal grains is summarized in Table 1-26. A large variation appears to exist in various chemical constituents of cereals. These differences could be primarily attributed to differences in cultivars and analytical techniques used by different researchers. Starch is the major constituent of cereal endosperms, comprising 58–70% of the total kernel weight; total carbohydrates may account for as much as 68–90% of the seed weight (Table 1-27). The starchy carbohydrates are present in the endosperm, whereas the nonstarchy carbohydrates are primarily concentrated in the bran fractions. Processed cereal products, such as polished white rice and milled wheat flour of 72% or lower extraction rates, are generally lower in dietary fiber as compared to brown rice and whole wheat flour. The bran fractions of various cereals contain 9–12% of dietary fiber (Table 1-27).

In cereals, bran and germ are generally richer in proteins than is the endosperm, and protein content decreases toward the grain center. Protein content also shows great variation among cereal grains, ranging from 5.6% to 21% in wheat (Mattern, Schmidt, and Johnson 1970) and from 8% to 18.2% in corn kernel (Bressani and Mertz 1958); more recently developed corn cultivars have shown a larger variation in protein content (Salunkhe, Chavan, and Kadam 1985). Generally, selection for higher protein results in decreased yield in cereals (Gallagher 1982; Palmer 1989).

Even though the protein content of cereal grains is only half that of various food legumes, they still supply over 70% of the total dietary intake of proteins worldwide (Deshpande and Damodaran 1990). The amino acid composition of

Table 1-26. Proximate Composition of Cereal Grains (% Dry Weight).

Cereal	Nitrogen	Protein[a]	Fat	Fiber	Ash	NFE[b]
Wheat						
Bread	1.4 -2.6	12	1.9	2.5	1.4	71.7
Durum	2.1 -2.4	13			1.5	70.0
Rice						
Brown	1.4 -1.7	8	2.4	1.8	1.5	77.4
Milled			0.8	0.4	0.8	
Wild	2.3 -2.5	14	0.7	1.5	1.2	74.4
Corn	1.4 -1.9	10	4.7	2.4	1.5	72.2
Barley						
Grain	1.2 -2.2	11	2.1	6.0	3.1	—
Kernel	1.2 -2.5	9	2.1	2.1	2.3	78.8
Oats						
Grain	1.5 -2.5	14	5.5	11.8	3.7	—
Kernel	1.7 -3.9	16	7.7	1.6	2.0	68.2
Sorghum	1.5 -2.3	10	3.6	2.2	1.6	73.0
Rye	1.2 -2.4	10	1.8	2.6	2.1	73.4
Millets	1.7 -2.0	11	3.3	8.1	3.4	72.9
Triticale	2.0 -2.8	14	1.5	3.1	2.0	71.0

Adapted from: Simmonds (1978), which includes the original references.

[a] Typical or average figure.

[b] NFE = Nitrogen-free extract (an approximate measure of total carbohydrates other than fiber).

various cereal proteins indicates lysine as the first and tryptophan as the second limiting amino acids (Table 1-28). Cereal proteins are, however, rich in sulfur-amino acids (met + cys), and therefore complement very well the lysine-rich, sulfur-amino acid–deficient legume proteins. The major storage proteins of cereals are either prolamins or glutelins; oats are the only exception, with their major protein a globulin (Croy and Gatehouse 1985).

Being deficient in lysine, cereal proteins perform poorly in animal studies. Their protein efficiency ratio (PER) ranges from 0.8 to 2.0; that of milk casein is 2.5 (Table 1-29). Among various cereals, rice and oat proteins have better PER values; however, some of their good-quality protein is lost during processing. Sorghum and corn proteins have PER values comparatively low among those of the various cereals. Consumption of sorghum is also associated with poor absorption and retention of nitrogen, and with higher fecal losses of energy and nitrogen than is other cereals; it is also found to be inferior to wheat or corn in promoting growth of weaning rats (MacLean et al. 1982).

Representative data on the true digestibility of protein of various cereals and cereal products are shown in Table 1-30. The digestibility of wheat gluten is the highest, and is closely followed by that of wheat white flour. The protein

Table 1-27. Carbohydrate Contents of Cereal Grains and Their Products.

Cereal	Product	Total Carbohydrates (g/100 g)	Fiber (g/100 g)
Wheat	Durum	70.1	1.8
	Hard red spring	69.1	2.3
	Hard red winter	71.7	2.3
	Soft red winter	72.1	2.3
	White	75.4	1.9
	Bulgur		
	Club wheat	79.5	1.7
	Hard red winter	75.7	1.7
	White wheat	78.1	1.3
	Wheat flour		
	80% extraction	74.1	0.5
	Patent, all purpose	76.1	0.3
	Straight, hard wheat	74.5	0.4
	Straight, soft wheat	76.9	0.4
	Wheat bran	61.9	9.1
	Wheat germ	46.7	2.5
Rice	Brown	77.4	0.9
	Bran	50.8	11.5
	Polished	57.7	2.4
	White	80.4	0.3
Corn	Field corn	72.2	2.0
	Sweet corn, raw	22.1	0.7
	Popcorn		
	Unpopped	72.1	2.1
	Popped, plain	76.7	2.2
	Corn flour	76.8	0.7
Barley	Pearled	78.8	0.5
	Malt, dry	77.4	5.7
	Malt extract, dried	89.2	trace
Oats	Dry oatmeal	68.2	1.2
Sorghum	Grain	73.0	1.7
Rye		73.4	2.0
	Rye flour		
	Light	77.9	0.4
	Medium	74.8	1.0
	Dark	68.1	2.4
Millet	Proso	72.9	3.2
Buckwheat	Whole grain	72.9	9.9
	Buckwheat flour		
	Dark	72.0	1.6
	Light	79.5	0.5

Adapted from: Watt and Merrill (1963) and Lockhard and Nesheim (1978).

Table 1-28. Amino Acid Composition of Cereals (% by Weight).

Amino Acid	Wheat (HRS)	Rice (Brown)	Corn (Field)	Barley	Oats	Sorghum	Rye	Pearl Millet	Triticale
Ala	3.50	3.56	9.95	4.60	6.11	—[a]	5.13	—	3.53
Arg	4.79	5.76	3.52	5.15	6.58	3.79	4.88	4.60	4.99
Asp	5.46	4.72	12.42	5.56	4.13	—	7.16	—	5.00
Cys	2.19	1.36	1.30	2.01	2.18	1.66	1.99	1.33	1.55
Glu	31.25	13.69	17.65	22.35	20.14	21.92	21.26	—	31.80
Gly	6.11	6.84	3.39	4.55	4.55	—	4.79	—	4.05
His	2.04	1.68	2.06	1.87	1.84	1.92	2.28	2.11	2.48
Ile	4.34	4.69	4.62	4.26	5.16	5.44	4.26	5.57	3.71
Leu	6.71	8.61	12.96	6.95	7.50	16.06	6.72	15.32	6.87
Lys	2.82	3.95	2.88	3.38	3.67	2.72	4.08	3.36	2.77
Met	1.29	1.80	1.86	1.44	1.47	1.73	1.58	2.37	1.44
Phe	4.94	5.03	4.54	5.16	5.34	4.97	4.72	4.44	5.26
Pro	10.44	4.84	8.35	9.02	5.70	—	5.20	—	12.06
Ser	4.61	5.08	5.65	4.65	4.00	5.05	4.13	—	4.70
Thr	2.88	3.92	3.98	3.38	3.31	3.58	3.70	4.00	3.11
Trp	1.24	1.08	0.61	1.25	1.29	1.12	1.13	2.18	1.08
Tyr	3.74	4.57	6.11	3.64	3.69	2.75	3.22	—	2.14
Val	4.63	6.99	5.10	5.02	5.95	5.71	5.21	5.98	4.39

Adapted from: Simmonds (1978), which includes original references.

[a] Not estimated.

Table 1-29. Protein Quality of Cereal Grains (PER).

Cereal	Actual	Estimate[a]	Cereal	Actual	Estimate[a]
Wheat			Corn		
Whole	1.5	1.3	Normal	1.2	1.2
Germ	2.5	2.5	Opaque-2	2.3	1.9
Gluten	—	0.7	Barley	—	1.6
Flour			Oats	1.9	1.7
80–90% extraction	—	1.1	Sorghum	1.8	0.9
70–80% extraction	—	1.0	Rye	1.6	1.6
60–70% extraction	—	0.8	Millets		
Bulgur	—	1.2	Finger millet	0.8	—
Rice			Foxtail millet	—	1.0
Brown	1.9	1.8	Pearl millet	1.8	1.6
Polished	1.7	1.7	Proso millet	—	1.4
Buckwheat	—	1.8	Triticale	1.6	1.4

Adapted from: Simmonds (1978), which includes the original references.

[a] Estimated from the amino acid content assuming availability of amino acids the same as the amino acids in casein.

Table 1-30. True Digestibility by Adults of Protein in Some Cereal Protein Sources.

Protein Source	Processed Version	No. of Reports	Digestibility (%)	
			Mean	Range
Wheat	Whole	6	87	90 - 93
	Flour (white)	2	96	96 - 97
	Bread (white)	5	97	95 -101
	Bread (coarse, brown, or whole wheat)	2	92	91 - 92
	Gluten	4	99	96 -104
	Ready-to-eat cereal	9	77	53 - 88
Rice	Polished	4	89	82 - 91
	Ready-to-eat cereal	3	75	77 - 85
Corn	Whole	4	87	84 - 92
	Ready-to-eat cereal	5	70	62 - 78
Oats	Ready-to-eat cereal	4	72	63 - 89
Animal protein		41	96	90 -106

Source: Hopkins (1981).

Table 1-31. Utilizable Protein and Growth of Weaning Rats on Cereals Fed Alone (100%) and from 90% Cereal + 10% Bean Mixtures.

Protein Source	Protein in Diet (%)	Utilizable Protein (%)	Average Weight Gain (g/4 weeks)	PER
Wheat	11.0	4.28	19	1.05
+ bean	12.0	5.94	41	1.73
Rice	6.9	4.01	43	2.15
+ bean	7.9	4.96	56	2.32
Corn	8.5	2.41	13	0.87
+ bean	10.3	4.10	32	1.40
Oats	13.8	8.22	34	1.60
+ bean	14.6	8.73	75	2.37
Sorghum	7.7	2.23	12	0.88
+ bean	8.6	3.93	30	1.39
Casein	10.7	8.02	75	2.37

Source: Bressani (1975). Reprinted with permission.

digestibility of whole corn, rice, and wheat flour is comparable, but considerably reduced as a result of processing—that of ready-to-eat wheat, corn, and rice was 77%, 70%, and 72%, respectively (Table 1-30). The availability of proteins primarily depends upon their digestibility; incomplete digestion adversely affects the absorption and utilization of protein by the body. Utilizable protein is lowest in sorghum and highest in oats (Table 1-31).

Table 1-32. Mineral Contents (mg/100 g Dry Weight) of Cereal Grains and Cereal Products.

Cereal	Ca	Fe	Mg	P	K	Na	Cu	Mn	Zn
Wheat									
Grain	50	10	160	360	520	3	0.72	4.88	3.40
Bran	140	70	550	1,170	1,240	9	1.23	11.57	9.80
Rice									
Brown	40	3	60	230	150	9	0.33	1.76	1.80
White	30	1	20	120	130	5	0.29	1.09	1.30
Corn									
Grain	30	2	120	270	280	1	0.21	0.51	1.69
Bran	30	—	260	190	730	—	—	1.61	—
Germ	90	90	280	560	130	—	1.10	0.90	—
Barley	80	10	120	420	560	3	0.76	1.63	1.53
Oats	100	10	170	350	370	2	0.59	3.82	3.40
Sorghum	40	4	170	310	340	—	0.96	1.45	1.37
Rye	60	10	120	340	460	1	0.78	6.69	3.05
Millet (proso)	50	10	160	280	430	—	2.16	2.91	1.39
Triticale	20	4	—	—	385	—	0.52	4.26	0.02
Buckwheat	110	4	390	330	450	—	0.95	3.37	0.87

Adapted from: Lockhart and Nesheim (1978), which includes the original references.

The mineral and vitamin contents of cereal grains and their products are summarized in Tables 1-32 and 1-33, respectively. Cereals are excellent sources of phosphorus and potassium and are fairly rich in calcium, iron, and magnesium. About 70–80% of the total phosphorus in cereals is present as phytic acid (Reddy, Sathe, and Salunkhe 1982). Cereals are also important sources of thiamin, niacin, and pyridoxin; they do not, however, contain significant amounts of fat-soluble vitamins. Over 80% of the total minerals and vitamins in cereal grains are present in aleurone layers that are usually removed during processing operations such as polishing, pearling, or milling. Whole-grain cereals are therefore generally more nutritious than their processed counterparts.

As compared to food legumes, cereals generally do not contain appreciable amounts of antinutrients, such as enzyme inhibitors and lectins. Phytic acid (*myo*-inositol 1,2,3,5/4,6-hexakis [dihydrogen phosphate]), which chelates important dietary minerals (such as iron, calcium, and zinc) and lowers their bioavailability, is the major antinutritional compound in cereals; it is generally regarded as the primary storage form of both phosphate and inositol in cereal grains (Reddy, Sathe, and Salunkhe 1982).

Phytate is located in aleurone particles or grains (as globoids) in the aleurone layer (Lasztity and Lasztity 1990). The globoid particles contain high levels of phytic acid (25–70%) and are rich in potassium (2–20%) and magnesium (1.5–12%). Thus, phytate probably occurs in cereals as a K–Mg salt.

Table 1-33. Vitamin Contents[a] of Cereal Grains and Cereal Products.

Cereal	Thiamin	Riboflavin	Niacin	Vitamin B_6	Folic Acid	Pantothenic Acid	Biotin	Vitamin E
Wheat								
Grain	0.57	0.12	7.4	0.35	78	1	6	1
Germ	2.01	0.68	4.2	0.92	328	2		
Bran	0.72	0.35	21.0	1.38	223	3	14	—
Patent flour	0.13	0.04	2.1	0.05	25	1	1	—
Rice								
Brown	0.34	0.05	4.7	0.62	20	2	12	2
Polished	0.07	0.03	1.6	0.04	16	1	5	1
Corn	0.37	0.12	2.2	0.47	26	1	21	2
Barley	0.23	0.13	4.52	0.26	67	0	6	1
Oats	0.67	0.11	0.8	0.21	104	1	13	3
Sorghum	0.38	0.15	3.9					
Rye	0.44	0.18	1.5	0.33	34	1	—	2
Millet	0.73	0.38	2.3					1
Buckwheat	0.60		4.4			1		

Adapted from: Lockhart and Nesheim (1978), which includes the original references.

[a] Vitamin contents are in mg/100 g except folic acid and biotin (μg) and vitamin E (IU/100 g).

Representative data on phytate content of various cereals are summarized in Table 1-34. According to Nelson, Ferrara, and Storer (1968), phytate accounts for over 81% of the total phosphorus in brown rice, 60–80% in wheat, 18–53% in triticale, 83–88% in corn, 66–70% in barley, 59–66% in oats, and 72% and 89% in low- and high-tannin sorghum, respectively. Morphological distribution of phytic acid in various cereals suggests that it is primarily concentrated in the aleurone layer and to a lesser extent in the germ (Table 1-35).

Since aleurone layers are removed during the milling of cereals, phytate becomes concentrated in the bran portion. Thus, products prepared from whole-grain flours or those fortified with cereal brans are generally the richest in phytic acid, whereas white breads prepared from low-extraction flours are the poorest. The chemistry, biochemistry, and nutritional and processing aspects of phytate in various cereals have been recently reviewed (Lasztity and Lasztity 1990).

Among other antinutrients, tannins are present in significant amounts in certain cereals, such as sorghum and millets (Deshpande, Sathe, and Salunkhe 1984). High-tannin sorghums thrive well under drought conditions and are resistant to bird attack. The red-pigmented, high-tannin sorghum varieties may contain as much as 7–8% tannins, although the normal levels range from 1% to 3% (Deshpande, Cheryan, and Salunkhe 1986).

The various deleterious effects of tannins in human nutrition have been reviewed (Deshpande, Sathe, and Salunkhe 1984). In animal studies, when fed

Table 1-34. Phytate Content (% Dry Weight) of Various Cereals.

Cereal	McCance & Widdowson (1935)	Averill & King (1926)	Oke (1965)	Lolas, Palamidis, & Markakis (1976)	Other Researchers
Wheat (whole grain)	0.596	1.230		0.62 –1.35	
Rice (unpolished)	0.851		0.284		
Corn			0.532		0.89[a]
Barley		1.130		0.97 –1.16	
Oats	0.770			0.79 –1.01	
Sorghum					0.57 –0.96[b]
Rye		1.340			0.97[c]
Millet		1.120	0.532		0.17 –0.47[d]
Triticale					0.50 –1.89[c]

Adapted from: Lasztity and Lasztity (1990).
[a] De Boland, Garner, and O'Dell (1975).
[b] Radhakrishnan and Sivaprasad (1980).
[c] Singh and Reddy (1977).
[d] Lorenz (1983).

Table 1-35. Phytic Acid Content (%) in Morphological Parts of Some Cereals.

Cereal	Type	Morphological Part	O'Dell, De Boland, & Koirtyohann (1972)	Lorenz (1983)	Lasztity (1988)
Wheat	Hard winter	Endosperm			0.001–0.01
		Germ			0.86 –1.35
		Aleurone			0.91 –1.42
	Soft	Endosperm	0.001		
		Germ	1.10		
		Aleurone	1.16		
Rice	Brown	Endosperm	0.004		
		Germ	0.98		
		Pericarp	0.95		
Corn	Yellow dent	Endosperm			0.01 –0.03
		Germ			0.72 –1.78
		Hull			0.05 –0.19
	High-lysine	Endosperm	0.01		
		Germ	1.61		
		Hull	0.07		
Millet	Proso	Hull		0.51 –1.60	
		Dehulled grain		0.18 –0.27	

Adapted from: Lasztity and Lasztity (1990).

at levels that commonly occur in cereals (approximately 1–2%), tannins have depressed the growth rate and resulted in poor feed efficiency ratio and an increase in the amount of feed required per unit weight gain. Other deleterious effects of tannins include damage to mucosal lining of the GI tract, alteration in the excretion of certain cations, and increased excretion of proteins and essential amino acids. The deleterious effects of tannins in the diet are generally related to their interactions with dietary proteins (Deshpande and Damodaran 1990).

PROCESSING AND PRODUCTS

Wheat

Processing

Wheat must be converted to flour before different products can be prepared. The miller thus desires a wheat that mills easily and gives a high flour yield. Wheat kernels should be plump and uniformly large for ready separation of foreign material without undue loss of millable wheat (Lawande and Adsule 1985; D'Appolonia 1987; Pomeranz 1987; Yamazaki 1987). The wheat should produce a high yield of flour with maximum and clean separation from the bran and germ. Since the endosperm is denser, high-density wheats produce more flour. Some environmental factors also influence the ease of milling; for example, the bran of weathered and frosted wheats tends to pulverize, and it is difficult to secure clean separation of flour from bran (Pomeranz 1987).

Wheat as harvested is not suitable for milling; therefore, processing overall includes preparation (wheat selection and blending, cleaning, tempering, and conditioning), followed by milling (breaking, sifting or sieving, purification, and reduction), and finally treatment (bleaching, enrichment, and supplementation). Roller milling operations for wheat processing have been comprehensively reviewed by Lawande and Adsule (1985) and Pomeranz (1987), upon whose excellent work much of this section is based.

The primary objective in the production of wheat flour is separation of the starchy endosperm of the wheat kernels from the bran and germ. The separated endosperm is then pulverized. A partial separation of the starchy endosperm is possible since its physical properties differ from those of the fibrous pericarp and oily germ. The bran is tough because of its high fiber content, whereas the starchy endosperm is friable; the oily germ flakes when passed between smooth rolls. In addition, particles from various parts of the wheat kernels differ in density, allowing their separation by the use of air currents. The differences in friability of the bran and the starchy endosperm are enhanced by wheat conditioning. The addition of water before milling toughens the bran and mellows the endosperm. The actual milling process comprises a gradual reduction in particle size, first between corrugated break rolls and later between smooth reduction rolls. This process results in the production of many streams of flour and offals that can be combined in different ways to produce different grades of flour.

Preparation

Selection and Blending. The selection of wheats and binning according to quality for proper blending are essential phases of modern milling. Flours of desired characteristics can be obtained by blending different varieties or types of wheat in different proportions.

Cleaning. Wheat received in the mill contains many impurities that affect the uniformity and appearance of flour, flour yield, and ultimately the flour quality. These impurities must be removed before the milling of wheat. The types of impurity present in wheat include vegetable matter (foreign seeds and plant residues), animal matter (rodent excreta, hairs, insects, mites, etc.), mineral matter (mud, dust, stones, nails, etc.), and such other impurities as binder twine, string, and miscellaneous rubbish. Wheat is initially conveyed through a water trough to the base of a centrifugal machine to remove adhering dirt. Wire screens are then used to remove impurities based on their size and shape. Magnetic separators remove metal impurities, and aspirators remove lighter materials such as chaff, straw, and small seeds. Dry scourers are used to remove by friction hair and dirt adherent to grain. In this process, wheat is forced against a perforated iron casting by beaters fixed to a rapidly revolving drum. Depending upon the nature and extent of impurities, the miller follows a suitable combination and sequence of the above operations.

Tempering. Wheat is tempered by the addition of water to raise its moisture content to 15–19% for hard wheat and 14.5–17% for soft wheat. During this process, wheat is allowed to lie in tempering bins for periods of 18–72 h with little or no temperature control. The moisture enters the bran and diffuses inward.

Conditioning. Conditioning involves the use of heat for quick diffusion of water into the kernels. It improves milling properties with the consequent saving of time. There are three conditioning methods: In *warm conditioning,* wheat is conditioned for 1–1.5 h at temperatures of up to 46 °C. The warm-conditioned wheat is then rested for 24 h prior to milling. *Hot conditioning* is similar except that temperatures are raised to 60 °C or higher. *Steam conditioning* is the most time saving of the three. It requires less power and gives higher yields of flour.

Milling

The cleaned and conditioned wheat is now ready for milling. The grinding of wheat evolved from primitive hand methods to air- and water-power sources turning heavy stones. Milling evolution continued with the introduction of screw conveyors, bucket elevators, steel rollers, and purifier machines. Subsequently, several patents were issued covering improvements and refinements for cleaners, dust collectors, grain washers, mechanical purifiers, and other milling operations. Advances in science and technology have led to the development of automatic modern flour mills. In most of these mills, wheat is milled by rollers, which are of two types: break and reduction. A flowchart of modern wheat flour milling is shown in Fig. 1-13.

Breaking. The first part of the grinding process is carried out on corrugated rolls (break rolls), usually 24–30 in. long and 9 in. in diameter. Each stand has two pairs of rolls revolving in opposite directions at a speed differential of about 2.5 : 1. In the first set of break rolls, there are usually ten or twelve corrugations per inch, which increases to twenty-six or twenty-eight corrugations on the fifth break roll. During the breaking process, the grains are cracked. After each break, the resulting mixture of bran, free endosperm, and bran that contains endosperm is sieved, the coarsest material is conveyed to the second break roll, and so on. The material that goes to each succeeding break contains less and less endosperm. After the last break, the longest fragments consist of flakes of the wheat pericarp. They are passed through a wheat bran duster that removes a small quantity of low-grade flour.

Sieving or Sifting. After each set of break rolls, the crushed material ("stock" or "chop") is subjected to a combination of sieving operations (plan sifters) and air aspirators (purifiers). The process results in separation of three classes of material:

1. coarse fragments that are fed to the next break until only the bran remains;
2. flour or fine particles that pass through the finest flour sieve; and
3. intermediate granular particles or "middlings."

Purification. Purifiers consist of long oscillating sieves inclined downward through which air current is passed upwardly. This causes the flour to stratify into bran and middlings of different sizes. The middlings are taken to appropriate reduction rolls. The "overtails," including bran and the bran + endosperm, are taken back to the break roll or to the mill feed stock. The number of purifiers may range up to twelve for a system with four break rolls.

Reduction. Reduction rolls differ from break rolls in two important aspects: The roll surfaces are quite smooth, and the speed differential between the two rolls is lower, usually 1.25 : 1 or 1.50 : 1. The purified and classified middlings are gradually pulverized to flour between the smooth reduction rolls. Endosperm fragments passing through the rolls are reduced to finer middlings and flour, and the bran is flaked or flattened. After each reduction step, the resulting

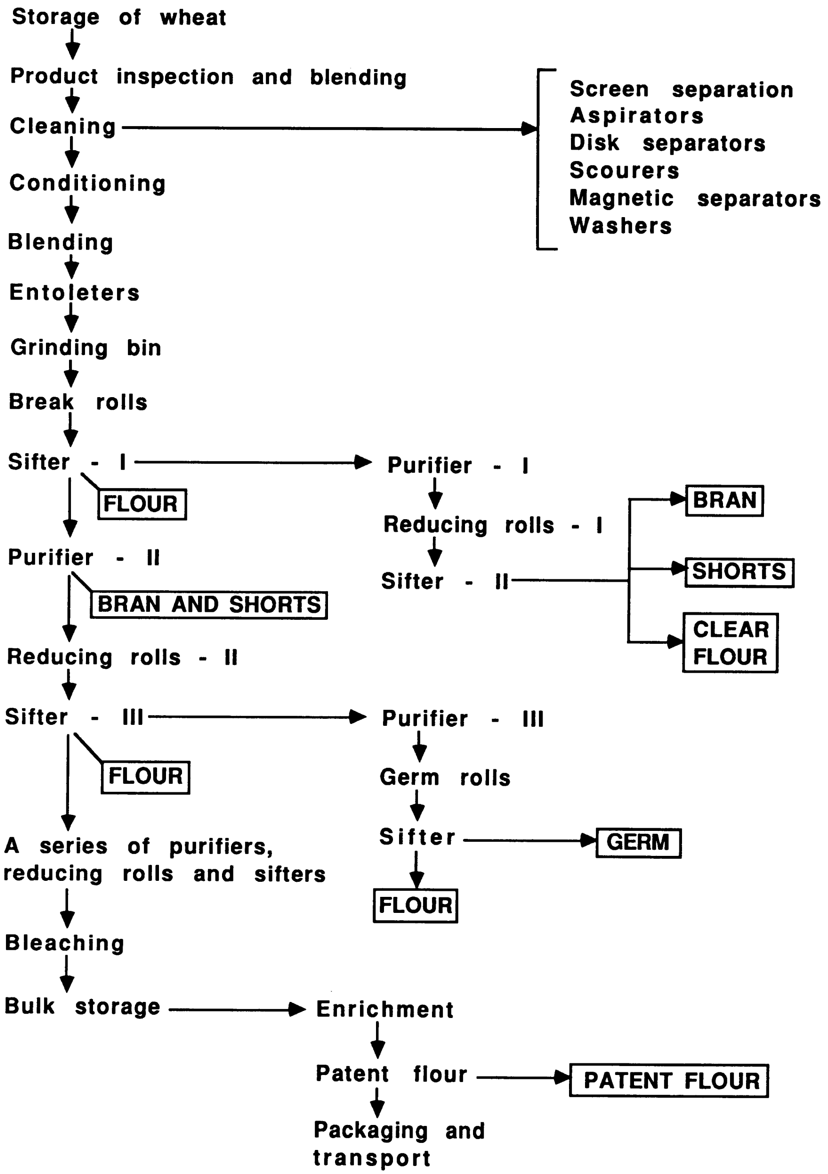


Fig. 1-13. Flowchart for flour milling of wheat.

stock is sifted. Most of the bran is removed on the top sieve, the flour passes through the finest bottom sieve, and the remaining middlings are separated according to size, moved to their respective purifiers, and passed to other reduction rolls. The entire process is repeated until most of the endosperm is converted to flour and the bran has been removed as offal by the reduction sifters. What remains is a mixture of fine middlings and bran with a little germ: This is called "feed middlings."

Scratching. In addition to the break and reduction system, a scratch system is sometimes employed as a standby to maintain proper release of endosperm from the bran. The system contains fluted rolls, similar to lower break rolls, which scratch off the adhering husk or bran from the endosperm.

Entoleter. The stock from the earliest reduction rolls is treated on a specially designed "entoleter" machine, which acts almost like a detacher and increases the yield of flour. The entoleter contains disks with concentric rings rotating at high speed: Any living matter present, such as insects, is killed due to the centrifugal force. This machine thus avoids the use of chemicals to control these organisms.

Air Classifiers. Some flour mills add yet another system to their millstream for further separation of particles. Wheat flour produced by conventional roller milling contains particles of different sizes (1–150 μm). These include large endosperm chunks, small particles of free protein, free starch granules, and small chunks of protein attached to starch granules. The flour can be ground—pin-milled to avoid excessive starch damage—to fine particles in which the protein is freed from the starch. The pin-milled flour is then passed through an air classifier (Fig. 1-14). A fine fraction of ≤40-μm particles is removed and passed through a second classifier, where particles of ≤20 μm are separated. This fraction comprises about 10% of the original flour and contains up to twice the protein of the unfractionated flour. Air classification has created considerable interest within the milling industry and is relatively inexpensive. It produces more uniform flours from different wheats, increases the protein content of the bread flour (and decreases that of cake and cookie flours), controls particle size and chemical composition, and produces special flours for specific end uses. The technology of the process is well known; however, its benefits and potential have not been fully explored, primarily because of the availability of low- and high-protein wheats and the high energy costs involved in air classification.

Milling Soft and Durum Wheats. Soft wheats are also milled by the method of gradual reduction with minor alterations, such as processing variables, grinding technique, and stream selection (Lawande and Adsule 1985; Pomeranz 1987). Patent flours milled from soft red winter wheats containing 7–9% protein are especially suitable for chemically leavened biscuits and hot breads. Special mixes of soft wheats containing ≤8% protein and milled to very short patents (about 30%) are used to make cake flours.

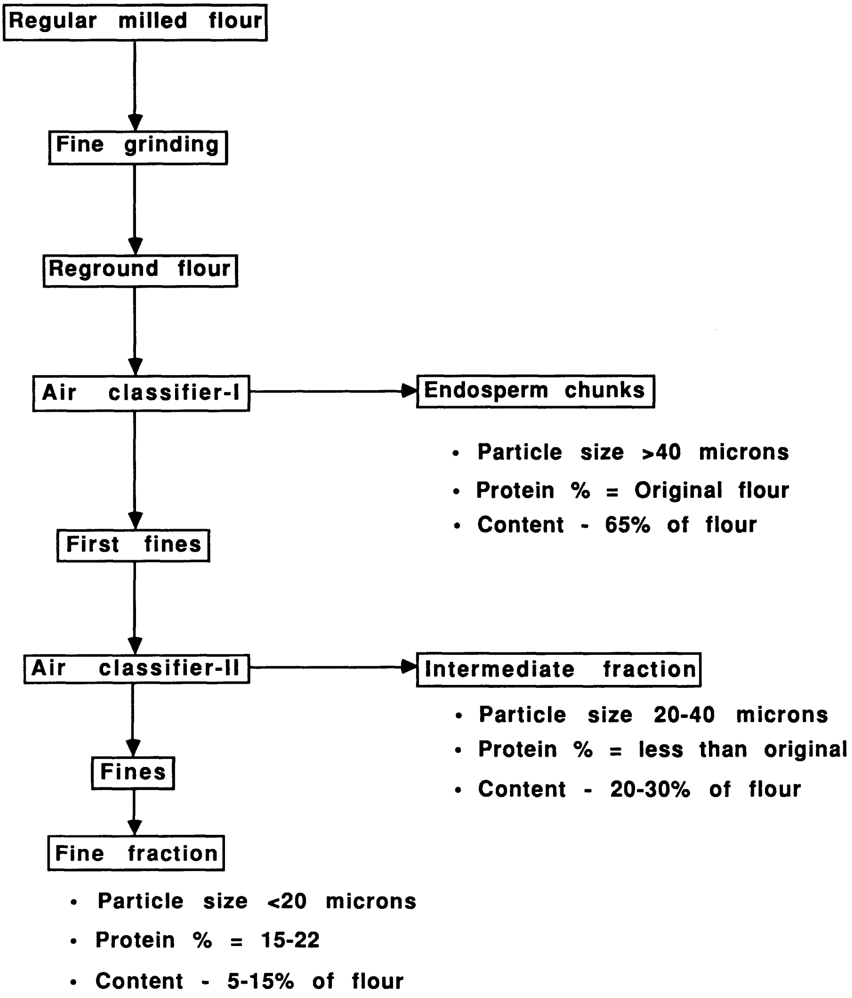


Fig. 1-14. Flowchart for air classification of wheat flour.

In durum wheat milling, the main objective is to produce a maximum yield of highly purified semolina. Although the sequence of operations involved in the production of semolina and flour is the same, the milling systems differ in their design. In semolina manufacture, impurities and mill offals must be removed by cleaning and purification systems. The breaking, sizing, and purification systems are much more elaborate and extensive than in flour mills, but the reduction systems are shorter since the primary product is removed in a granular condition. For maximum yield of large endosperm particles, break rolls with

U-cut corrugations are employed. A durum wheat of good milling quality normally yields 62% semolina, 16% clear flour, and 22% feeds. The particle size distribution and granulation of semolina are highly important in the production of macaroni (Pomeranz 1987).

Flour Grades and Improvements

Each milling operation in the roller flour mill results in a stream of flour of individual characteristics and properties. If all streams are combined, the resulting flour is a straight-run flour that represents about 72% of the wheat kernel. The remaining 28% is called "mill feed" and includes 16% bran and 12% shorts. Frequently, only highly refined streams are taken off and sold separately as "patent flours"; the remaining streams containing more bran and germ are known as "clear flours." The percent recovery of wheat kernel in patent flour is lower than that in straight-run flour and is still lower in case of extra short or fancy patent flour. The ordinary power-driven stone mills commonly used on the Indian subcontinent do not completely separate the bran from the endosperm, and thus yield a long extraction flour that represents 90–95% of the whole kernel.

The quality and nutritive value of wheat flour can be improved by certain chemical additives and physical means. Flour is bleached by chemicals such as chlorine, nitrogen trichloride, chlorine dioxide, benzoyl peroxide, and potassium bromate and iodate. During this process, xanthophyll, a yellow flour pigment, is oxidized to yield a white flour. Maturing agents—including potassium bromate, ascorbic acid, and azodicarbonamide—improve the baking properties of the flour by modifying gluten during fermentation. They oxidize the thiol group of cysteine to disulfide bonds, thereby tightening the dough, improving dough handling properties, loaf volume, and the fineness of crumb texture. Self-raising flour contains a mixture of sodium bicarbonate and one or more acid-reacting substances added to produce at least 0.5% carbon dioxide.

Wheat flours are also nutritionally enriched with vitamins such as thiamin, riboflavin, and niacin, and minerals such as calcium and iron. They can also be mixed with suitable legume flour to produce composite flours with improved nutritive value.

Products

Wheat flour is the basic ingredient for making bread, biscuits, pastry products, and semolina and farina for alimentary pasta. A small portion is also converted into breakfast foods. Unlike other cereals, wheat, due to its high price, has limited uses for industrial purposes; these include the manufacture of malt, potable spirits, starch, gluten, pastes, and core binders. *Wheat malt* is usually too costly to be used in the brewing industry. It is mainly used by the flour milling industry to increase the α-amylase activity of the high-grade flours (Pomeranz 1987). In the United States, small quantities of wheat flour (mainly low-grade clears) are used to manufacture *wheat starch* as a by-product of viable (functionally in bread making) gluten. *Wheat gluten* is used to supplement flour proteins in specialty baked goods, such as hamburger buns, hotdog buns, and hearth-type breads. It is also used as a raw material for the manufacture of monosodium glutamate. Some low-grade wheat flours are also used in the manufacture of pastes for bookbinding and paper hangings, in plywood adhesives, and in iron foundries as a core binder in the preparation of molds for castings.

Several monographs and texts have been written on the technology of bread, breakfast cereals, and other products prepared from wheats and other cereals (Pomeranz 1971; Pomeranz and Shellenberger 1971; Matz 1972; Williams 1975; Kent 1983; Pomeranz 1987). Only the salient features of these products are described below.

Bread

Bread is made by baking a dough whose principal ingredients are wheat flour, water, yeast, and salt. Other cereals, fat, malt flour, soy flour, emulsifiers, yeast foods, milk and milk products, fruits, and gluten may also be added for specialty breads.

There are three essential processes in bread making:

1. formation of a gluten network (mixing and dough development),
2. aeration of the mixture by incorporation of a gas, and
3. coagulation of the material to stabilize the structure (oven baking).

The dough generally used in commercial bakeries is of a standard consistency, usually requiring 55–61% water by flour weight. More water is added to flour with high protein (i.e., from strong wheats) or damaged starch content (i.e., from hard wheats) to attain this consistency. The starch in the dough is first hydrolyzed by amylases to maltose, which is then broken down to glucose by maltase. The resulting reducing sugars are fermented by the yeast to carbon dioxide and alcohol; the latter is evaporated during the baking process.

A dough undergoing fermentation with intermittent mechanical mixing is said to be “ripening.” It becomes less sticky as ripening proceeds, and more rubbery when molded. A ripe dough has maximum elasticity after molding and gives maximum spring in the oven. There are two main processes by which dough is prepared. Both systems are examples of *bulk* or *long fermentation.*

In the *straight dough method,* the ingredients are mixed, allowed to ferment for about two hours of a three-hour fermentation process, then knocked back to mix the dough thoroughly and even out the temperature, and allowed to rest for another hour. It is then divided into loaf-sized portions that, after 10–15 min at about 27 °C ("first proof"), are molded into the final shape. During this stage, the dough is mechanically worked to tighten it, so that the gas is better distributed and retained, and is placed in pans. The final mold is very important in giving good texture in bulk-fermented bread. The dough rests again in the pans for the final proof of 45–60 min at 43 °C and is then baked in the oven at a temperature of about 235 °C for 25–40 min.

In the *sponge and dough system,* widely used in the United States, only a part of the flour is mixed at first with all the yeast and sufficient water to make a dough, which is allowed to ferment for a few hours. This so-called sponge is then broken down by mixing, and the remaining ingredients are added to make a dough of standard consistency. This is then given only a short fermentation time prior to proofing and baking. The sponge and dough system is believed to produce bread with a fuller flavor than that from the straight dough system.

In the *mechanical development* processes, the ingredients are mixed with a prefermentation brew containing the yeast. The dough is allowed no fermentation time, but instead subjected to intense mechanical mixing to achieve the correct degree of ripeness for proofing and baking.

Unleavened breads, called *chapatties,* are commonly used in the Indian subcontinent. For the preparation of *chapatti,* a strong gluten is not required, but the water absorption of the flour should be high. Chapatties are made by mixing whole wheat flour with water to form a dough that is rested for about an hour. It is then divided into small portions, flattened by hand or roller, and baked on an iron plate over an open fire. Sorghum and millet flours are also used for the making of *chapatties.*

Breakfast Cereals

The breakfast cereal foods can be classified based on the amount of domestic cooking required, the form of the product or dish, and the cereal used as raw material. In the case of hot cereals, cooking is carried out domestically, whereas ready-to-eat cereals are cooked during manufacture. Ready-cooked porridges can be made merely by stirring the material with hot or boiling water in the bowl. Generally, they are prepared from the cream of wheat or rolled oats. Other ready-to-eat cereals comprise flaked, puffed, shredded, or granular products, generally made from wheat, corn, or rice, although barley and oats are also used. The basic cereal may be enriched with sugar, syrup, honey, or malt extract. All types are prepared by processes that tend to cause dextrinization rather than gelatinization of the starch. For flaked products, the cereal (generally wheat, corn, or rice) is conditioned to a suitable moisture content and then lightly rolled between smooth rolls to fracture the outer layers. They are then cooked at elevated pressure and the flavorings are added. The cooked cereal is then dried to 15–20% moisture content and rested for 24–72 h while conditioning takes place. The conditioned grain is flaked on heavy flaking rolls, toasted in a tunnel or traveling oven, and then cooled and packaged.

For the manufacture of puffed cereals, whole-grain wheat (or rice, oats, or pearl barley) is prepared by cleaning, conditioning, and depericarping. It is cooked for 20 min at 20 psi pressure, dried to 14–16% moisture content, and pelleted by extrusion through a die. The pelleted dough is then fed into a pressure chamber, which is sealed and heated both externally and by the injection of steam so that the internal pressure rapidly builds up to about 200 psi. The pressure is then suddenly released by opening the chamber, called a "puffing gun." The expansion of water vapor on release of the pressure blows up the grains or pellets to several times their original size. The puffed product is then dried to 3% moisture content by toasting, and finally cooled and packaged.

Shredded wheat breakfast cereals are prepared by cleaning and cooking the whole grain by the application of external heat and the injection of steam. The conditions are such that the cooked grain is soft and rubbery, the moisture content is about 43%, and the starch is fully gelatinized. The cooked grain is then cooled and rested for about 18 h to condition. The conditioned grain is fed to shredders comprising a pair of metal rolls—one smooth and the other with circular grooves between which the material emerges as long parallel shreds. The shreds fall onto a slowly traveling band, and a thick mat is built up by superimposition of several layers. The mat is then cut into tablets and later baked for 20 min at 260 °C in a gas-heated oven. After baking, the product is dried to 1% moisture content, passed through a metal detector, and packaged.

Pasta

Various pasta products (e.g., macaroni, spaghetti, vermicelli, noodles) are made from semolina milled from hard wheat by a special process described earlier (see "Milling Soft and Durum Wheats"). The highest-quality pasta products are made from durum wheats alone; other wheats are not suitable for this purpose. The semolina is made into a stiff dough using 25–30% water at 32–38 °C and mixing for 10–15 min. After a rest period, the dough is kneaded at about 30 °C in a cylindrical machine equipped with beveled helical blades. Kneading is carried out under vacuum to avoid bubbles, which would affect the quality, and to yield a brighter and more transparent product. Mixing and kneading take about 15 min. The dough is then extruded through the die of a press to make tubular or strap-shaped products. Heavy pressure is employed to ensure that the product is translucent and to squeeze out any small air bubbles. The extruded product is cut to the required length by rotating knives, and dried to about 12.5% from about 30% moisture content at emergence from the die.

Cakes

As discussed earlier (see "Milling Soft and Durum Wheats"), cake flours are derived from special blends of soft wheats. Cake premixes sold commercially often contain all the necessary ingredients, requiring only the addition of water before baking. Sometimes, eggs and/or milk are omitted, since the addition of fresh eggs makes lighter cakes of larger volume.

Rice

Processing

The primary objective of rice milling is to remove the hull, bran, and germ with a minimum breakage of the endosperm (Webb 1987). In the threshed grain (rough rice or "paddy"), the kernel is enclosed in a tough, siliceous hull, rendering it unsuitable for human consumption. The paddy is cleaned and conveyed to shelling machines that loosen the hulls. Conventional shellers consist of two steel plates, mounted horizontally, whose inner surfaces are coated with a mixture of cement and carborundum. As the moving plate revolves around the stationary plate, the pressure on the ends of the upturned grains disengages the hulls, which are removed by aspiration. The mixture of (de)hulled and unhulled grains is separated on a large box shaker fitted with vertical, smooth steel plates set on a slight incline to form zigzag ducts. The plates and the shaking action cause the less dense paddy grains to move upward and the heavier hulled grains to move downward. Paddy may also be shelled with rubber rollers or with a rubber belt operating against a ribbed steel roll. The rubber shellers cause less mechanical damage and improve the stability against rancidity.

Hulled (brown) rice is then milled to remove the outer and inner bran layers, the aleurone layers, and the germ. The milling and polishing machines consist of grooved, tapering cylinders that revolve rapidly in stationary, uniformly perforated cylinders. The entire machine is filled with grain, and the packing force is regulated by a blade that protrudes between the upper and lower halves of the perforated cylinders. The bran, aleurone, and germ are removed by the scouring action of the rice grains against each other near the surface of the perforated cylinders. After passing through a succession of hullers, the rice is practically free from germ and outer bran. Scouring is usually completed by polishing in a brush machine. The polished (white) rice is then sorted according to size class: *whole kernel* (*head*) rice is at least three-quarters of the whole endosperm; *second-head* comprises large pieces of broken milled kernels; *screenings* are smaller pieces of broken milled kernels; and very small pieces of broken milled kernels are called *brewer's rice*. Fig. 1-15 is a flowchart of the rice milling process.

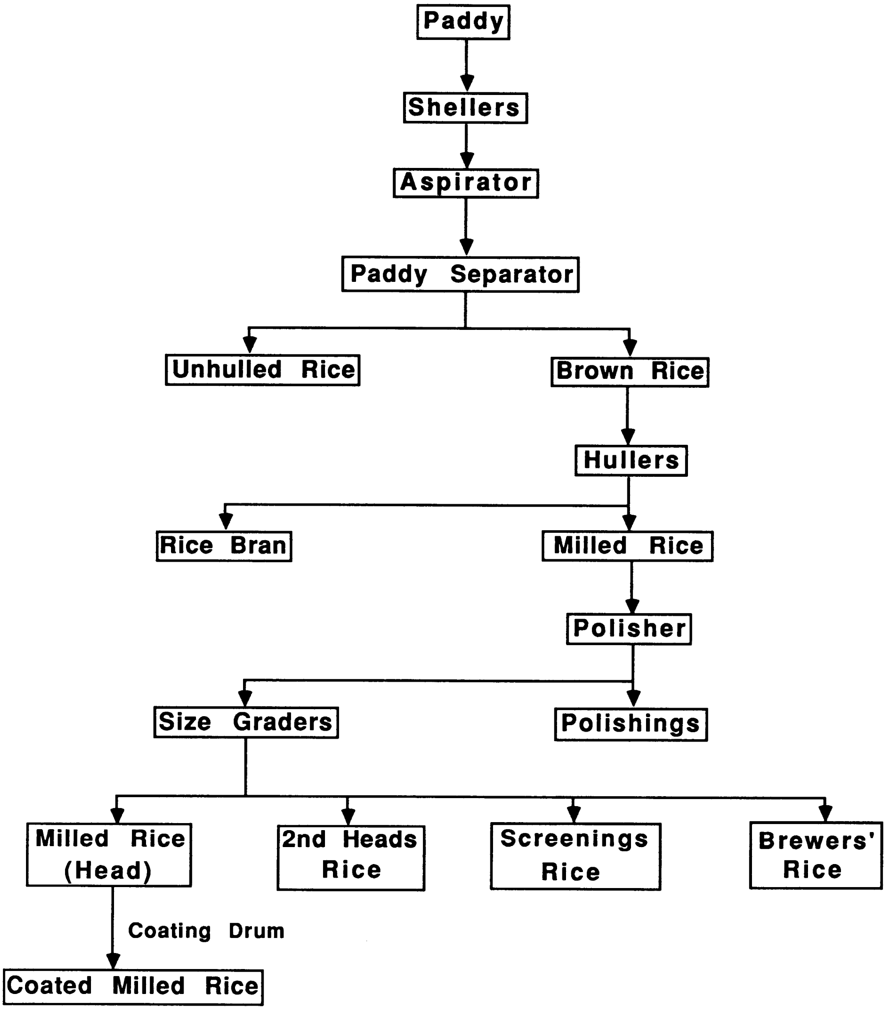


Fig. 1-15. Flowchart for the milling of rice.

Based on the weight of rough rice or paddy, the yield of white rice normally varies between 60% and 70%. The yield of head rice ultimately determines the milling quality of rough rice. The price obtained for the various classes of rice decreases with size (Pomeranz 1987). The yields of head rice vary widely depending upon the variety, grain type, cultural practices, and other environmental factors affecting the chalkiness and plumpness of the grains, and the conditions of handling, drying, storage, and milling (Webb 1987). The extent to which the bran layers and germ are removed from the endosperm during milling is referred to as the "degree of milling." The U.S. National Bureau of Standards recognizes four degrees of milling: well milled, reasonably well milled, lightly milled, and undermilled (Webb 1987).

A solvent extraction process is also developed to increase the yield of whole-grain rice (Pomeranz 1987). Hulled brown rice is softened with rice oil to improve bran removal. Fully milled rice is sometimes treated with a talc and glucose solution to improve its appearance. After the coating is evenly distributed on the kernels and dried with warm air, the rice emerges from the equipment with a smooth, glistening luster and is known as "coated rice."

Brown rice—though little in demand as food since it tends to become rancid and is prone to insect infestation—is more nutritious than polished, white rice. This is because protein, vitamins, and minerals are predominantly concentrated in the bran and aleurone layers of the kernel, their concentration decreasing progressively toward the center of the grain. Among the minerals, iron, potassium, phosphorus, and manganese are concentrated in the aleurone layers; these last three are particularly high in the subcellular particles of the aleurone layer, whereas calcium is abundant in the pericarp (Bhattacharya and Ali 1985). The conversion of brown rice to white or polished rice removes about 15% of the protein, 65% of the fat and fiber, and 55% of the minerals. Similarly, head rice contains only 20% as much thiamin, 45% as much riboflavin, and 35% as much niacin as brown rice (Pomeranz 1987). These losses have necessitated the development of several practical methods to retain more of the B-vitamins and minerals in the milled rice kernel. This is usually achieved by processing the paddy or rough rice before milling to diffuse the vitamins and other water-soluble nutrients from the outer portion of the grain into the endosperm. The processing of paddy to increase the retention of these nutrients involves parboiling or some modification thereof (Bhattacharya and Ali 1985). A flowchart of various steps involved in the preparation of different kinds of parboiled, expanded, and/or flaked rices is shown in Fig. 1-16. For parboiling, the paddy is soaked in water either at room or at elevated temperatures, then drained, steamed, and dried.

Parboiling improves both the nutrition of rice and its storage and cooking qualities. The major changes include the transfer of some vitamins and minerals from the aleurone and the germ into the starchy endosperm, dispersion of lipids into the endosperm, inactivation of lipolytic enzymes, and the destruction of molds and insects (Bhattacharya and Ali 1985; Gariboldi 1974). These changes are accompanied by reduced chalkiness and increased vitreousness and translucence of the milled parboiled rice. Compared to nonparboiled rices, parboiled rices disintegrate less during cooking and remain better separated and less sticky after cooking. This is mainly due to the reduction of solids leached into the cooking water and the extent to which the kernels solubilize during cooking (Pomeranz 1987).

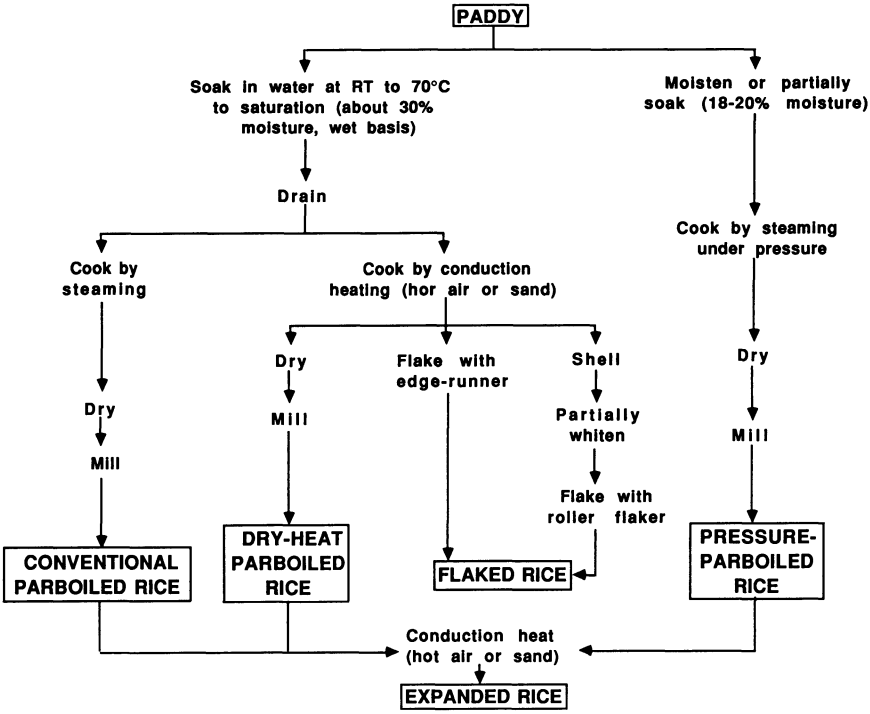


Fig. 1-16. Flowchart showing various processes for the parboiling of rice. *Source:* Bhattacharya and Ali (1985).

Products

The rice milling industry generates considerable amounts of by-products: There is an annual potential of 5 million metric tons of food protein and 6 million MT of edible oil (from rice bran), 256,000 billion kcal as fuel (from husks), and 30,000 billion kcal as metabolizable energy for cattle (from straw) (Pomeranz 1987).

In the United States, rice is classified for marketing purposes into long-, short-, and medium-grain types. Each type is associated with specific cooking and processing behavior. U.S. long-grain varieties cook dry and fluffy, and the cooked grains tend to remain separate. In contrast, the cooked kernels of high-quality medium- and short-grain varieties are more moist and chewy than those of the long-grain varieties, and the kernels tend to cling together. Different ethnic and cultural groups prefer specific and varied textures in home-cooked rice.

The modern trend in processed foods is toward convenience items. Quick-cooking rices may be prepared by precooking in water and then drying under controlled conditions, or by the application of dry heat (Pomeranz 1987). Other convenience items include canned and frozen cooked rice.

As mentioned above (under "Wheat Products"), some breakfast cereals are made from rice.

Corn

Processing

Corn processing is one of the largest food-processing industries in the United States. About three-fifths of the processed corn is used to produce cornstarch, sweeteners, corn oil, and various feed by-products. The remainder is used to prepare various food products and alcoholic beverages.

The milling of corn is centered on the transformation of a basic agricultural product into even more basic fractions for consumption by people and animals. There are two main types of process: dry milling and wet milling.

Dry Milling

Dry milling of corn is carried out both by old-process milling from non-degermed grain and by new-process milling from degermed grain (Pomeranz 1987). In old-process milling, corn is ground to a coarse meal between millstones run slowly at a low temperature, with the meal frequently not being sifted. In the larger mills, about 5% of the coarse particles of the hulls are sifted out. The meal is essentially a whole corn product and has a rich oily flavor; the lipids, however, lower its storage stability. In some large mills, the corn is dried to 10–12% moisture before grinding. Kiln drying facilitates rapid grinding and improves the keeping qualities of the meal (Pomeranz 1987).

In new-process milling, steel rolls are used to remove the bran and germ and to recover the endosperm in the form of hominy or corn grits, coarse meal, fine meal, and corn flour. (A flowchart is shown in Fig. 1-17.) The corn is cleaned and passed through a scourer to remove the tip cap from the germ end of the kernel. The hilar layer under the tip is frequently black and causes black specks in the meal. Depending on the variations of the processes, the corn is either untempered or tempered by the addition of water to a moisture content of 21–24%. Subsequently, it is passed through a corn degerminator, which frees the bran and germ and breaks the endosperm into two or more pieces. The stock from the degerminator is dried to 14–16% moisture and cooled in revolving or gravity type coolers.

The large endosperm pieces obtained from the first break are used for making corn flakes. The stocks are passed through a hominy separator first to separate the fine particles, and then to grade the larger fragments to various sizes

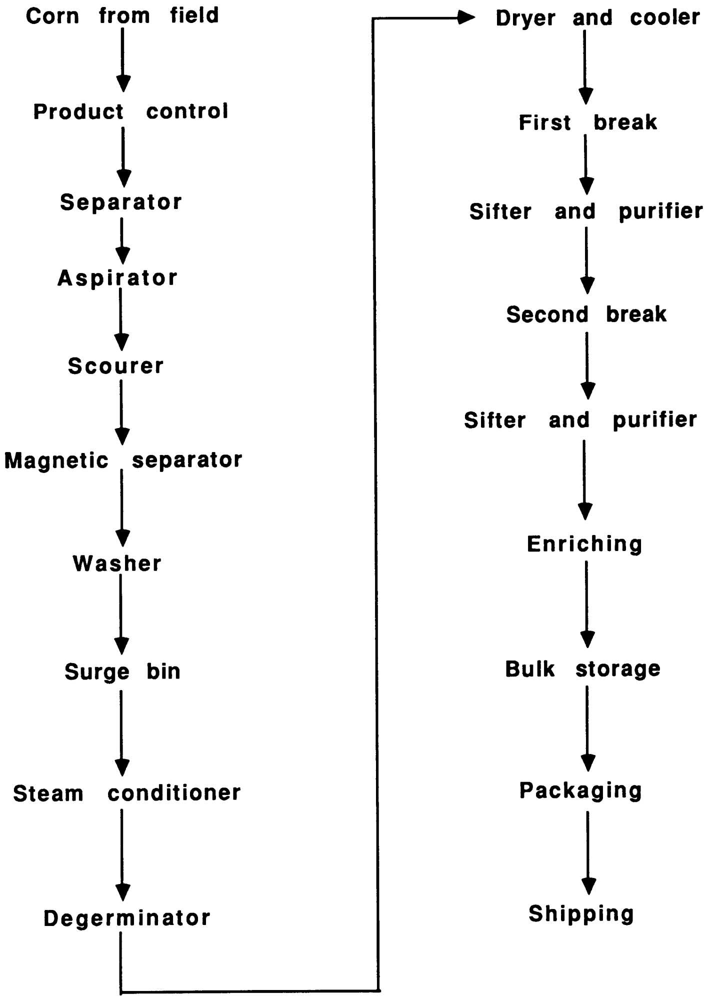


Fig. 1-17. Flowchart for corn milling by the new process.

and polish them. The various grades of broken corn are passed through aspirators to remove the loose bran from the endosperm fragments. These are reduced to coarse, medium, and fine grits by gradual reduction between corrugated rolls and subsequent sifting of the stock. The coarsest stock from the aspirator, which is highly contaminated with germ, goes to the first break rolls. The germ is flattened between the break rolls with minimum endosperm grinding and separated by sieving. The successive steps in the gradual reduction for corn are similar to those used in wheat milling (Pomeranz 1987).

Wet Milling

In the wet-milling process, the clean corn is first softened by steeping in a very dilute solution of SO_2 at 48–52 °C for 30–50 h. For optimum milling and separation of corn components, the corn should have absorbed about 45% water at the end of the steeping period, released about 6.0–6.5% of its dry solids as solubles into the steepwater, absorbed about 0.2–0.4 g SO_2/kg, and become quite soft (Pomeranz 1987). When corn has been optimally steeped, the germ can be removed easily and intact in the degerminating mills. After the removal of germ, the kernels are transported to the grinding mills, where they are broken down in a slurry mixture of starch, gluten protein, and hull. The hulls are removed by specially designed screens to produce a slurry of gluten and starch. This slurry is then sent through a hydrocyclone that separates out a purified cornstarch stream and a gluten feed stream. This entire process lends itself to a continuous operation in the wet-milling plants.

Corn Oil. In the manufacture of corn oil, the germ—the first major fraction isolated in the corn processing—is removed by centrifugation. It is then sent to a continuous screw press where its oil content is reduced from roughly 50% to 20%. In larger commercial processing plants, the remaining 20% residual oil is reduced further by solvent extraction, after which the germ meal contains 1–3% oil. The germ meal is used as an animal feed.

The crude corn oil from the extraction process must be refined further before it is acceptable for use in food products. The undesirable components of the corn oil (free fatty acids, phospholipids, waxes, carotenoids, odors, and flavors) lower the quality of the oil. They are removed during the oil refining process (Fig. 1-18). After refinement, the oil consists of approximately 99% triglycerides, phytosterols, and tocopherols.

Sweeteners. Corn-derived sweeteners are produced by hydrolyzing the starch that has been refined during wet-milling operations. The corn sweeteners produced by the wet-milling industry are very diverse and can range from little or no sweetness to very high levels of sweetness. The characteristics and functional properties of corn syrups vary according to their composition. The simplest means of identifying a syrup is by referring to its dextrose equivalent (DE) value. The DE represents a measurement of the total reducing sugars on a dry solids basis in the syrup, and indicates the level of starch hydrolysis used to produce the product. Based on DE value, corn syrups are classified into four types (Pomeranz 1987):

Type I, 20–38 DE	Type III, 58–73 DE
Type II, 38–58 DE	Type IV, >73 DE

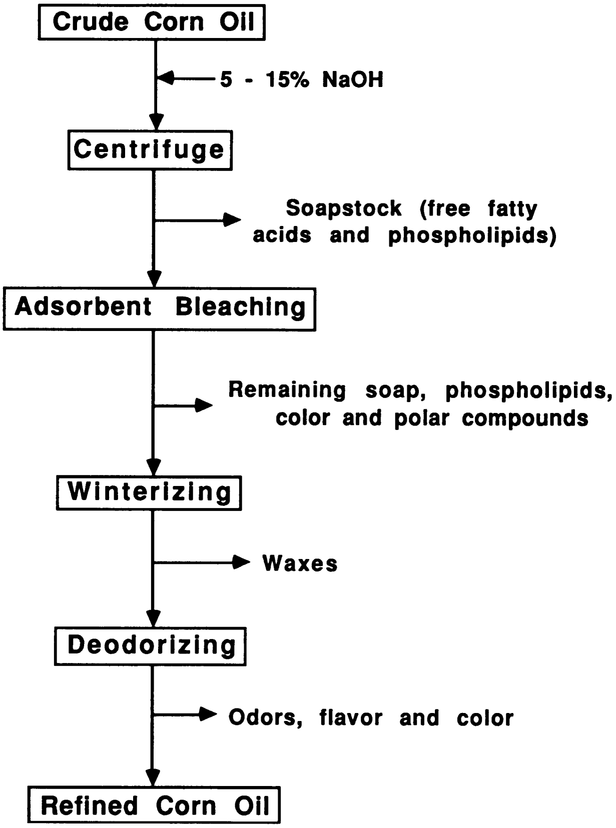


Fig. 1-18. Schematic diagram of the corn oil refining process.

The manufacture of corn sweeteners is a multistep process. There are three commonly used methods for syrup production, with the final type of syrup indicating which method is used (Pomeranz 1987):

1. acid catalyzed hydrolysis (acid conversion),
2. acid-enzyme conversion, and
3. enzyme conversion.

A flowchart of commercial corn syrup production using these three methods is outlined in Fig. 1-19. Each method produces a certain type of syrup with different saccharide distributions that give them their specific qualities.

In the *acid conversion process*, a starch slurry of about 35–40% dry matter is acidified with hydrochloric acid to pH of about 2 and pumped to a converter. Here, the steam pressure is adjusted to 30 psi, and the starch is gelatinized and

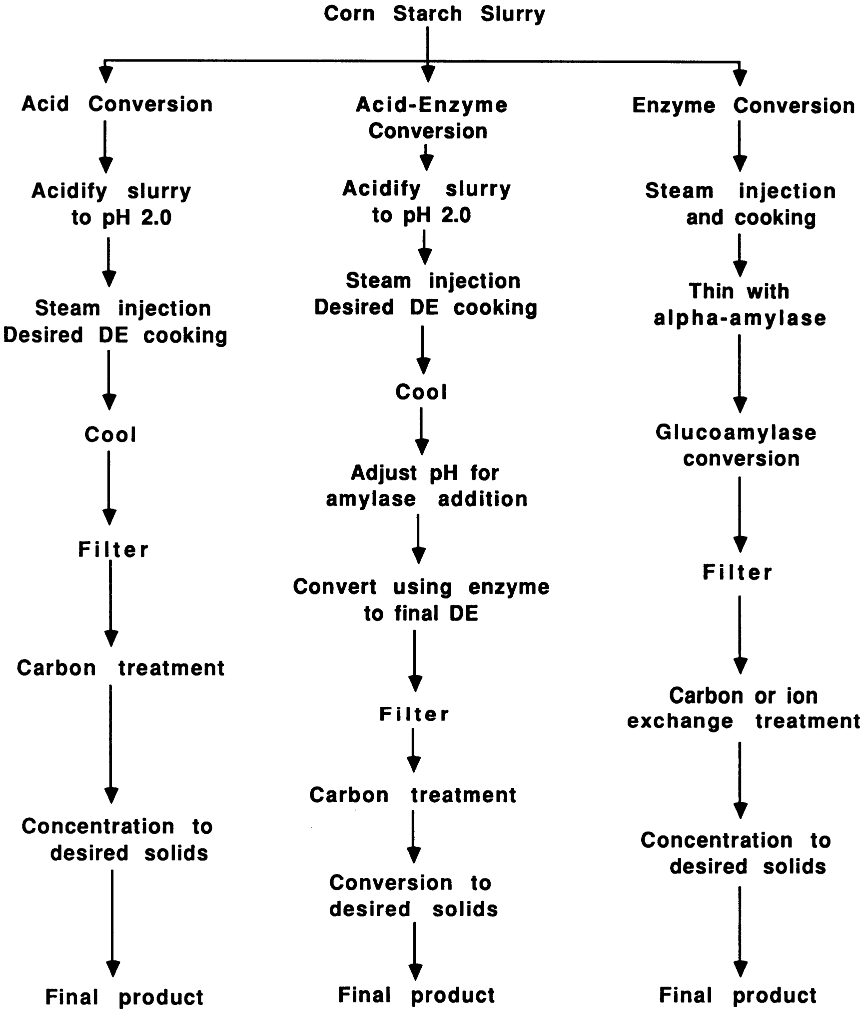


Fig. 1-19. Flowchart for the preparation of corn syrups by various methods.

depolymerized to a predetermined level. The process is ended by adjusting the pH to 4–5 with an alkali. The liquor is clarified by filtration and/or centrifugation, and concentrated by evaporation to ~60% dry matter. The syrup is further clarified and decolorized by activated carbon treatment, and refined by ion-exchange to remove soluble minerals and proteins and to deodorize and decolorize. It is further concentrated in large vacuum pans or continuous evaporators.

In the *acid-enzyme process,* the liquor, containing a partially converted product, is treated with an appropriate enzyme or combination of enzymes to complete the conversion. Thus, in the production of 42-DE high-maltose syrup, acid conversion is carried out until dextrose production is negligible; at this point, β-amylase (a maltose-producing enzyme) is added to complete the conversion. The enzyme is deactivated, and purification and concentration are continued as in the acid process (Fig. 1-19).

In the *enzyme conversion process,* the starch granules are cooked, preliminary starch depolymerization is done by starch-liquefying α-amylase, and the final depolymerization is effected by either a single enzyme or a combination of enzymes. Different enzyme combinations make possible the production of syrups with specific composition and/or properties (e.g., high maltose or high fermentable syrup).

Products

Corn is utilized in several ways as human food: parched to be eaten whole; ground to make hominy, corn meal, or corn flour; treated with alkali to remove the pericarp and germ to make lye hominy; and converted to a variety of breakfast foods (see "Breakfast Cereals" in the discussion of wheat).

Dry Milling

Modern corn mills can produce a variety of grits, meals, and flours. They are dried at 65 °C and cooled before packing. The flattened germs are used to produce corn oil. For such industrial uses as brewing and wallpaper paste manufacture, hominy or grits are flaked: The grits are steamed and passed between heavy-duty heated iron rolls, and the flakes are dried. The heating process gelatinizes the cornstarch.

The relative yields of various products from dry milling of corn depend on whether the main objective is to produce grits or meal and whether the corn was degermed before grinding. In milling corn for grits and meal by the degerminating process, the following average yields are obtained: grits 52%, meal and flour 8%, hominy feed 35%, and crude corn oil 1%. When the corn is not degermed before grinding, about 72% corn meal and 20% feed are produced (Pomeranz 1987). Of the total meal produced, about two-thirds contain 1.4% fat and the rest 4.6% fat. The grits and meal are largely produced from the horny or vitreous endosperm, and they contain less than 1.0% and 1.5% fat, respectively. The flour produced by grinding the starchy endosperm contains 2–3% fat from broken germ during process.

Wet Milling

The main products of corn wet milling are starch (unmodified and modified, including syrups and dextrose) and several coproducts. Cornstarch is a widely used stabilizer in food systems. The preparation, properties, and uses of both modified and unmodified cornstarches have been comprehensively reviewed (Pomeranz 1987). The coproducts of cornstarch wet milling amount to about one-third of the total output. Except for corn oil (which is very bland in flavor and odor and can be used in an assortment of food applications) and steep liquor (condensed corn fermentation extractives, used in industrial fermentations), the coproducts are mainly sold as feed ingredients. In decreasing commercial value, these include corn gluten meal, corn gluten feed, spent germ meal, cornstarch molasses or hydrol, steep liquor, corn bran, and hydrolyzed fatty acids.

In recent years, isomerized corn syrups have become a sizable part of the total production of syrups by the U.S. corn wet-milling industry (Pomeranz 1987). Commercial isomerized corn syrups are clear, bland, sweet, low-viscosity sweeteners high in dextrose (glucose) and fructose (levulose). High-fructose corn syrups (HFCS) are functionally equivalent to liquid invert sugar in most foods and beverages, and can be substituted with little or no change in formulation, processing, or final product. HFCS is prepared by the enzymatic action of glucose isomerase, which isomerizes glucose into fructose. The fructose content in the syrup may be 50% or more, depending on the substrate and the method of preparation; the principal HFCS marketed in the United States contains 42% fructose. HFCS and other corn sweeteners are widely used in bakery products, candy manufacture, and beverages.

Barley

Barley is often consumed as pot barley or pearl barley. They both are manufactured by gradually removing the hull and the outer portions of the barley kernels by abrasive action, although pearl barley is decorticated or pearled to a greater extent: Typically, 100 lb of barley yields 65 lb of pot barley or 35 lb of pearl barley (Pomeranz 1987). Barley flour is a secondary product, and the polishings are a by-product of the pearling process. This flour is milled from barley grain that has been pearled, steamed, and ground to produce a stable product. It is commonly used as a thickener, stabilizer, binder, or protein source for baby foods, malt beverages, prepared meats, and pet foods (Pomeranz 1974). Sometimes, quick-cooking barley is used as a major ingredient in dry soups and as a thickener. Barley flakes are a creamy white, pearled barley that has been steamed and rolled into thin flakes; these provide a less chewy texture than oat flakes and are used in granola products. The various uses of barley and barley products are summarized in Table 1-36.

Since barley produces many hydrolytic enzymes (including large amounts of α- and β-amylase) during malting, it occupies a unique position in the brewing industry. The combination of the two amylases result in a more complete and

Table 1-36. Present Uses of Barley and Barley Products.

Type	Use
Feed	Livestock, poultry
Pearling	Pot barley for soups and dressings; pearled barley for soups and dressings, flour, feed
Milling	Flour for baby foods and food specialties, grits, feed
Malting	Brewed beverages; brewer's grains for dairy feeds; brewer's yeast for animal feed, human food, and fine chemicals; distiller's alcohol or spirits; distiller's solubles or grains for livestock and poultry feeds
Specialty malts	High-dried, dextrin, caramel, or black for breakfast cereals, sugar colorings, dark beers, and coffee substitutes
Export	Malt flour for wheat flour supplements and human and animal food production; malted milk concentrates for malted milk, malted milk beverages, and infant foods; malted syrups for medicinal, textile, baking uses, and for breakfast cereals and candies; malted sprouts for dairy feeds, vinegar manufacture, and industrial fermentations

Source: Phillips and Boerner (1935).

rapid degradation of starch than in malts from most other cereal grains. Two general types of malt are produced commercially: brewer's and distiller's malts. *Brewer's malts* are made from barleys of plumper, heavier kernels with a mellow or friable starch mass. They are steeped and germinated at moisture contents ranging from 43% to 46%, and the final temperature used in drying them to about 4% moisture content is in the 71–82 °C range. The high final drying temperature reduces the enzymatic activities of the malt and the wort made from it and increases the flavor and aroma. *Distiller's* (or *high-diastatic*) *malts* are made from small-kerneled barley high in protein content and enzymatic potential (Pomeranz 1987). The barley is steeped and malted at higher moistures (45–49%) and dried at lower temperatures (49–60 °C) to higher finished moisture contents (5–7%) than is brewer's malt. *Malt sprouts* are the main byproducts of barley malting. They are easily separated from the kilned malt by passing the malt through revolving reels of a wire screen, and are mainly used in feed formulation.

Pomeranz (1987) has reviewed the various brewing processes and the associated chemical changes. In a typical brewhouse process, the dried barley malt is milled and then extracted with water ("mashing") in one of two basic ways: In the traditional (and simpler) *infusion mashing process,* the mixed grist and liquor are allowed to stand in a mash tub, and the temperature is gradually raised but kept below the boiling point. In the *decoction method,* a part of the mash is withdrawn, boiled, and returned to the mash tub to raise the temperature of the whole mash. In both processes, the mash passes to a lauter tub with a false bottom. The grain husks deposit on this false bottom and form a filter bed for the subsequent straining of the sugar-rich wort. After the spent grains are separated from the wort, the clear extract (sweet wort) is then boiled with hops, strained, and cooked. Yeast is then added and the whole mixture pumped to settlers. After 10–12 h, it is transferred to fermentation tanks where it remains until the fermentation is completed. The fermented wort is allowed to age and is prefiltered, chill-proofed, filtered, carbonated, and bottled. The bottled or canned beer is either pasteurized or sterilized by ultrafiltration. The main by-products of the brewing process are spent grains, trub (break), spent hops, and yeast. They are mostly used as adjuncts in feed formulations.

Oats

Oat spikelets typically contain two or three kernels: the primary, which is the largest, the somewhat smaller secondary, and the occasional, quite small tertiary. Each kernel has a two-part hull (lemma and palea), which when removed exposes the groat. The groats are milled to provide oatmeal for porridge and oatcake, rolled oats for porridge, oat flour for baby foods, and ready-to-eat breakfast cereals (see "Breakfast Cereals" in the discussion of wheat). Rolled oats and oatmeal are essentially whole-grain products (Doggett 1970; Pomeranz 1987).

The schematics of oat processing are shown in Fig. 1-20. Only high-grade oats are employed in milling. The initial stages include cleaning and drying or slow-roasting of the kernels to reduce their moisture content to about 6%; this increases the brittleness of the hulls, thus facilitating their easy removal. The size-graded oats are then (de)hulled. Most of the oats destined for food are rolled. There are two major types of rolled oats (actually rolled groats): regular (old-fashioned) and quick. Regular rolled oats are made from primary groats. The entire groat is rolled to produce large flakes. These take longer to cook, but have a desirable texture. In contrast, quick-rolled oats are made from secondary or small broken groats. They are steel-cut into two or three pieces and rolled into thinner-than-regular flakes to produce a product that cooks rapidly. In either case, the groats are steamed prior to rolling to inactivate the lipases and precondition the groats for rolling. The medium-quality grade no. 2 white oats yield about 42% good-quality rolled oats, 30% hulls, and 28% other products (including oat shorts, oat middlings, cereal grains, weed seeds and other material removed in the cleaning process) (Pomeranz 1987).

Oat hulls are an important by-product of oat milling. The pentosans in the hulls are used for commercial production of furfural, which is used extensively in the manufacture of phenolic resins and as a solvent (Pomeranz 1987).

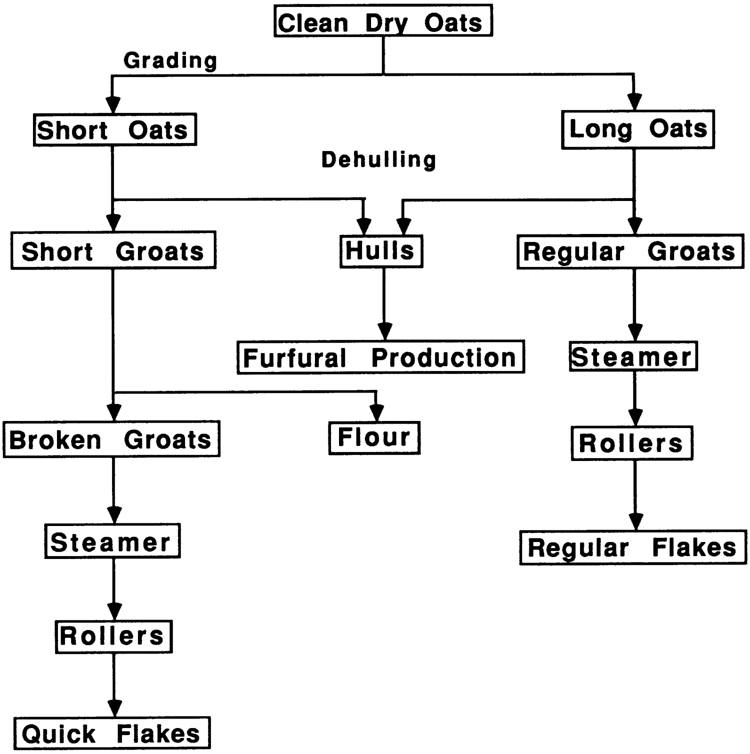


Fig. 1-20. Schematic diagram showing the various steps in oat processing.

Sorghum

Sorghum is often cultivated as a staple food crop in the semiarid agricultural regions, especially of the developing countries, where it serves two purposes: sorghum fodder and stover are used as feed for dairy and farm animals, and the grain is used as human food. In the developed countries, however, it is primarily used for industrial or animal feed purposes. In recent years, sorghum has attracted the attention of researchers because of its potential use in the form of composite flour with wheat (Jadhav and Joglekar 1984). The development of suitable technology to improve the acceptability of sorghum products is essential for popularizing its use and for meeting human nutritional requirements.

Sorghum processing is not fully developed on a commercial scale. Dehusking of the grain is followed only if it is utilized for special food products; however, modern concepts in cereal grain processing can also be used for sorghum.

Nevertheless, household and traditional techniques of sorghum processing that have been followed in African and Asian villages are of considerable importance. They generally involve the use of mortar and pestle and the stone mill. The husk (bran) is removed from the grain by pounding and discarded by winnowing, and the remaining grains are further pounded until the flour is suitable for sieving (Muller 1970; Joglekar and Jadhav 1984). The stone mill consists of two grooved circular stone slabs. The upper slab is manually rotated around a short axle at the center of the lower, stationary slab while grain is periodically fed through the hole on the top of the upper slab. The flour is released around the lower slab. Mechanical grinding of grain sorghum into whole flour is common in India, where it is done in a *chakki,* essentially based on the principle of the traditional stone mill. Grinding of sorghum by these traditional methods, however, results in high losses of important nutrients (Carr 1961).

The conventional dry, roller-milling process can be employed for the preparation of whole and refined sorghum products. Sorghum is harder to grind than wheat, barley, or oats, but slightly easier than corn (Pomeranz 1987). The preliminary operations in dry milling of sorghum involve the removal of impurities such as adhering glumes, broken kernels, chaff, dirt, foreign seeds, sticks, and stones. The addition of moisture to the grain (i.e., conditioning or tempering) prior to milling is a common practice. Preconditioning of the grains offers such advantages as swelling and separation of the germ from the cementing layer of endosperm, toughening of the bran, and mellowing of the endosperm (Larsen 1959). Also enabled are removal of pericarp in large pieces (due to the hydration of cellulose and hemicellulose) and efficient separation of the products with desirable properties. Conditioning also makes the endosperm soft and friable (Joglekar and Jadhav 1984).

In conventional roller milling, the grooved or corrugated rollers break open the grains. The exposed endosperm is then crushed between a series of smooth reduction rollers and freed from the toughened bran. The fine grains are separated by screening, and the coarse fraction is further fed to the next set of rollers after every pass. The bran is generally removed by screening and aspiration. The utility of dry milling largely depends upon the maximum yield of endosperm and the use of germ and bran as valuable by-products. The break flour (10–15% yield) obtained from the first set of rollers is mostly floury endosperm and contains little protein (4.0–4.5% as compared to 8–9% in whole grain) (Pomeranz 1987). The roller-milled flours are sieved to yield products varying in extraction and composition. A product obtained in 70% yield contains 0.5% ash and 0.8% fiber, and is reasonably free of objectionable specks. For the production of high-extraction flours (i.e., 90%), impact grinding is preferred as it requires less space and equipment than the roller-mill system.

Since the sorghum kernel is round, the bran can be removed mechanically by abrasion. Without tempering, a 75–80% yield of almost completely dehulled sorghum can be obtained (Pomeranz 1987). Proper tempering to assist in loosening the hull can increase the yield to 85%. Joglekar and Jadhav (1984) reported that a 15.5% moisture content in the peeled grain is essential for germ removal and further milling. Most polishers or decorticating machines are designed to remove the outer bran layers from the kernel. The sorghum is fed to a cylindrical millstone rotating continuously inside a cylindrical screen. Pearling is continued until adequate amount of bran is removed. The bran is separated from the grain by sifting while fine particles are aspirated.

Peeling of bran layers from sorghum kernels can also be achieved chemically (Pomeranz 1961). A caustic dip (0.25%) of sorghum grain after solvent extraction loosens the seed coat, which is then removed by rinsing and brushing (Thrasher 1950). Barta, Kilpatrick, and Morgan (1966) described another caustic method in which the grains are soaked in 25% sodium hydroxide at 82 °C for several minutes.

Attrition milling has also been used for the dehusking of sorghum grains. De Man et al. (1973) described a Palyi compact attrition mill fitted with sawtooth-blade plates that provide the dehulling action. The grains were further abraded by a drum rotating in a cylindrical screen. Finally, hulls were separated from kernels by an air separator. Most attrition-type dehullers are comprised of two stone or metal disks, either or both of which rotate around a vertical or horizontal axis (Joglekar and Jadhav 1984). The attrition is provided by introducing metal pins or blades into the surface of either or both rotors, or of the rotor and the stator.

Reichert and Young (1976) compared two commercial mills, an abrasive and an attrition type, with a laboratory-type barley pearler for the dehusking of pigmented Nigerian sorghum. They found the abrasive mill (Hill grain thresher) more suitable. The abrasive mill consists of thirteen carborundum stones (12-in. diameter) driven at a speed of up to 200 rpm. In a continuous operation, the grains are fed through a hopper at one end and released after stone action through an overflow outlet at the other end. The amount of kernels removed as fine is determined by the retention time in the mill, which in turn depends upon the grain-feeding rate. The grains are then passed through an air separator on the attrition mill to remove the fines.

Degermination of the dehusked sorghum is essential to obtain products with low lipids for better storage stability. The germ can be removed by passing the dehusked kernel through cracking rolls or impact machines (Pomeranz 1987). The germ separation is then achieved by flattening and sieving, air classification, or by gravity separation. The by-products of sorghum dry milling (bran, germ, and shorts) are used in the production of hominy feed.

Wet-milling processes similar to that of corn have also been used for sorghum processing. However, finer-mesh screens are necessary for efficient operation (Pomeranz 1987). Chemically and microscopically, sorghum starch is similar to cornstarch. Milo starch is blander in flavor and does not develop rancidity. Other products of sorghum wet-milling operations include oil and gluten feeds.

Some sweet sorghum varieties produce large quantities of sugar in the stalks. The pressed juice is boiled to produce a distinctively flavored syrup, which is then used for sugar and alcohol production. Sugar production from sweet sorghum is described in detail in Chapter 4.

Rye

Rye breads are quite popular in Europe and Russia. The quality characteristics of rye with regard to bread production have been comprehensively reviewed by Weipert and Zwingelberg (1980). It is impossible to wash out gluten from a dough made entirely of rye flour; thus rye flour is inferior to wheat flour in yeast-leavened bread. In the United States, most of the so-called rye bread is baked from mixtures of rye and wheat flour (Pomeranz 1987; Webb 1987). Most of the major mills market rye blends made from a mixture of strong spring or hard winter wheat and rye. They roughly follow the pattern of 80% clear and 20% dark rye, 70% clear and 30% medium rye, or 50% clear and 50% white rye.

Pomeranz (1987) has reviewed the technology of rye milling. Rye is milled into flour by a process similar to that of wheat milling. However, because the bran in rye adheres tenaciously to the endosperm, it is not practical to produce clear "middlings" from rye or to purify them by aspiration. Also, if ground between smooth rolls, rye middlings tend to flake or flatten rather than pulverize. The primary objective of rye milling is to produce flour during the breaking process. The break rolls are therefore set relatively close and have finer corrugations than those used for corresponding breaks in milling wheat. The highest grade of flour is produced by the first break rolls. As the purity of the flour decreases, it becomes increasingly dark: The light (white) rye flour represents 50–65% of the grain, the medium flour corresponds to straight-grade wheat flour, and the dark rye flour corresponds to the "clear." Sometimes, "cut" or "stuffed" straights are also produced. The former is a medium rye flour from which a small percentage of white rye flour has been removed; the latter has a small amount of dark rye flour added to it. The milling of rye normally yields 65% light or patent rye, 15–20% dark rye, and 15–20% offal (CIGI 1975; Bushuk 1976).

Millets

Millets are processed and utilized in ways quite similar to sorghum, which are elaborated above.

Buckwheat

Over two-thirds of the buckwheat grain production in the United States and Canada is used as a feed for livestock and poultry; the remainder is milled into buckwheat flour (Pomeranz 1983). Buckwheat flour is usually dark in color due to the presence of hull fragments not removed during the milling process. For this reason, millers prefer Japanese buckwheat, the hulls of which are easier to remove. Buckwheat may be milled either for flour or for groats (hulled grains). Tartary buckwheat is not used for milling because of its darker color and a bitter taste.

Buckwheat flour is primarily used for making buckwheat griddle cakes. It is more commonly marketed as pancake mixes than as pure buckwheat flour. These mixes may contain wheat, corn, rice, or oat flours and a leavening agent (Marshall and Pomeranz 1982). Buckwheat is also used in mixtures with wheat flour for bread, noodles, spaghetti, macaroni, and ready-to-eat breakfast cereals.

Two types of milling process are used for the manufacture of breakfast flour. In one process, the seeds are dehulled and then milled. In the other, the whole seeds are milled and the flour then screened to remove hulls. Rohrlich and Thomas (1967) have described a detailed commercial process for buckwheat milling. The freshly harvested seed is cleaned to remove sand, weeds, small and immature seeds, and other foreign material. The cleaned seeds are then steamed at 145 °C for 5 min and kilned. Steaming is essential to improve the swelling capacity and to reduce the cooking time of the final product. Kilning reduces the moisture content to about 7–8% and facilitates husk removal. After cooling and cold-conditioning, the seeds are separated by sieving into four fractions of various sizes and then dehulled. The dehulled groats are sized, and the hulls and flour are separated by screening. The whole groats are cut and sieved, and the hulls still adhering to them are removed. Buckwheat flour is produced by milling small groat pieces on smooth reduction rolls, similar to those used in wheat milling. As many as four types of flour are produced. These range in protein from 4.7% to 15.9%, in crude fiber from 0.4% to 1.2%, and in ash from 0.6% to 2.2%. High-quality buckwheat yields 60–65% groats and flour, 30% hulls, and 10–12% flour-containing bran. The hulls are an excellent packaging material and a good source of fuel, whereas the bran is used in swine feeding (Pomeranz 1983).

Sobagiri noodles prepared from buckwheat flour are quite popular in Japan. Since buckwheat flour itself is not glutinous, it is usually mixed with wheat flour. The mixture is kneaded into a tight dough, which is then rolled into a thin sheet. The sheet is cut into long, solid strips. The noodles are boiled in water, put into a bamboo basket, and dipped into cold water. The water is swished off the noodles before they are cooked. *Sobagiri* noodles are either used in soups (*kake-soba*) or eaten after being dipped into a thick soy sauce (*mori-soba*).

FUTURE RESEARCH NEEDS

The importance of cereals in nurturing our civilizations cannot be overemphasized. These earliest domesticated plant sources still play the most vital and pivotal role in sustaining our daily lives and our very existence on this planet. In fact, if any of the other food groups were to become unavailable, humankind still could survive and remain tolerably healthy; a failure of cereal crops, however, would bring starvation and malnutrition to most parts of the world.

Global cereal production has increased rapidly during the past three decades. The introduction of new high-yielding genotypes (especially of rice and wheat), the success in developing hybrid varieties of corn and sorghum, and new agronomic practices account for much of the success of the so-called green revolution in many parts of the world. The United States, Canada, the Soviet Union, China, and India together produce over 70% of the world's cereals. Yet, both global environmental and political trends during the past couple of years suggest that their production may decline in the coming few years. The Soviet Union, in the midst of a prolonged drought and a rapidly changing political scene, is expected to become a major importer of cereal grains for the next few years. Similarly, continuous drought conditions during the past five years in vast areas of both the United States and Canada will certainly add to the global shortfall of cereal supply. Agriculture in India still depends on the vagaries of nature. In fact, a failure of monsoon in the Indian subcontinent and the Eastern Hemisphere for two years in a row still has a large ripple effect on the world's food supply and economy. Increased production and loss-reduction technology rather than improved processing will thus continue to dominate research on the cereal front. Some of these research challenges are briefly highlighted below.

Commercial Fertilizers and Biological Nitrogen Fixation

Unlike legumes, which are partially self-sufficient through symbiotic N_2 fixation, cereals primarily rely on commercial nitrogen sources of manures and fertilizers for their growth. In fact, it is the single most important economic constraint in cereal production. Continuous increase in global cereal production no doubt will depend on a sustained economic supply of commercial nitrogen fertilizers. Nevertheless, several bacteria and blue-green algae are capable of fixing atmospheric nitrogen in cereal fields. Although cereal–bacteria associations contribute significantly to the overall nitrogen economy of the plants, the actual contribution of N_2 fixation in cereal crops is not known. However, at least in the foreseeable future, it is unlikely that biological nitrogen fixation alone would satisfy all the nitrogen requirements of the high-yielding cereal genotypes.

Fertilizers are the most important industrial inputs into modern agricultural production systems, accounting for about one-third of the total energy input.

They also account for about the same degree of increase in the total crop productivity achieved during the past three decades. Fertilizer management under field conditions will therefore be of increasing importance in the coming years. For example, nitrogen fertilizer inputs exceed over $1 billion annually in the United States for corn alone. Yet only 50% of the nitrogen and less than 35% of the phosphorus and potassium applied as fertilizers in the United States are recovered by crops (Wittwer 1980). In contrast, the recovery of fertilizer nitrogen in the rice paddies of the tropics is only 25–35%, the balance being lost to the environment. Worldwide, about 12–15 million metric tons of nitrogen fertilizers are lost to denitrification alone. Both natural and synthetic nitrification inhibitors, which could be applied with ammonia or urea to effectively deter leaching and atmospheric losses of nitrogen, must be expeditiously researched on a global scale to preserve our ever-depleting natural hydrocarbon resources. Since denitrification occurs only under anaerobic soil conditions, such research should go hand in hand with newer and better soil compaction methods, improved drainage, use of soil-improving crops, and careful attention to irrigation procedures.

Foliar application of fertilizer has long been declared the most efficient method of fertilizer placement (Wittwer and Bukovac 1969), yet technology of application on a large scale is still lacking. Future yield barriers may well be broken up, by utilizing the absorptive capacity of leaves and roots, for applying nutrients at crucial stages of development. Although research results in this area are not very encouraging, the rising costs of fertilizer and its nonrenewable resource requirement should be continuing stimuli for further developments of this technology.

Although improved technologies of fertilizer nitrogen production and increased efficiency of fertilizer use by plants could make more nitrogen available for the plants, alternative technologies must be developed to lessen the dependence of plants on fertilizer nitrogen. In fact, development of high-yielding cereal genotypes that are also self-sufficient in their nitrogen requirements may indeed prove to be the most crucial breakthrough in the years ahead. The possible transfer of nitrogen-fixing (*nif*) genes from free-living bacteria such as *Klebsiella* to higher plants has been proposed quite frequently in recent years. There have been rapid advances made in understanding the seventeen *nif* genes in nitrogen-fixing bacteria, particularly their order, gene products, and regulation of expression (Roberts and Brill 1981), but complications do arise in their transfer and expression in higher plants. Nitrogenases that catalyze the ATP-dependent six-electron reduction of dinitrogen (N_2) to ammonia are oxygen-labile. This fact is circumvented in *Azotobacter* by rapid respiration to reduce oxygen tension, and by the presence of leghemoglobin in *Rhizobium* nodules, which facilitates oxygen diffusion to bacteroids without inactivating the enzyme. Therefore, all efforts of transferring the genes to higher plants should include some methods for the protection of the nitrogenase enzyme system. In addition, extra host genes will be required to assimilate and transport the ammonia produced during this process. The bacterial gene control sequences may also have to be modified for the expression in higher plants. Newer biotechnological approaches of gene transfer will undoubtedly offer some solutions in this regard in the years to come.

Interspecific Gene Transfer

Genetic improvement by conventional plant breeding techniques accounts for at least half of the increased productivity of the high-yielding cereal genotypes. Breeding for specific traits, such as resistance to pests and diseases and other quality characteristics desirable in cereals, has also made considerable progress over the past few decades. In fact, one of the major reasons for the vast increase in global wheat production is due to the transfer of rust resistance to wheat genotypes from its wild relatives. Conventional plant breeding techniques, however, are time consuming, and their success is limited due to the natural barriers of cross incompatibility between species that restrict the possibility of combining genomes and the transfer of desired traits from one species to another. Recent advances in gene manipulation and interspecific gene transfer technology will prove quite useful in effecting transfer of desired genes from wild species into related cultivars, as also between different species. These techniques will also be useful in enhancing the nutritional quality of cereal proteins by breeding for high-lysine genotypes. Such approaches as microinjection of DNA into plant cells, injection of genetic material into plants, the use of pollen and embryos for DNA uptake, and *Agrobacterium*- and viral-based vector systems have been suggested and tried under laboratory conditions for gene transfer applicable to cereals. We may have, in the not too distant future, genetically improved species and genotypes for crop production.

Breeding for Drought and Salinity Tolerance

Two other areas will require our continuing attention and research efforts in plant breeding: development of drought- and salinity-tolerant cultivars. We need to expand our data base regarding underlying drought-tolerant mechanisms and their influence on crop productivity. Much of our agriculture still depends on annual rainfall. To maintain a sustained level of cereal production, we must identify traits that will allow crops to grow under water-stressed environments and yet maintain a high level of productivity. Genetic links, if any, need to be established in this regard.

The reckless use of irrigation water in several parts of the world has created hitherto unknown problems. Salt levels in irrigated soils have been continually rising, making vast areas of fertile lands unavailable for economic crop production. Improvements in irrigation systems and techniques are required to minimize this problem. For soils that already have high levels of salinity and alkalinity, genotypes must be developed that are tolerant to these conditions.

Photorespiration and Photosynthesis

Great challenges lie ahead in developing varieties of cereals having low photorespiration and in the formulation of chemicals that will modify plant architecture and increase photosynthesis. In no research area are the opportunities more attractive and the potentials greater for achieving results, reflected in increased crop productivity, than in maximization of the photosynthetic process. Photosynthesis still remains the most important biochemical energy-producing process on earth. The greatest challenge we face in food-producing systems today is how to manipulate plants under varying environmental conditions to maximize this energy conversion process. The importance of building a stock of plants for agricultural purposes with the C-4 pathway in photosynthesis has long been recognized. Thus far, this approach has been notably unsuccessful. Of the larger research investments allocated to a better understanding of the photosynthetic process, there has been little payoff with food crops under field conditions. Nevertheless, there are some specific examples of photosynthesis enhancement. The new, short, stiff-strawed rice varieties have a higher proportion of grain to plant. The short, erect leaves capture light more efficiently and have better light-receiving systems in the the densely planted, heavily fertilized, tropical rice paddies.

The feasibility of transferring the different photosynthetic pathways from one species to another has been demonstrated, although not to date in crop plants. The prospects for achieving this through genetic engineering are also distant due to the large number of genes that need to be transferred. Nevertheless, the practical benefits to be derived from progress in this field suggest that such research is worthy of our greater attention in the decade ahead.

Research on the physiological mechanisms that control growth and ultimate size of the individual plant and its potential for economic yield also needs to be expedited. Over 90% of the dry weight of a plant is the net product of photosynthesis. A plant is limited by time in the amount of assimilate it can produce. Both environmental factors and agronomic practices significantly influence the partitioning of photosynthates and the subsequent dry-matter accumulation. Continuing interdisciplinary research is needed to understand the complex interrelationships among the mechanisms that control plant growth, development, and partitioning of photosynthates, so as to develop techniques and guidelines for improved management practices and select for increased economic yield of cereal crops.

Pre- and Postharvest Losses

In spite of the best pest control and management practices, preharvest losses in cereals generally exceed 20% in the developed countries. World crop losses to pests and diseases amount to over 35%. High-yielding genotypes of cereals are generally more susceptible to pests and diseases than were their old counterparts. Reliance on pesticides as the single line of defense during the past two decades has now introduced several new problems of pesticide resistance, destruction of natural enemies, outbreaks of secondary pests, reductions in pollinators, potential environmental and groundwater contamination, and health hazards. To circumvent these problems, research on integrated pest management techniques should be expedited. Similarly the tremendous losses (up to 50% of total grain production) that occur during the storage and handling of cereals, particularly in the developing countries, need to be minimized. In this regard, particular attention must be paid to developing the necessary infrastructure to handle the yield increases achieved in cereal production in tropical developing countries. If such losses are eliminated through improved storage, postharvest handling, and prompt processing, the world food supply could be increased by at least 30–40% without bringing any additional land under cultivation or incurring any expensive inputs.

With regard to processing, a major improvement may be expected in the Western countries to expand the uses of cereal grains in traditional ethnic foods for local markets. A greater reliance would certainly be placed on making the various cereal processing operations more energy efficient. Computer-aided technologies will play a key role in both process management and quality control. In contrast, most efforts in this regard in the developing countries should be aimed at formulating technologies that suit given environments, are cost effective, use indigenous energy resources, and take into consideration local food habits and customs. Wherever possible, industries should be established to process food crops for export markets—not only to earn the valuable foreign exchange that most developing countries need, but also to utilize the vast, untapped labor pool that is frequently found in these regions.

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