

ARABLE CROP PRODUCTION – CEREALS.

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Scientific research and development in the last few decades have resulted in improved agricultural production with significant results in crop production techniques. This improvement have been brought about mainly by the development of new varieties of crops, better understanding of the climatic factors and crop environment in general, improvement in soil sciences and better farming methods.

The crop growing environment is of major importance and can only be manipulated to a certain extent. The biotic component of the environment is under control a farmer can sow at the optimum density, weed and spray against pests and diseases but the abiotic component is much less amenable to change. Man can seldom alter the climate (Gilbert, 2004) so the sunshine, average temperature and photoperiod are largely fixed. Man can plough (to aerate the soil); drain or irrigate (to seek optimum water levels); plant shelter-belts (to reduce wind speed); lime (to raise the pH – there is little he can do to lower it); and, of course, add fertilisers (to correct nutrient deficiencies).

But the three limiting factors for photosynthesis – light, temperature and carbon dioxide can only be controlled in a greenhouse or laboratory. It is important to realise that the Laws of ‘Limiting Factors’ and of ‘Diminishing Returns’ apply here; except the expected profits is much in excess of the cost of production there would be no need to alter anything.

The origin, uses, production, properties, description, growth and development, ecology, propagation, management, diseases and pests, yield, post harvesting handling,. breeding and prospects of five most important cereals : Wheat (*Triticum aestivum L.*), Rice (*Oryza sativa L.*), Maize (*Zea Mays L.*), Millet (*Pennisetum glaucum (L.) R.Br.*) and Sorghum (*Sorghum bicolor (L.) Moench*) in the food security of most countries in the world are discussed.

WHEAT (*Triticum aestivum L.*)

Family

Poaceae (Gramineae)

Chromosome number

$2n = 42$

Origin and geographic distribution

Bread wheat arose in the corridor extending from Armenia in Transcaucasia to the south-west coastal areas of the Caspian Sea in Iran. Hybridization of a wild *Aegilops* species (*Aegilops tauschii* Coss., with the D-genome) with emmer, an old type of cultivated wheat belonging to *Triticum turgidum L.*, gave rise to the hexaploid wheats, but it is unknown whether bread wheat or spelt wheat (*Triticum spelta L.*) appeared first. The earliest

archaeological finds of spelt wheat are from the southern Caspian area and are dated at around 5000 BC. Finds of bread wheat are difficult to distinguish from durum wheat (*Triticum turgidum*), but one thinks that those found in the Caucasus, on the anatolian plateau (Turkey), in Central Europe and in Central Asia from the fifth millennium onwards belong to bread wheat. The D-genome in fact conferred to bread wheat and spelt wheat the adaptation to cold winters and humid summers, allowing them to conquer temperate Eurasia, whereas the Mediterranean remained the area of emmer and durum wheat. By the third millennium BC, bread wheat had reached China. In 1529, the Spanish took it to the New World. Bread wheat was introduced into tropical Africa by Arab traders, missionaries and colonial settlers. It is not known exactly when it reached Ethiopia. It was brought from northern Africa to West Africa, where it was already known around 1000 AD. In the early 20th century it was introduced into Kenya and eastern DR Congo. Bread wheat today is grown in almost all parts of the world. In tropical Africa, it is mainly produced in Nigeria, Sudan, Ethiopia, Kenya, Tanzania, Zambia and Zimbabwe.

Uses.

Bread wheat flour is made into numerous products including bread (leavened or flat; baked, steamed or deep fried), pastries, crackers, biscuits, pretzels, noodles, farina, breakfast foods, baby foods and food thickeners. It is also used as a brewing ingredient in certain beverages (white beer). Leavened breads are the most popular use of wheat in almost all parts of the world. Increased bread consumption is often linked to increasing urbanization and higher per capita income. Bread wheat utilization has also been adapted to local cuisine. In Ethiopia, for instance, the flour is used to prepare 'injera' (pancake-like unleavened bread), porridge and soup. The grain is eaten as a snack and during social gatherings as 'nifro' (boiled whole grain often mixed with pulses), 'kollo' (roasted grain) and 'dabo-kollo' (ground and seasoned dough, shaped and deep fried). Industrial uses of wheat products centre on the production of glues, alcohol, oil and gluten. By-products of flour milling, particularly the bran, are used almost entirely to feed livestock, poultry or prawns. Wheat germ (from wheat embryos) is sold as a human food supplement. Straw is fed to ruminants or used for bedding material, thatching, wickerwork, newsprint, cardboard, packing material, fuel and as substrate for mushroom production. In many dry parts of the world it is chopped and mixed with clay to produce building material.

Production and international trade.

According to FAO estimates, the average world production of wheat grain (bread wheat and durum wheat together) in 1999–2003 amounted to 576 million t/year from 209 million ha. Worldwide, bread wheat constitutes more than 90% of the area under the cultivated wheats. The main wheat producing countries are China (96.8 million t/year from 25.2 million ha), India (71.0 million t/year from 26.4 million ha), the United States (56.9 million t/year from 20.6 million ha), the Russian Federation (39.4 million t/year from 21.7 million ha) and France (35.1 million t/year from 5.0 million ha). Wheat production in tropical Africa in 1999–2003 was 2.5 million t/year from 1.6 million ha, the main producing countries being Ethiopia (1.4 million t/year from 1.1 million ha), Kenya (272,000 t/year from 137,000 ha), Sudan (254,000 t/year from 124,000 ha), Zimbabwe (237,000 t/year from 43,000 ha),

Zambia (87,000 t/year from 13,000 ha), Tanzania (82,000 t/year from 60,000 ha) and Nigeria (75,000 t/year from 53,000 ha). In Ethiopia close to 50% of the wheat production consists of bread wheat, the other 50% of durum wheat. From 1961–1965 to 1999–2003 the world production of wheat increased from 248 to 576 million t/year, whereas the harvested area remained stable at around 210 million ha. In the same period the wheat production in tropical Africa increased from 960,000 to 2.5 million t/year, and the harvested area from 1.2 to 1.6 million ha.

Average world export of wheat amounted to 115 million t/year in 1998–2002, the main exporters being the United States (26.7 million t/year), Canada (16.5 million t/year), Australia (15.9 million t/year), France (15.9 million t/year) and Argentina (10.0 million t/year). Main importers are Italy, Brazil, Japan and Iran, each importing more than 5 million t/year. All countries in tropical Africa are net importers. The main importer in tropical Africa is Nigeria (1.9 million t/year in 1998–2002), followed by Ethiopia (770,000 t/year), Sudan (710,000 t/year) and Kenya (570,000 t/year). The share of food aid in wheat imports is as high as 80% for some countries.

Properties.

The composition of wheat grain is 7–8% coat material, 90% endosperm and 2–3% embryo. The embryo mainly comprises oil and protein, and little starch. The endosperm is starchy, and is surrounded by the aleurone layer which is rich in proteins. When a wheat grain is milled, the outer layers and embryo are separated from the endosperm. The pulverized endosperm becomes wheat flour, while the other parts form the bran. The endosperm varies both in hardness and vitreousness: hard bread wheat grain high in gluten protein tends to be vitreous and low-protein soft wheat grain tends to be opaque. Hard bread wheat grain is best suited for bread making while the soft wheat grain is best for cookies, cakes and pastries. Flour colour varies from white to slightly yellow.

Bread wheat grain (hard red spring type) contains per 100 g edible portion: water 12.8 g, energy 1377 kJ (329 kcal), protein 15.4 g, fat 1.9 g, carbohydrate 68.0 g, dietary fibre 12.2 g, Ca 25 mg, Mg 124 mg, P 332 mg, Fe 3.6 mg, Zn 2.8 mg, vitamin A 9 IU, thiamin 0.50 mg, riboflavin 0.11 mg, niacin 5.7 mg, vitamin B₆ 0.34 mg, folate 43 µg and ascorbic acid 0 mg. The essential amino-acid composition per 100 g edible portion is: tryptophan 195 mg, lysine 404 mg, methionine 230 mg, phenylalanine 724 mg, threonine 433 mg, valine 679 mg, leucine 1038 mg and isoleucine 541 mg. The principal fatty acids are per 100 g edible portion: linoleic acid 727 mg, palmitic acid 283 mg and oleic acid 236 mg. Soft, white bread wheat grain contains per 100 g edible portion: water 10.4 g, energy 1423 kJ (340 kcal), protein 10.7 g, fat 2.0 g, carbohydrate 75.4 g, dietary fibre 12.7 g, Ca 34 mg, Mg 90 mg, P 402 mg, Fe 5.4 mg, Zn 3.5 mg, vitamin A 9 IU, thiamin 0.41 mg, riboflavin 0.11 mg, niacin 4.8 mg, vitamin B₆ 0.38 mg, folate 41 µg and ascorbic acid 0 mg (USDA, 2005). Bread wheat grain is deficient in the amino acids lysine and threonine, and somewhat in isoleucine and valine. It is a good source of B-group vitamins and minerals. Wheat grain possesses a unique viscoelastic and insoluble storage protein complex known as gluten, comprising 78–85% of the total wheat endosperm protein. Gluten is composed mainly of glutenin (polymeric) and gliadin (monomeric) proteins. Glutenins confer elasticity and dough strength, while gliadins confer mainly viscous flow and extensibility to the gluten complex. Wheat flour contains roughly equal amounts of glutenins and gliadins, and their imbalance

may influence its visco-elastic properties.

Description.

Annual, tufted grass up to 150 cm tall, with 2–5(–40) tillers; stem (culm) cylindrical, smooth, hollow except at nodes. Leaves distichously alternate, simple and entire; leaf sheath rounded, auricled; ligule membranous; blade linear, 15–40 cm × 1–2 cm, parallel-veined, flat, glabrous or pubescent. Inflorescence a terminal, distichous spike 4–18 cm long, with sessile spikelets borne solitary on zigzag rachis. Spikelet 10–15 mm long, laterally compressed, 3–9-flowered, with bisexual florets, but 1–2 uppermost ones usually rudimentary, sometimes only 1 of the florets bisexual; glumes almost equal, oblong, shorter than spikelet, thinly leathery, keeled towards the tip, apiculate to awned; lemma rounded on back but keeled towards the tip, leathery, awned or blunt; palea 2-keeled, hairy on the keels; lodicules 2, ciliate; stamens 3; ovary superior, tipped by a small fleshy hairy appendage and with 2 plumose stigmas. Fruit an ellipsoid caryopsis (grain), at one side with a central groove, reddish brown to yellow or white.

Other botanical information.

Triticum is a classic example of allopolyploidy consisting of diploid ($2n = 14$), tetraploid ($2n = 28$) and hexaploid ($2n = 42$) species. Selection at the diploid and tetraploid levels has proceeded from wild species with hulled grain and brittle rachis to the free-threshing species with tough rachis; hexaploid wheats are not known in the wild, they appeared in cultivation. The classification of the genus *Triticum* and other related genera within the tribe *Triticeae* was strongly debated. Polyploidy and biphyletic genome differentiation (B vs. G genome) are isolating mechanisms offering adequate species borders. In this approach, *Triticum* comprises only 5–6 species, including the diploid *Triticum monococcum* L. (einkorn, grown sporadically in southern Europe and western Asia), the tetraploid *Triticum turgidum* L. and the hexaploid *Triticum aestivum* L. (comprising all cultivated hexaploids). Spelt wheat (*Triticum spelta* L.) is sometimes separated from *Triticum aestivum*. It is a hexaploid, not free-threshing wheat, with only 2–3 florets per spikelet, cultivated in small quantities in Europe, Africa and on the plateau of western Iran. It can be cultivated under extreme circumstances, not demanding fertile soils, being relatively disease resistant, and having good taste, food and baking qualities. Before 1850 it was a very important wheat in Europe, declining afterwards, especially because it has to be hulled before milling, but is now gaining in popularity in organic wheat cultivation. Commercially, wheat is classified into distinct categories of grain hardness (soft, medium-hard, and hard) and colour (red, white and amber). Based on growing habit, bread wheat is divided into two subclasses, spring or winter, but facultative types exist. These subclasses in turn may also be divided into grades, which are generally used to adjust prices, based mainly on grain soundness (effects of rain, heat, frost, insect and mould damage), cleanliness, grain protein content and α -amylase activity. In tropical Africa mostly spring wheats are grown.

Hybrids of wheats (tetraploid or hexaploid) and rye called triticale (\times *Triticosecale*) have been developed and these show a mix of characteristics from the parents, combining the

hardiness of rye with the high yield and quality of wheat. Triticale is presently grown only locally in tropical Africa, e.g. in Ethiopia, Kenya, Tanzania and Madagascar, and also in northern Africa and South Africa. As a new food crop, it fell short of expectations, but it is becoming increasingly popular as a forage crop.

Growth and development.

Germination of wheat occurs at temperatures of 4–37°C, the optimum being 12–25°C. The radicle emerges first and the coleoptile emerges 4–6 days after germination. The primary roots may remain functional for life unless destroyed by disease or mechanical injury, but they constitute only a small portion of the total root system. The first true leaf of the seedling emerges from the coleoptile. Secondary roots start to develop about two weeks after seedling emergence. They arise from the basal nodes and form the permanent root system, which spreads out and may penetrate as deep as 2 m, but normally no more than 1 m. Leaf and tiller production increase rapidly soon after crop emergence. The duration of the vegetative stage may vary from 20–150 days depending on temperature and the cultivar's vernalization and daylength response. For floral induction, spring types usually require temperatures between 7°C and 18°C for 5–15 days, while winter types require temperatures between 0°C and 7°C for 30–60 days. Flowering begins at the middle third of the spike and continues towards the basal and apical parts in 3–5 days. All spike-bearing tillers eventually flower almost simultaneously. Wheat is normally self-pollinated; cross-pollination is 1–4%. Pollen is largely shed within the floret. Stigmas remain receptive for 4–13 days. Pollen is viable for up to 30 minutes only. Grains in the centre of the spike and in the proximal florets tend to be larger than the other ones. Physiological maturity is reached when the flag leaf (uppermost leaf) and spikes turn yellow and the moisture content of the fully formed grain has dropped to 25–35%. The complete crop cycle of bread wheat varies from 50–200 days in tropical Africa.

Ecology.

Bread wheat can be grown from within the Arctic Circle to near the equator, but it is most successful between 30–60°N and 27–40°S. Optimum temperatures for development are 10–24°C, with minima of 3–4°C and maxima of 30–32°C. An average temperature of about 18°C is optimal for yield. Temperatures above 35°C stop photosynthesis and growth, and at 40°C the heat kills the crop. Wheat does not grow well under very warm conditions with high relative humidity, and in the tropics it is best grown at higher elevations (1200–3000 m) or in the cooler months of the year. Bread wheat requires at least 250 mm water during the growing season for a good crop; it can be grown in areas that receive 250–750 mm rain annually. The sensitivity to daylength differs among genotypes, but most are quantitative long-day plants; they flower earlier at long daylengths, but they do not require a particular daylength to induce flowering.

Soils best suited for bread wheat production are well aerated, well drained, and deep, with 0.5% or more organic matter. Optimum soil pH ranges between 5.5 and 7.5. Wheat is

sensitive to soil salinity.

Propagation and planting.

Bread wheat is propagated by seed. The 1000-seed weight is 30–50 g. It is advisable to use certified seed that has been treated with fungicides against soil- and seed-borne diseases, but this is rarely practised in tropical Africa. Wheat is sown by hand or machine. When broadcast, the seed is incorporated in the soil using an animal-drawn plough or machine-drawn disc. The seed may also be dibbled directly into a furrow behind a plough and covered, or machine-planted in rows. Common seed rates are 150–200 kg/ha for broadcasting and 75–120 kg/ha for row-planting. The optimum spacing is 10–25 cm between rows, but it may extend up to 35 cm. The sowing depth is 2–5(–12) cm, with deeper planting required in dry conditions. At a sowing depth beyond 10–12 cm seedling emergence is poor. When using a no-till planting machine, sowing can be done straight into the stubble of the previous crop. For rainfed wheat, the seed can be dry-sown, before the start of the rainy season, or when the soil is moist. Bread wheat is usually grown in sole cropping.

Management.

Uniform crop stand and early vigour discourage weed growth in bread wheat. In this respect tillering allows the crop to compensate for poor stands and variable weather conditions. Yield losses due to weeds are caused by early competition in the first 4–5 weeks. Hand weeding, tillage practices, stubble management, pre-sowing irrigation, proper crop rotation and herbicides may control weeds. Herbicide use in tropical Africa ranges from little to none in many countries (e.g. Sudan, Rwanda, Burundi, Madagascar) to almost complete coverage in Kenya, Tanzania, Zambia and Zimbabwe.

In tropical Africa bread wheat is produced mainly under rainfed conditions, except in Malawi, Zambia and Zimbabwe where it is grown as an irrigated (flood and sprinkler) ‘winter’ season crop. In Nigeria wheat production is restricted to the river basin irrigation schemes of its northern states. Irrigation has great potential to increase wheat production in Sudan and Somalia. Care must be taken not to over-irrigate since wheat is sensitive to early waterlogging. Irrigation timing is based either on pre-defined crop stages or on estimates of soil moisture depletion.

The mean nutrient removal per 1 t/ha of grain is 40–43 kg N, 5–8 kg P, 25–35 kg K, 2–4 kg S, 3–4 kg Ca, 3–3.5 kg Mg, and smaller amounts of micronutrients. The exact values depend on the available nutrients and water in the soil, the temperature, and the cultivar. Average fertilizer rates in tropical Africa range from 9 kg N and 10 kg P on rainfed wheat in Ethiopia to 180 kg N, 84 kg P and 50 kg K on irrigated wheat in Zimbabwe. Commercial fertilizer application ranges from less than 1% of the wheat area in Burundi to 100% in Kenya and Zimbabwe. Organic manure and compost are not commonly used on wheat, except in Rwanda. Boron deficiency, resulting in grain set failure, can be observed on certain soils;

boron is applied to irrigated wheat in Zambia, Zimbabwe and Madagascar. Copper is applied to most rainfed wheat in Kenya, and manganese is needed in certain areas of Tanzania. Soil acidity can be a constraint, e.g. in wheat production areas at lower elevations in Zambia. Liming might raise the pH, but its economic returns are poor for rainfed wheat. Wheat is best rotated with non-grass crops, particularly with pulses. In the highland areas of East Africa wheat is grown continuously or in rotation with other cereals, pulses or rapeseed (*Brassica* oilseed crops). In other regions double cropping systems are common, with irrigated wheat grown in the cool dry season and crops such as cotton, sorghum, maize, soya bean and groundnut in the hot rainy season. In Zimbabwe, for instance, double cropping of irrigated wheat and rainfed soya bean is widely adopted, with the same machinery for sowing and harvesting used for both crops.

In tropical Africa wheat is produced in farming systems ranging from small scale, labour-intensive, rainfed systems, e.g. in Kenya and southern Tanzania, to highly mechanized schemes and farms, e.g. in Nigeria, Sudan, northern and central Tanzania and Zimbabwe.

Diseases and pests.

Bread wheat is affected by several diseases and pests. In tropical Africa stripe rust or yellow rust (*Puccinia striiformis*), spread by air-borne uredospores, and Septoria blotches, particularly Septoria leaf blotch (*Septoria tritici*, synonym: *Mycosphaerella graminicola*), are the major diseases in the highlands. Stem rust or black rust (*Puccinia graminis*) can be very damaging in Ethiopia, Kenya and some parts of Sudan; like stripe rust it is spread by air-borne uredospores. Other diseases important in some years are common bunt (*Tilletia* spp.), loose smut (*Ustilago tritici*, synonym: *Ustilago nuda* f.sp. *tritici*), barley yellow dwarf virus (BYDV) and bacterial leaf streak or black chaff (*Xanthomonas translucens*). The use of resistant cultivars is the most effective control measure against these diseases. However, resistance breakdown is very frequent for stripe rust. Fungicide application to control stripe rust occurs in Kenya, Uganda and Tanzania.

The most important insect pests in tropical Africa are aphids, which may also transmit viruses. The African migratory locust (*Locusta migratoria*) is a periodic pest that causes crop damage in northern and eastern Ethiopia. The Hessian fly (*Mayetiola destructor*) has long been an important pest in regions adjacent to the Mediterranean Sea in northern Africa, southern Europe and western Asia. Pest control with commercial insecticides in tropical Africa is rare, except in Sudan, Zambia and Zimbabwe for aphids. Birds (especially *Quelea quelea*) are especially important in irrigated wheat.

Important storage insects, e.g. in Ethiopia, include *Sitophilus* spp. on whole grains, and *Tribolium* spp. and *Ephestia cautella* (synonym: *Cadra cautella*, flower moth) on wheat flour. Clean storage conditions and maintaining grain moisture and temperature at sufficiently low levels inhibit insect activity and development. Rodents, mainly the black rat (*Rattus rattus*), also damage stored seeds.

Yield.

Yields of bread wheat in tropical Africa vary from 400 kg/ha in Somalia and 700 kg/ha in Angola to 5 t/ha in Zambia and 6.3 t/ha in Zimbabwe. The mean yield of wheat in tropical

Africa is estimated at about 1.5 t/ha. Lower yields are due to high temperature, high humidity, disease pressure and the low levels of fertilizer applied. Maximum recorded grain yields of irrigated winter and spring wheats are 14 and 9.5 t/ha, respectively; the absolute maximum yield, based on genetic potential, is estimated at 20 t/ha.

Handling after harvest.

Threshed grain of bread wheat is winnowed, cleaned and prepared for store or market. Seeds should be dried to a moisture content of 13–14% for safe storage. High temperatures and moist conditions may result in spoilage. Regular re-drying may be necessary to maintain seed viability, if the seed is not stored in an airtight container.

Genetic resources and breeding.

The International Maize and Wheat Improvement Center (CIMMYT), Mexico City, Mexico (60,400 accessions) and the International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria (9700 accessions) maintain extensive germplasm collections of *Triticum aestivum*. Large germplasm collections are also held in the United States (USDA-ARS National Small Grains Germplasm Research Facility, Aberdeen, Idaho, 42,000 accessions), China (Institute of Crop Germplasm Resources (CAAS), Beijing, 35,900 accessions), and the Russian Federation (N.I. Vavilov All-Russian Scientific Research Institute of Plant Industry, St. Petersburg, 25,900 accessions). In tropical Africa the Institute of Biodiversity Conservation (Addis Ababa, Ethiopia) has the largest collection of bread wheat (3400 accessions). Wheat is a priority crop for collection and conservation. More collection needs to be done of its wild and weedy relatives in regions where they are native, of landraces in areas where they have not been collected before, and of new or obsolete improved cultivars with specific traits from breeding programmes around the world for future improvement work.

Breeding.

CIMMYT and ICARDA have large breeding programmes and, upon request, have the international mandate to disseminate bread wheat germplasm to national programmes. In tropical Africa, Ethiopia and Kenya have strong public sector breeding programmes. In Zimbabwe, there is private sector wheat research, and to some extent in Kenya and Zambia too. High grain yield and disease resistance, mainly to stripe rust and Septoria, are the major objectives. Major breeding methods used in tropical Africa are conventional. A number of high-yielding cultivars, mostly spring types derived from CIMMYT germplasm, have been released in tropical African countries. In 1995 their estimated usage ranged from 5% in Malawi to 100% in Zambia and Zimbabwe.

Bread wheat is one of the crops that benefited most from transfer of genes from other species, such as *Aegilops*, *Hordeum* and *Secale* spp., by artificial hybridization, mainly to increase resistance to diseases, especially rusts. Developments in molecular genetics and

genetic engineering of wheat have been slower than in cereals such as rice and maize, due to its ploidy level, size and complexity of its genome, the low level of polymorphism and relatively inefficient transformation systems. Consequently, far fewer maps exist in wheat and few QTL (quantitative trait loci) studies have been reported. On the other hand, the hexaploid nature of bread wheat and its amenity to cytogenetic manipulation have offered unique tools for molecular genetic studies. These include the uses of aneuploid stocks to assign molecular markers to specific chromosome arms, of chromosomal deletion stocks for physical mapping and of chromosome substitution lines to map genes of known chromosomal location. The development of improved chemical hybridizing agents, which allows breeders to surmount the problems associated with cytoplasmic male sterile systems, has considerably increased the progress towards the development of economically acceptable hybrid wheat cultivars. Recently, an efficient *Agrobacterium*-mediated transformation system has been developed for the large-scale production of transgenic wheat plants. Private companies have developed transgenic herbicide-resistant bread wheat cultivars, but these have not yet been produced commercially.

Prospects.

Since bread wheat is the most important food grain source for humans, the need to continuously increase its production cannot be overemphasized. Bread consumption from wheat in tropical Africa is low and varies from country to country; wheat consumption ranges from 2.5 kg/person/year in Uganda to 43.3 kg/person/year in Sudan. However, with the increasing trends of urbanization and income, there is likely to be a concomitant demand for traditional and new convenient, processed wheat-based products. No tropical African countries are 100% self-sufficient for wheat and the region is confronted by rapidly increasing wheat imports. In many of these countries wheat production is constrained by limited usage of high-yielding cultivars, fertilizer, other inputs and irrigation. Increases in wheat production may come from area expansion to non-traditional areas, coupled with social and economic incentives, and further increases in yield by agronomic research and breeding. Since the 1990s, area expansion of bread wheat has been observed in Sudan, Ethiopia, Kenya, Tanzania and Zambia. Research to improve wheat yields at a global scale includes further mixing of germplasm through wide hybridization and synthetic hexaploids, biotechnology tools, hybrid wheat, and basic studies on wheat physiology and host-plant relationships of various diseases and pests. Tolerances to drought, heat, aluminium soil acidity and waterlogging are some of the abiotic factors that require continued research attention.

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RICE (*Oryza sativa* L.)

Family

Poaceae (Gramineae)

Chromosome number

$2n = 12, 24, 36$

Origin and geographic distribution

Oryza sativa evolved in Asia, but the exact time and place of its domestication are not known for certain. Remains of rice in China have been dated to 6500 BC; the earliest archaeological evidence from India goes back to 2500 BC. *Oryza sativa* was brought from Asia into tropical Africa along different routes. Seamen-farmers began sailing from Indonesia to Madagascar probably a few centuries BC and started cultivating *Oryza sativa* there. Another important contact between Africa and Asia at the dawn of the Christian era was the trade route from Sri Lanka and India via Oman to Somalia and the islands Zanzibar and Kilwa off the coast of Tanzania. Most probably *Oryza sativa* migrated from Egypt, where it was introduced about 800–900 AD, to West Africa. The final penetration of *Oryza sativa* into Africa was along the slave trading routes from the East African coast and Zanzibar to DR Congo from about 1500 AD onwards. At the same

time *Oryza sativa* was introduced into Senegal, Guinea Bissau and Sierra Leone by the Portuguese on their return from expeditions to India. Nowadays it is cultivated throughout the humid tropics and in many subtropical and temperate areas with a frost-free period longer than 130 days

Uses

The rice grain is cooked by boiling or steaming, and eaten mostly with pulses, vegetables, fish or meat. Flour from rice is used for breakfast foods, baby foods, bread and cake mixes and cosmetics. Starch made from broken rice is used as laundry starch and in foods, cosmetics and textile manufacture. Beers, wines and spirits are made from rice.

The husk or hull is used as fuel, bedding, absorbent, packing material and as carrier for vitamins and drugs; it is also made into building board. The charred hull is used for filtration of impurities in water, a medium for hydroponics and manufacture of charcoal briquettes.

Rice bran or meal obtained in pearling and polishing is a valuable livestock and poultry feed. Oil is extracted from the bran. Crude rice bran oil is processed into solidified oil, stearic and oleic acids, glycerine and soap. Processed bran oil is used for cooking, antirust and anticorrosive agents, textile and leather finishers, and in medicine.

Rice straw is used for animal feed and bedding, for the manufacture of straw boards and pulp for paper, for the production of compost and mushroom growing medium, for mulching vegetable crops, for making ropes, sacks, mats and hats, for roof thatching, and to make plastering material (mixed with clay mud) for the construction of houses, and for incorporation into the soil or burning on the field as a way to maintain/improve soil fertility. Several traditional medicinal applications of rice have been reported from tropical Africa: leaf dressings are applied to ulcers and grain decoctions are drunk to treat diarrhoea, as a diuretic and as an emollient. Rice powder is applied against itch in Senegal. In DR Congo a decoction of the roots, leaves and husks is taken against madness and beriberi.

Production and international trade.

According to FAO estimates the average annual world production during 1999–2003 was 593 million t paddy (unhusked grain) from 153 million ha. Asia accounts for 90% of the world production and area. During 1999–2003 tropical Africa produced on average 11.9 million t paddy (2% of world production) annually on 7.7 million ha (5% of world area); these data include African rice (*Oryza glaberrima* Steud.), which occupies less than 20% of the rice area in West Africa. The main producers are Nigeria (3.5 million t from 2.9 million ha), Madagascar (2.6 million t from 1.2 million ha) and Côte d'Ivoire (1.1 million t from 0.5 million ha). The annual world paddy production increased steadily from 241 million t/year in 1961–1965 to 593 million t/year in 1999–2003, and the harvested area from 121 to 153 million ha. In the same period the annual paddy production in tropical Africa increased from 3.6 to 11.9 million t/year, and the harvested area from 2.8 to 7.7 million ha.

Only 5% of the world's rice production enters into international trade. Thailand is the world's largest exporter of milled rice (26% of world trade during 1998–2002) followed by Vietnam, India, the United States, China and Pakistan. All countries in tropical Africa are net importers of milled rice and during 1998–2002 an average of 4.8 million t milled rice was imported annually. This means that more than one third of the rice consumption in tropical Africa is satisfied through imports. Main rice importers are Nigeria, Senegal and

Côte d'Ivoire. Per capita annual milled rice consumption in tropical Africa varies tremendously between 0.15 kg and 95 kg with an average of about 18 kg for the period 1998–2002. In Madagascar, Sierra Leone and Guinea Bissau it is the main source of energy.

Properties.

Raw brown rice contains per 100 g edible portion: water 13.9 g, energy 1518 kJ (363 kcal), protein 6.7 g, fat 2.8 g, carbohydrate 81.3 g, dietary fibre 3.8 g, Ca 10 mg, Mg 110 mg, P 310 mg, Fe 1.4 mg, Zn 1.8 mg, thiamin 0.59 mg, riboflavin 0.07 mg, niacin 5.3 mg, vitamin B₆ 0.56 mg, folate 49 µg, ascorbic acid 0 mg. Raw polished rice contains per 100 g edible portion: water 11.7 g, energy 1536 kJ (367 kcal), protein 6.5 g, fat 1.0 g, carbohydrate 86.8 g, dietary fibre 2.2 g, Ca 4 mg, Mg 13 mg, P 100 mg, Fe 0.5 mg, Zn 1.3 mg, thiamin 0.08 mg, riboflavin 0.02 mg, niacin 1.5 mg, vitamin B₆ 0.30 mg, folate 20 µg, ascorbic acid 0 mg (Holland, Unwin & Buss, 1988). The essential amino acid composition of raw polished rice per 100 g edible portion is: tryptophan 87 mg, lysine 250 mg, methionine 140 mg, phenylalanine 330 mg, threonine 230 mg, valine 390 mg, leucine 560 mg and isoleucine 260 mg (Paul, Southgate & Russell, 1980). Milling and polishing result in a loss of protein, fat, minerals (phosphorus and potassium) and vitamins (thiamin, riboflavin and niacin).

However, these operations improve the storability and reduce the cooking time.

Rice grain endosperm may be waxy (glutinous) or non-waxy (non-glutinous) depending on the content of amylose and amylopectin. The higher the amylopectin content, the more glutinous the product is. The endosperm also contains sugar, fat, crude fibre, vitamins and inorganic matter. The flavour of rice is variable and aromatic rice cultivars are highly appreciated throughout the world. A major component of the flavour is 2-acetyl-1-pyrroline. Rice bran contains: water 9.9%, gross energy 1940 kJ (463 kcal) per 100 g, crude protein 13.8%, crude fibre 7.8%, ether extract 16.4%. After oil extraction, rice bran contains: water 9.8%, gross energy 1590 kJ (380 kcal) per 100 g, crude protein 14.4%, crude fibre 9.3%, ether extract 3.1%. The husk forms about 20% of the unhusked grain weight, and is very rich in silica. Rice straw contains approximately: water 7.0%, protein 3.4%, fat 0.9%, carbohydrate 47.8%, fibre 33.4% and ash 7.5%. It is nutritionally inferior to other cereal straws unless ensiled.

Rice straw is not particularly suitable for papermaking due to the high silica content (12–18%) and is used for this purpose mainly in countries where wood is scarce, e.g. in India and China. The ultimate fibre cells are (0.4–)1.4(–3.4) mm long and (4–)9(–16) µm wide.

Description.

Annual grass up to 1.8 m tall (up to 5 m long in some floating types), forming small tufts; roots fibrous, arising from the base of the shoots; stem (culm) erect or ascending from a geniculate base, terete, smooth, glabrous. Leaves alternate, simple; sheath coarsely striate, tight when young, later somewhat loose, often somewhat spongy, green or sometimes tinged with brown or purple, smooth, glabrous; ligule 1.5–3 cm long, triangular, acute, entire or split, membranous, usually glabrous; auricles often present, falcate, 1–5 mm long, hairy; blade linear, tapering to an acute point, 12–65 cm × 0.5–2 cm, bright green to glaucous, glabrous or puberulous, smooth on the lower surface, slightly rough on the upper surface,

midrib usually distinct. Inflorescence a terminal panicle up to 50 cm long, erect, curved or drooping, with 50–500 spikelets; branches solitary or clustered, nearly erect to spreading. Spikelet solitary, asymmetrically oblong to elliptical-oblong, 7–11 mm × 2.5–3.5 mm, with pedicel up to 4 mm long, 3-flowered but 2 lowest florets reduced to sterile lemmas 2–3 mm long; glumes small; lemma of fertile floret 6–10 mm long, boat-shaped, sometimes awned; palea about as long as lemma; lodicules 2; stamens 6; ovary superior, with 2 plumose stigmas. Fruit a caryopsis (grain), ovoid, ellipsoid or cylindrical, 5–7.5 mm × 2–3.5 mm, often whitish yellow or brown to brownish grey.

Other botanical information.

Oryza comprises about 20 wild species distributed throughout the tropics and subtropics, and 2 cultivated species, *Oryza sativa* and *Oryza glaberrima*. In the most recent classification *Oryza* has been divided into 3 sections: sect. *Padia*, sect. *Brachyantha* and sect. *Oryza*. Section *Oryza* is subdivided into 3 series: ser. *Latifoliae*, ser. *Australiensis* and ser. *Sativae*. *Oryza sativa* is classified in ser. *Sativae*, together with, among others, *Oryza glaberrima*, *Oryza barthii* A.Chev., and *Oryza longistaminata* A.Chev. & Roehr. *Oryza glaberrima* cultivars are grown only in Africa. Introgression of characters from *Oryza glaberrima*, *Oryza barthii* and *Oryza longistaminata* may have added new dimensions to the variability of *Oryza sativa*.

Cultivated rice *Oryza sativa* is supposed to have evolved from perennial types (*Oryza rufipogon* Griff.) to annual types (*Oryza nivara* S.D.Sharma & Shastri, sometimes included in *Oryza rufipogon*). There is a natural gene flow between these 3 species, and they form a large species complex together with weedy forms of rice (popularly called 'red rice' because of their red endosperm). There are 2 major eco-geographical cultivar groups of *Oryza sativa*: Indica Group, which mainly includes cultivars from the tropics, and Japonica Group, which includes cultivars from temperate/subtropical areas. Traditional cultivars from Indica Group are tall, leafy, strongly tillering, and prone to lodging; they respond poorly to fertilization, particularly to nitrogen, and are sensitive to photoperiod; they are hardy, resistant to disease and tolerate unfavourable growing conditions; they will produce fair yields under conditions of low management. Modern Japonica Group cultivars are small, and are less tillering, less leafy, resistant to lodging, insensitive to photoperiod and are early maturing. The characteristics of the two cultivar groups have become less distinct because of the interbreeding programmes in recent years. Rice may also be classified according to the conditions under which it is grown, according to the size, shape and texture of the grain, or according to the period needed to mature

Growth and development.

Rice seed germinates in 24–48 hours. The optimum temperature for germination is 30–32°C. Most cultivars have a short dormancy or none at all, but in some it may last up to 4 months. Ten days after germination the plant becomes independent as the seed

reserve is exhausted. Tillering begins thereafter, although it may be a week later in transplanted seedlings. In modern cultivars with an average maturation period, maximum tillering stage is attained around 45 days after transplanting and coincides with panicle initiation. The duration of the vegetative stage ranges from 7 to more than 120 days. The reproductive stage starts at panicle initiation, and the period from panicle initiation to flowering is around 35 days. Rice is almost 100% self-pollinating, but small amounts of cross pollination by wind do occur. It takes around 7 days to complete the anthesis of all spikelets in a panicle, starting from the top and progressing downwards. The period from flowering to full ripeness of all the grains in a panicle is usually about 30 days. Low temperature can delay maturity and high temperature accelerates it. Floating rice has a long maturation period of 7 months or more. Rice roots can grow under low oxygen concentrations. The roots are not typically aquatic as they are much branched and have a profusion of root hairs; later, spongy tissue (aerenchyma) develops in the cortex.

Ecology.

Rice is grown as far north as 53°N in Moho, northern China and as far south as 35°S in New South Wales, Australia. It grows on dry or flooded soil and at elevations ranging from sea level to at least 2400 m. The average temperature during the growing season varies from 20–38°C. Night temperatures below 15°C can cause spikelet sterility. Temperatures above 21°C at flowering are needed for anthesis and pollination. Upland rice requires an assured rainfall of at least 750 mm over a period of 3–4 months and does not tolerate desiccation. Lowland rice tends to be concentrated in flat lowlands, river basins and deltas. The average water requirement for irrigated rice is 1200 mm per crop or 200 mm of rainfall per month or an equivalent amount from irrigation. Relative humidity within the crop canopy is high, since there is standing water in most rice crops. A low relative humidity above the canopy during the dry season aggravated by strong winds can cause spikelet sterility. Traditional cultivars are generally photoperiod sensitive, and flower when daylengths are short (critical daylength of 12.5–14 hours). Many modern cultivars are photoperiod insensitive. The soils on which rice grows vary greatly: texture ranges from sand to clay, organic matter content from 1–50%, pH from 3–10, salt content up to 1%, and nutrient availability from acute deficiencies to surplus. Rice does best in fertile heavy soils. The optimum pH for flooded soil is 6.5–7.0. The often sandy texture of soils in tropical Africa is a constraint to productivity due to drought stress, low inherent soil fertility and leaching. Groundwater salinity problems occur in the dry Sahel zone where rice is grown under irrigation. In lowland coastal West Africa rice productivity is affected by saline water intrusion. The majority of mangrove swamp soils along the West African coast are furthermore potential or actual acid sulphate soils. In West Africa iron toxicity in valley bottoms is most severe in areas where the adjacent uplands are strongly leached Ultisols. Lowland rice and deep-water rice may be subjected to both drought or complete submergence. In submerged soil the pH tends to be neutral, i.e. the pH of acid soils increases whereas the pH of calcareous and sodic soils decreases. Ions of Fe, N and S are reduced, the supply and availability of the elements N, P, Si and Mo improve, whereas the concentration of water-soluble Zn and Cu decreases. Toxic reduction products such as methane, organic acids and hydrogen sulphide are formed. The flooding of rice soils also creates a favourable environment for anaerobic microbes and

the accompanying biochemical changes. As a result, the decomposition rate of organic matter decreases. However, a thin surface layer generally remains oxidized and sustains aerobic microbes

Propagation and planting.

Rice is propagated by seed. The 1000-seed weight is 20–35 g. The seed may either be broadcast or drilled directly in the field, or seedlings may be grown in nurseries and transplanted. Direct seeding is done in dry or puddled soil. In puddled soil the (pre-germinated) seeds are broadcast. After sowing the water level is kept at 0–5 cm under tropical conditions. In dry soil the seeds are sown just before or after land preparation. In the latter case the seeds are then covered lightly with soil. The seeds are sown just before the rains begin and germination occurs after heavy continuous rains. This method makes it possible to have initial crop growth from early rains.

In tropical Africa various rice-growing systems are distinguished:

- Upland rice, which may be subdivided into dryland rice, whereby moisture supply is entirely dependent on rainfall, and hydromorphic rice where the rooting zone is periodically saturated by a fluctuating water table, in addition to rainfall;
- Lowland rice, including mangrove swamp rice along the coastal regions with tidal intrusion, inland swamp rice on flat or V-shaped valley bottoms with varying degrees of flooding, and rice on banded fields under rainfed or irrigated conditions;
- Deepwater rice, in which the rapid growth of the internodes keeps pace with the rising water up to 5 m or more, starting from 50 cm of standing water.

In upland rice cultivation the fields are normally cleared through the slash-and-burn practice. Soil preparation is normally minimal. The rice is broadcast or dibbled when the rains start. It is often grown as the first crop in rotation or intercropped with other crops such as cassava, maize, sorghum, cowpea, groundnut and other pulse crops.

In lowland rainfed-rice areas the land is mostly prepared while it is wet and only in rare occasions when it is dry. The wetland tillage method consists of soaking the land until the soil is saturated, ploughing to a depth of 10–20 cm using a plough drawn by oxen/small machines or by using a hand hoe, preferably when there is a little water on the land, and harrowing, during which big clods of soil are broken and puddled with water. The important benefits of puddling include the apparent reduction of moisture loss by percolation, better weed control, and easy transplanting. In lowland rice cultivation seedlings are mostly raised on wet nursery beds and sometimes on dry nursery beds. Wet nursery beds are made in the puddled or wet field. Normally farmers use 50–60 kg of rice seeds to plant one ha. Seeds are pre-germinated and spread on the bed which is kept constantly wet. Dry nursery beds are prepared near the water source before land preparation. The seeds are sown and then covered with a thin layer of soil and watered until saturation for uniform germination.

Further watering is applied as needed. In both cases the seedlings are ready for transplanting 20–35 days after sowing. At transplanting heavy tillering cultivars in fertile valley bottoms are wider spaced (30 cm × 30 cm) than slightly tillering cultivars in upper, sandy fields (20 cm × 20 cm). The spacing in irrigated rice is normally 20 cm × 20 cm with 2–4 plants per hill (500, 000–1,000,000 plants/ha). Rice is generally a sole crop under lowland conditions. Near harvest, relay planting is rarely practised. In many parts of the tropics 2 or even 3 crops of rice can be grown per year. There is a lack of accurate data on the extent of

different rice systems in tropical Africa. The upland rice ecosystem, including hydromorphic rice, accounts for an estimated 50% of the total rice area in tropical Africa; lowland rice cultivation, including mangrove swamp rice, inland swamp rice and irrigated rice, accounts for 45% of the total rice area; deep-water rice cultivation occupies the remaining 5%. Most rice is grown on smallholdings of 0.5–2 ha

Management

The agronomy of rice is diverse due to the differences in cultivation systems. Growing of upland rice is usually relatively labour-extensive, but transplanting rice by hand in puddled soil is a labour-intensive operation. Weeding is generally not necessary in the first 2 weeks. Manual weeding is common practice, although chemical weed control is also becoming popular in tropical Africa, especially in irrigated rice areas. Three timely weedings are normally necessary in broadcast rice.

In the cultivation of lowland rice, the land is inundated from the time of planting until the approach of harvest. The water is supplied either by flooding during the rainy season, by growing the crop in naturally swampy land or by controlled irrigation. The water level is kept at a height of 5–15 cm to suppress weed growth and to ensure water availability. Continuous flooding at a static 2.5–7.5 cm depth is best. The fields may be drained temporarily to facilitate weeding and fertilizing. At flowering the water level is gradually reduced until the field is almost dry at harvest. Generally 1.5–2 m of water (rainfall plus irrigation) are required to produce a good crop. The period in which rice is most sensitive to water shortage is from 20 days before to 10 days after the beginning of flowering.

Fertilizer application is limited in rice cultivation in tropical Africa. Only in irrigated rice with controlled water supply and modern cultivars do farmers generally use significant amounts of mineral fertilizers. The amount of fertilizer used is usually 60–120 kg N, 10–20 kg P and 0–30 kg K per ha. Higher nitrogen rates are used during the dry season when solar radiation is higher and increase in grain yield is larger. Generally, nitrogen fertilizer is only topdressed, mostly before or at panicle initiation. Fertilizer is broadcast by hand. The most common mineral deficiencies in rice cultivation are of nitrogen and phosphorus, with potassium and sulphur in limited areas and sometimes zinc and silicon on peaty soils. Deficiency of potassium is often associated with iron toxicity. Upland rice often suffers from sulphur deficiency. Zinc deficiency occurs regularly in rice areas because of the high pH and strong reduction of the soil. Influenced by reduction and poor internal drainage, several toxic elements such as iron, which inhibit the uptake of phosphorus in the plant, may accumulate in the environment of the root. Often a harmful excess of elements such as calcium is accompanied by a lack of other elements such as phosphorus, iron and zinc. Double cropping is inadvisable where physiological diseases occur. Green manure and *Azolla* are rarely used in tropical Africa. However, the fast growing and actively nitrogen-fixing *Sesbania rostrata* Bremek. & Oberm. is a promising green manure crop. Nitrogen fixation also takes place in paddy soils by *Azotobacter* and blue green algae (cyanobacteria). Organic fertilizers such as farmyard manure and compost are not commonly applied to rice crops in tropical Africa. Although soil conditions are normally improved by incorporating organic fertilizers, the result is not immediately apparent. Poor availability, transport problems and the high amount of labour involved also discourage its

use.

The degree of mechanization is in general limited in rice cultivation in tropical Africa. Occasionally farmers use tractors or small two-wheel power tillers for land preparation and powered threshing machines during harvest.

For various reasons many rice fields are left fallow in the dry season. In areas with suitable climatic and soil conditions for dry-season cultivation, rice may be rotated with crops such as other cereals, pulses and vegetables.

Diseases and pests.

The most common and severe disease of rice in tropical Africa is blast (*Pyricularia grisea*, synonym: *Pyricularia oryzae*). Although this disease is often related to drought stress and therefore especially severe in upland and drought-prone areas, it may also be severe elsewhere. Low light intensity, nutritional imbalances (especially K-deficiency), excessive N-supply, and relatively low temperatures (20–28°C) are further factors favouring this disease. The blast fungus can infect rice leaves, nodes and floral parts, particularly the basal part of the panicle. Other important diseases of rice in tropical Africa are bacterial leaf blight (*Xanthomonas oryzae* pv. *oryzae*), rice yellow mottle virus (RYMV, only found in Africa), brown spot (*Cochliobolus miyabeanus*), leaf scald (*Microdochium oryzae*), sheath blight (*Thanatephorus cucumeris*), narrow brown leaf spot (*Cercospora janseana*) and sheath rot caused by *Sarocladium oryzae*. The use of resistant cultivars, the judicious application of N fertilizer, adjusted planting time, crop rotation and phytosanitary and quarantine measures limit losses from rice diseases. Chemical control for blast and other rice diseases is hardly used in tropical Africa.

Nematodes attack roots and young, unfurled leaves and reduce rice production in certain parts of tropical Africa. Most insect species causing damage to rice in the field and to the grain during storage in tropical Africa are indigenous, and different from those found in Asia. Internal stem feeders such as stem borers, the stalk-eyed fly and gall midge generally cause the most severe damage. The most common species of stem borers in tropical Africa are white stem borer (*Maliarpha separata*), pink stem borers (*Sesamia* spp.) and striped stem borer (*Chilo* spp.). Damage results from larvae feeding within the stem, severing the vascular system. Dead heart is the damage to the tiller before flowering. White head is the damage after flowering which causes the entire panicle to dry. The damage from the stalk-eyed fly (mainly *Diopsis macrophthalma*) resembles the dead heart damage from stem borers as it generally attacks the rice plant at the early tillering stage. The feeding of the gall midge maggot (*Orseolia oryzivora*) stimulates the leaf sheath to grow into a gall and tillers with galls do not bear panicles. Termites and mole crickets attack rice plants especially in rainfed upland rice.

The most serious insect pests of stored rice are the rice weevil (*Sitophilus oryzae*) and the lesser grain borer (*Rhyzopertha dominica*). These insects can completely destroy the grain. Insects can be controlled by chemical, cultural, and biological methods. In tropical Africa farmers use insecticides but at far lower levels than in Asia. It is important to use various crop protection methods in an integrated pest management (IPM) system for rice in tropical Africa that is sustainable, inexpensive, and environmentally safe. It should combine the use of resistant cultivars, cultural methods, biological control and, finally, chemical control when pest damage threatens to exceed the economic injury threshold. Cultural methods

include sanitation (the destruction of crop residues, of alternative hosts including weeds and of habitats), tillage and flooding of fields, crop rotation, intercropping, proper timing of planting and harvest, use of trap crops, and proper fertilizer and water management. Birds eat broadcast seeds, disturb young transplanted seedlings and eat rice grains; losses can be very high. Rodents attack rice at all stages of growth and also stored grain, and losses due to rodents are often serious. Less damage is caused by snails, crabs and shrimps. Parasitic weeds of the genus *Striga* may cause serious losses in upland rice, e.g. *Striga aspera* (Willd.) Benth. and *Striga hermonthica* (Delile) Benth. in West Africa, and *Striga asiatica* (L.) Kuntze in the Indian Ocean Islands.

Harvesting.

Grain should be harvested before it is fully mature (around 21–24% moisture), usually about 30 days after flowering, or when 90% of the grains are firm and do not have a greenish tint. Wetting and drying cause grain cracking, cracks being formed more readily when the grain is quite hard. Harvesting by hand, the commonest method, is very labour-intensive. In some areas a small knife is used, but in many areas farmers use a sickle to cut the panicles plus some or all of the culms. Mechanical harvesters are very rare in tropical Africa. The harvested rice plants are either allowed to dry in the field or bundled for processing in a selected area.

Yield

Average rice yields are 1.4 t/ha in tropical Africa, 4.1 t/ha in Asia and 4.0 t/ha in the world in general. Yields are generally higher during the dry season than during the wet season, and higher in lowland rice than in upland rice. The yield of upland rice varies between 0.5 and 1.5 t/ha in tropical Africa but may reach 4 t/ha in Latin America. Rainfed lowland rice is higher yielding than upland rice but may suffer a drastic reduction in years with drought or floods. In a rainfed bunded lowland rice area in Tanzania yields are 3–4 t/ha in good years, but can drop to 0.5 t/ha in bad years. Yields of irrigated lowland rice in tropical Africa are generally 3–6 t/ha. Yields in the deep-water rice areas are generally low (0.6–1.2 t/ha), but they are more stable than in the upland rice areas of tropical Africa.

Handling after harvest

Threshing is generally done by hand, by beating the bundles on a stone or drum, or by beating the panicles with wooden sticks on a canvas. However, motorized and pedal-driven threshing machines are becoming popular. Winnowing is usually done by shaking and tossing the grain on a basket-work tray with a narrow rim. Sometimes hand-winnowing machines are used. After winnowing, the grain is dried in the sun and is then ready for hulling or transport to the mill. Proper drying of the rice grains is important to prevent germination and rapid loss of quality. Optimum moisture content for storage is 12.5%. Rice grain is mostly stored in sacks after drying. Increase in fat acidity during improper storage reduces the eating quality. Temperature and humidity during storage affect rice quality. Rice for home consumption is stored unhusked, as it is less susceptible to deterioration.

In rice milling the aim is to avoid breaking the kernels because whole kernels command a higher price. There are different methods of milling. On milling, the grain gives approximately: husk 20%, whole kernels 50%, broken kernels 16%, bran and meal 14%. The husked or hulled rice is usually called brown rice, and this is then milled to remove the outer layers, after which it is polished to produce white rice. During milling and polishing some of the protein and much of the fat, minerals and vitamins are removed, reducing the nutritional value but increasing storability and reducing cooking time. Parboiling (soaking, boiling and drying) before milling improves the nutrient value of the grains but it is not common in tropical Africa.

Genetic resources and breeding

The exploration and collection of germplasm of African wild and cultivated rice species was started in 1959 by Japanese researchers who were attracted by the great diversity. The earliest collections of rice genetic resources in West Africa were built up at research stations at Rokupr, Sierra Leone and Badeggi, Nigeria. Later on the French research institutes ORSTOM and IRAT started collecting rice germplasm from francophone countries and IITA, Ibadan, Nigeria, from mainly anglophone countries. A combination of these germplasm collections with almost 15,000 accessions was then established by WARDA at Bouaké, Côte d'Ivoire. Most of these accessions are also available in the International Rice Germplasm Collection at the International Rice Research Institute (IRRI), Los Baños, the Philippines where the largest *Oryza sativa* collection is found with more than 86,000 accessions, characterized on the basis of about 80 traits. These traits not only include morphological characters but also susceptibility to diseases and pests, and reaction to environmental stresses, mineral deficiencies or toxicities. Large germplasm collections of *Oryza sativa* are also held in China (China National Rice Research Institute, Huangzhou, 70,000 accessions) and India (National Bureau of Plant Genetic Resources, New Delhi, 26,000 accessions). Apart from at WARDA, in tropical Africa large collections are present in Nigeria (International Institute of Tropical Agriculture (IITA), Ibadan, 9400 accessions; National Cereals Research Institute, Badeggi, 3500 accessions) and Madagascar (Département de Recherches Agronomiques de la République Malgache, Antananarivo, 2000 accessions). Collection of wild rices is being emphasized for possible new sources of important genes.

Breeding

Rice grain yields in the tropics have increased dramatically since the mid 1960s with the introduction of 'IR8' and other semi-dwarf cultivars, which do not lodge easily and allow high nitrogen fertilizer doses. In tropical Africa these green revolution cultivars are mainly used in irrigated rice with controlled water supply. Genetic improvement of rice in Africa was mainly focused on the upland crop. This has led to the 'New Rice for Africa' ('NERICA') cultivars, WARDA's major breakthrough in the early 1990s. 'NERICA' cultivars were the result of successful crossing of *Oryza glaberrima* with *Oryza sativa*. They combined higher tolerance to deep water, drought, weeds, blast and stalk-eyed fly

from *Oryza glaberrima* with greater grain productivity and retention on the plant from *Oryza sativa*. 'NERICA' cultivars are proving to be popular with farmers, not only because of their growth characteristics, but also for their grain quality and nutritive value. They are further well suited to low-input conditions. Breeding activities of WARDA on lowland cultivars have led to the release of cultivars with improved grain yield, resistance to blast and rice yellow mottle virus and tolerance to drought and iron toxicity. The improved cultivar 'Sahel 108', released in 1994 by WARDA, has a short life cycle enabling double-cropping in the irrigated rice systems in the Sahel. Wild *Oryza* species, such as *Oryza barthii*, *Oryza longistaminata* and *Oryza punctata* are useful sources of resistance to various biotic and abiotic stresses. For instance, resistance to bacterial leaf blight has successfully been transferred from *Oryza longistaminata*.

Biotechnology techniques used in rice breeding include plant tissue culture, molecular biology and genetic engineering. Two tissue culture techniques, embryo rescue and anther culture, have already made important contributions. Saturated genetic linkage maps based on molecular markers have been developed for rice, using crosses between cultivars of Indica Group and Japonica Group, or between *Oryza sativa* and *Oryza longistaminata*. These maps have made possible the identification of QTLs for many useful traits, such as resistance to diseases and tolerance to drought. More than 3000 molecular markers are available now, making rice the best characterized crop. The project for sequencing the complete rice genome has recently been completed. Biotechnology's most novel contribution will probably be in adding alien genes to the rice gene pool through genetic engineering. One example is 'Golden Rice', which is rice enriched with vitamin A. It is, however, still not clear if this genetically modified rice will yield well, not be susceptible to diseases and pests and be palatable. Several insecticidal toxin genes from *Bacillus thuringiensis* (Bt) have been transferred to rice and plants containing Bt genes have shown substantial resistance to stem borers and leaf folders. Recently, transgenic rice has been obtained conferring resistance to sheath blight. Genetic engineering is a relatively new technology and one of the principal biosafety concerns is the spread of foreign genes by pollen dispersal from transgenic rice to other rice cultivars and wild rice species.

Prospects

At present, only an estimated 2% of the 200 million ha of wetlands in tropical Africa are used for lowland rice cultivation. Therefore one of the biggest challenges for rice development in tropical Africa is the utilization of the large potential for expansion of lowland rice. The emphasis of genetic improvement should be directed to lowland rice ecosystems, which have a higher production potential than upland rice, for example the breeding of crosses of *Oryza sativa* and *Oryza glaberrima* for lowland rice ecosystems. Any new types recommended should be well adapted to the local environment and methods of cultivation. For that matter it is advisable that in the breeding process greater use is made of farmer participatory varietal selection (PVS) and farmer participatory plant breeding (PPB). Breeding activities for tropical Africa should include tolerance of and adaptation to iron toxicity, salinity, alkalinity, acid sulphate soils, and relatively extreme cool and hot temperatures. In tropical Africa there is still much room for increased and integrated use of organic and mineral fertilizers with a higher efficiency and greater use of nitrogen-fixing

legumes, bacteria and blue-green algae. The applicability of methods of integrated soil fertility management (ISFM) in a certain locality can be best tested through farmer field schools. An increased use of farmer field schools is also advocated for the adoption of methods of integrated pest management (IPM) by more rice farming households in tropical Africa. Further improvements are expected from mechanization of rice farming, especially regarding land preparation, weeding, harvesting, threshing and further processing. All these suggestions require research adjusted to the local conditions, a well-functioning extension service, government support, and active participation of farming households. Some of the above topics are already being researched.

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MAIZE (*Zea mays* L.)

Family

Poaceae (Gramineae)

Chromosome number

$$2n = 20$$

Origin and geographic distribution

Maize was domesticated in southern Mexico around 4000 BC. Early civilizations of the Americas depended on maize cultivation. When the Europeans arrived in the Americas, maize had already spread from Chile to Canada. Maize was reported for the first time in West Africa in 1498, six years after Columbus discovered the West Indies. The Portuguese brought floury grain types from Central and South America to São Tomé, from where they spread to the West African coast. Portuguese and Arab traders introduced Caribbean flint maize types into East Africa in the mid 1500s, from where they spread to southern Africa. Through the trans-Saharan trade, the Arabs introduced the flinty types that had been brought to northern Africa into sub-Saharan Africa. The flinty types still predominate in northern parts of West Africa while the floury types prevail in the southern parts, with some variation from this pattern. Maize had become a staple food in East and southern Africa by the 1930s. Maize has an extremely wide distribution. It is grown from latitude 58°N in Canada and Russia, throughout the tropics, to latitude 42°S in New Zealand and South America, and in areas below sea level in the Caspian Plain up to areas as high as 3800 m in Bolivia and Peru. It is grown in all countries of Africa, from the coast through savanna regions to the semi-arid regions of West Africa, and from sea-level to the mid- and high-altitudes of East and Central Africa.

Uses

Maize grain is used for three main purposes: as a staple food, as feed for livestock and poultry, and as a raw material for many industrial products. In tropical Africa nearly all maize grain is used for human food, prepared and consumed in many ways. It may be eaten fresh on the cob and simply roasted, but the grain is usually ground and the meal is boiled into porridge or fermented into beer. In tropical Africa maize is mainly consumed as thick porridge ('ugali' in East Africa, 'sadza' in Zimbabwe). It is commonly eaten with cooked vegetables and, when available, meat. A thin porridge ('uji' in East Africa, 'ogi' in Nigeria, 'koko' in Ghana) is also commonly eaten especially as weaning food. In Ethiopia local beer ('tella') and spiritual liquor ('arakie') are prepared from maize grain malt. Popcorn is a popular snack.

The main industrial products obtained from maize are breakfast products such as cornflakes, starch, sugar and oil. The main product is starch that is used for human consumption or made into syrup, alcohol, but also among others as laundry starch and as a source material for many chemical products. Most industrial products are obtained by the wet-milling process, in which the grain is first steeped in water, after which the germ and bran are separated from the endosperm. The various products are subsequently obtained by physical or chemical processes, and e.g. sugars from maize now account for half of the sugars used in human nutrition. Dry milling produces grits, consisting of coarsely ground endosperm from which most of the bran and the germ have been separated. The germ yields an oil that can be refined for human consumption, widely used as cooking or salad oil and in margarines. It is

the second most widely consumed vegetable oil in the United States and is also made into soap or glycerine. The residues from the production of starch or oil, together with the bran, are used in animal feeds (corn gluten meal and corn gluten feed).

Unripe cobs are consumed as vegetable or green maize, boiled or roasted. Very young female inflorescences ('baby cobs') are a fancy vegetable in Western countries and in Asia. Mature maize plants are used for animal feed. Silage maize is one of the leading crops in industrialized Western countries, where special cultivars and production technologies have been developed. The stalks are used for fuel, fodder and thatching and as compost. The fibre in the stems and the inner leaves surrounding the cob are made into paper. These cob leaves are often used to wrap foods, and may also be made into cloth or mats, and be used for mattress filling. Ash of the burnt stem is sometimes a substitute for salt. The cob is made into pipe-bowls. In southern Africa the incinerated cob is included in a snuff.

Maize has a range of uses in traditional African medicine. Urino-genital problems are treated with prescriptions based on the whole or parts of the maize plant, especially a decoction of the styles, which is also used to treat jaundice. A leaf maceration is drunk to treat fever. Charcoal made from the culms is included in medicines to treat gonorrhoea; an infusion from the burnt cob is used to wash wounds.

Properties

The composition of mature white maize grain per 100 g edible portion is: water 10.4 g, energy 1527 kJ (365 kcal), protein 9.4 g, fat 4.7 g, carbohydrate 74.3 g, dietary fibre 7.3 g, Ca 7 mg, Mg 127 mg, P 210 mg, Fe 2.7 mg, Zn 2.2 mg, thiamin 0.39 mg, riboflavin 0.20 mg, niacin 3.6 mg, vitamin B₆ 0.62 mg, folate 19 µg and ascorbic acid 0 mg. The essential amino-acid composition per 100 g edible portion is: tryptophan 67 mg, lysine 265 mg, methionine 197 mg, phenylalanine 463 mg, threonine 354 mg, valine 477 mg, leucine 1155 mg and isoleucine 337 mg. The principal fatty acids per 100 g edible portion are: linoleic acid 2097 mg, oleic acid 1247 mg and palmitic acid 569 mg (USDA, 2004). Maize is deficient in tryptophan and lysine, but cultivars with higher content of these amino acids have been bred using the recessive gene Opaque-2 with modifiers. These cultivars are referred to as Quality Protein Maize (QPM). In general 100 kg of whole maize, with 16% moisture content, yields about 64 kg starch and 3 kg oil. The endosperm, which accounts for 80% of the weight of the grain, is poor in phosphorus and calcium and contains most of the starch and two-thirds of the protein. More than 80% of the fat and most minerals are in the embryo or germ, which constitutes about 12% of the grain. The starch of the endosperm usually consists of a mixture of about 75% amylopectin and 25% amylose, but waxy maize contains only amylopectin. The most common grain colours are yellow and white. Yellow maize predominates in the United States, China and Brazil, whereas white maize predominates in tropical Africa, Central America and the northern part of South America. White maize has harder grain and gives sweeter, more flavourful products; it is primarily grown for food, whereas yellow maize is mainly used as animal feed. Yellow maize contains the provitamin A cryptoxanthin. Most vitamins are found in the outer layers of the endosperm and in the aleurone layer. Maize is deficient in gluten and therefore unsuitable for making leavened bread; it is tolerated by patients with coeliac disease. Maize oil is considered a premium oil for human consumption, due to its flavour, colour and stability and the presence of linoleic acid and vitamin E.

Maize grain in tropical Africa often contains mycotoxins such as aflatoxins and fumosinins, which are harmful to humans and livestock. Aflatoxins are produced by *Aspergillus* spp., especially *Aspergillus flavus*; they are powerful carcinogens, especially affecting the liver, and have immunosuppressive properties. Fumosinins are produced by *Fusarium* spp., especially *Fusarium verticillioides*; they have been implicated in various animal diseases. Human health risks due to fumosinins are possible, but so far there is no conclusive evidence, although correlation studies have suggested a link between consumption of maize with fumosinins and high incidence of human oesophageal carcinoma.

Description

Robust annual grass up to 4(–6) m tall; root system consisting of adventitious roots, developing from the lower nodes of the stem near the soil surface, usually limited to the upper 75 cm of the soil, but single roots sometimes penetrating to a depth of over 2 m; stem (culm) usually single and simple, solid. Leaves alternate, simple; leaf sheaths overlapping, auricled at the top; ligule c. 5 mm long, colourless; blade linear-lanceolate, 30–150 cm × 5–15 cm, acuminate, margins smooth, midrib pronounced. Male and female inflorescences separate on the same plant; male inflorescence ('tassel') a terminal panicle up to 40 cm long, lateral branches with paired spikelets 8–13 mm long, one sessile, the other on a short pedicel, each spikelet with 2 glumes and 2 florets, each floret with an ovate lemma, a thin palea, 2 fleshy lodicules and 3 stamens; female inflorescence a modified spike, usually 1–3 per plant in leaf axils about half way up the stem, composed of a thick spongy axis with paired sessile spikelets in 8–20 longitudinal rows and enclosed by 8–13 modified leaves (spathes), spikelet with 2 glumes and 2 florets, lower floret sterile, consisting solely of a short lemma and palea, upper floret with a short, broad lemma and palea, a single superior ovary and a long threadlike style and stigma ('silk') up to 45 cm in length and emerging from the top of the inflorescence, receptive throughout most of its length. Fruit a caryopsis (grain), usually obovate and wedge-shaped, variously coloured from white, through yellow, red and purple to almost black, up to 1000 together in an infructescence ('cob') enclosed by modified leaves up to 45 cm × 8 cm.

Other botanical information

ZEA comprises 5 species, including cultivated *ZEA mays* and 4 wild relatives, all from tropical America and called teosintes. *ZEA mays* is a heterogeneous species and cultivars can be divided into 8 types (or cultivar groups) according to the structure and shape of the grain:

- Dent maize: the sides of the grain have corneous endosperm, but the inside has soft white starch, extending to the apex, shrinking on drying to produce the characteristic dent, the wedge-shaped grains are usually yellow or white; it is the principal maize in the United States and northern Mexico;
- Flint maize: the grain can be coloured variously and consists mainly of hard endosperm with a little soft starch in the centre, it has rounded ends and is generally smaller than the grain of dent maize, it matures earlier, is harder, and when dry it is more resistant to insect

attack; it is the predominant type grown in Europe, Asia, Central and South America and parts of tropical Africa;

- Flint-dent maize: this group resulted from hybridization between flint and dent maize, and has intermediate characteristics; it appeared first in the United States at the end of the 18th century, and spread to Europe in the 20th century, where it is widely cultivated;

- Pod maize: this is the most primitive type of maize in which the grain is enclosed in bracts; it is not grown commercially;

- Pop maize or popcorn: it has small grains with a high proportion of very hard corneous endosperm and a little soft starch in the centre; on heating the steam generated inside the grain causes it to pop and explode, the endosperm becoming everted about the embryo and hull to produce a palatable white fluffy mass ('popcorn'); in 'rice popcorn' cultivars the grains are pointed and in 'pearl popcorn' cultivars rounded; popcorn is most important in the United States and Mexico, but has also become a popular snack in tropical Africa;

- Flour maize or soft maize: the grain can have all types of colours, it usually has no dent and the endosperm consists of soft starch, when parched it can be chewed more easily than flint maize and it is also easier to grind, but it is susceptible to mould and breakage during handling; it is one of the oldest maize types and was widely grown in the drier parts of the United States, western South America and South Africa, and it is still widely grown in the Andes and small amounts are grown in the United States; people in the southern parts of West Africa relish flour maize;

- Sweet maize: the grain contains glossy endosperm with little starch, giving a wrinkled appearance after drying, and it is usually eaten in the immature state as a fresh vegetable; it is mostly grown in the United States, but has become popular among the elites in African countries;

- Waxy maize: the starch is composed entirely of amylopectin and is used for the manufacture of adhesives; it is mainly grown in eastern Asia for human consumption, but also in the West for industrial applications..

Within the various grain types, there are many cultivars grown in different parts of the world.

Growth and development

The first leaf of maize emerges from the soil usually 4–6 days after planting. The minimum temperature for germination is 10°C; the optimum around 20°C. The plant sometimes has a few tillers that are of value in low density stands. At a later stage some whorls of aerial roots ('brace roots') may develop from the lower nodes above the ground which partly help to anchor the plant while also contributing to the uptake of water and nutrients. Flower initiation is generally 20–30 days after germination. Maize is protandrous: in cultivars that mature in 4 months the male inflorescence emerges 50–60 days after planting and the styles of the female inflorescence appear about a week later. Maize is mature 7–8 weeks after flowering. The period from planting to harvesting varies considerably. It may be as short as 70 days in some extra early cultivars and as long as 200 days in some very late cultivars. Climatic conditions, latitude and altitude influence growth duration. In tropical highland areas it may take 9–10 months to maturity. Maize is predominantly cross-pollinating (90–95%), but is self-fertile. Maize follows the C₄-cycle photosynthetic pathway.

Ecology

Maize is adapted to a wide range of environments, but it is essentially a crop of warm regions where moisture is adequate. The bulk of the crop is grown in tropical and subtropical regions. In West and Central Africa the Guinea savanna zone offers the best ecological conditions for maize. The mid-altitude regions of East and southern Africa are also suitable for maize production. In Ethiopia, for instance, maize is mainly grown at 1000–2400 m altitude. Maize is generally less suited to semi-arid or equatorial climates, although drought-tolerant cultivars adapted to semi-arid conditions are now available. The crop requires an average daily temperature of at least 20°C for adequate growth and development; the optimum temperature for growth and development is 25–30°C; temperatures above 35° reduce yields. Frost is not tolerated. Maize requires abundant sunlight for optimum yields. The time of flowering is influenced by photoperiod and temperature; maize is considered a quantitative short-day plant. Maize is less drought-resistant than sorghum, pearl millet and finger millet. In the tropics it does best with 600–900 mm well-distributed rainfall during the growing season. It is especially sensitive to drought and high temperatures around the time of flowering. Maize can be grown on a wide range of soils, but performs best on well-drained, well-aerated, deep soils containing adequate organic matter and well supplied with nutrients. The high yield of maize is a heavy drain on soil nutrients and maize is therefore often grown as a first crop in the rotation. It can be grown on soils with a pH of 5–8, but 5.5–7 is optimal. It does not tolerate waterlogging and is sensitive to salinity. Since a young crop leaves much of the ground uncovered, soil erosion and water losses can be severe and attention should be paid to adequate soil and water

Propagation and planting

Maize is propagated by seed and direct sowing is common. The 1000-grain weight is 150–300 g. Sowing should preferably be done early in the season, as soon as soil conditions and temperature are favourable and the rainfall is well established. Smallholders plant maize by hand while mechanical planting is practised on large commercial farms. Planting by hand requires 5–10 man-days/ha. Seed is dropped in the plough furrow or in holes made with a planting stick or hoe. Planting may be done on hills or in rows, on flat land or on ridges. Ridging or heaping is usually done on heavy soils, to improve drainage. The seed rate is up to 25 kg/ha in sole cropping, and 10–15 kg/ha in intercropping. When maize is sown in rows, the spacing is usually 75–90 cm between rows and 25–50 cm within the row, with 1–3 seeds per pocket, resulting in a plant density of 40,000–80,000 plants/ha. Wide spacing results in more weed growth and increases erosion. To obtain a high yield, a uniform crop stand is very important, as the tillering capacity of maize is limited. The sowing depth is commonly 3–8 cm, depending on soil conditions and temperature. Deep sowing is recommended on light, dry soils. On smallholdings the land is usually cultivated by hand or by animal traction. The usual depth of ploughing is 8–10 cm and ploughing is done just before or at planting time. Sometimes animal manure or fertilizers are applied at the time of planting.

Maize may be grown as a sole crop or in intercropping with other food crops such as

common bean, cowpea, pigeon pea, groundnut, yam, cassava, sweet potato, pumpkin, melon or watermelon. In some parts of tropical Africa two crops of maize are planted per year. In areas where the rainy season is shorter, the crop is planted only once, although a second planting is possible under irrigation, on residual moisture on heavy soils or on hydromorphic soils.

Management

Maize is very sensitive to weed competition during the first 4–6 weeks after emergence, and weed control is very important. The crop should be planted as soon as possible after the preparation of the seed-bed. Interrow cultivation to control weeds and to break up a crusted soil surface may be done until the plants reach a height of about 1 m. Weeding is mostly done by hand, requiring at least 25 man-days/ha. Chemical weed control is gaining importance in tropical Africa, because hand weeding is time-consuming and expensive as a result of the increasing scarcity of labour. Ridging or earthing-up is sometimes practised. Most maize production in tropical Africa is rainfed. Occasionally it is grown on bunds in irrigation schemes. Maize usually responds well to fertilizers. A maize crop yielding 2 t grain and 5 t stover per ha removes about 60 kg N, 10 kg P and 70 kg K per ha from the soil. Nitrogen uptake is slow during the first month after planting, but increases to a maximum during formation of the inflorescences. Maize has a high demand for nitrogen, which is often the limiting nutrient. High nitrogen levels should be applied in 2 doses; the first dose at planting or 2–3 weeks after emergence and the second one about 2 weeks before flowering. Phosphate is not taken up easily by maize and, moreover, many tropical soils are deficient in available phosphate. It is advisable to apply organic manures before ploughing to improve soil structure and supply nutrients. Smallholder farmers in tropical Africa apply little or no fertilizer to the maize crop. When they do, it is usually only once, about 4 weeks after planting when the crop is knee high.

Maize is grown in rotation with groundnut, common bean, cowpea, cotton and tobacco. Rotation with soya bean is gaining popularity in northern Nigeria; it increases maize yields by providing nitrogen and by reducing parasitism. In the United States maize is often grown in rotation with soya bean.

Diseases and pests

The most important fungal diseases of maize in tropical Africa are rots affecting female inflorescences (*Fusarium* spp. and other fungi), the stalk-rot complex (*Diplodia maydis*, *Fusarium moniliforme*, *Macrophomina phaseoli* and *Pythium aphanidermatum*) and leaf blights (*Exserohilum turcicum* and *Bipolaris maydis*). Of more local importance are downy mildew (*Peronosclerospora sorghi*), smut (*Ustilago maydis*) and rusts (*Puccinia sorghi* and *Puccinia polysora*). Grey leaf spot (*Cercospora zea-maydis*) is important in East and southern Africa, but in West and Central Africa it occurs only in mid-altitude regions. Host-plant resistance is the most effective disease control measure. Cultivars resistant to *Exserohilum turcicum* leaf blight and downy mildew are available. Maize cultivars that possess resistance to multiple diseases are now available in tropical Africa.

Measures to reduce mycotoxin contamination of the cob include early harvesting, rapid drying, sorting out of damaged and infected grains, sanitation (removal of crop residues, cleaning of stores, removal of heavily damaged cobs), improved storage, and the use of fungicides. The most important virus disease of maize is maize streak virus (MSV), which is restricted to Africa and may cause 100% yield loss. It is transmitted by leafhoppers (*Cicadulina* spp.) and is most serious in late-planted crops. Cultivars resistant to maize streak virus are available. Of lesser importance in tropical Africa are maize dwarf mosaic virus (MDMV), sugar cane mosaic virus (SCMV) and maize chlorotic mottle virus (MCMV). Maize is relatively tolerant to nematodes occurring in tropical soils.

The most serious insect pests of maize in tropical Africa are cutworms (*Agrotis* spp.), stem borers (especially *Busseola fusca*, *Eldana saccharina*, *Sesamia calamistis* and *Chilo partellus*), cob borer (*Mussidia nigrivenella*), cotton bollworm (*Helicoverpa armigera*), armyworm (*Spodoptera exempta*), leafhoppers (*Cicadulina* spp.) and less commonly variegated grasshopper (*Zonocerus variegatus*). Occasionally termites and locusts also infest maize fields. Application of insecticides may be necessary to control these pests. Cultural methods for insect control include early planting and burying or burning of crop residues. Although biological control of stem borers using natural enemies has not been very successful, it is still considered a potentially viable control option. Maize is not prone to bird damage.

Common storage pests of maize are grain moths (*Sitotroga cerealella* and *Ephestia cautella*), grain weevils (*Sitophilus* spp.) and the larger grain borer (*Prostephanus truncatus*). Grains may be mixed with small amounts of an insecticide (e.g. malathion) to control these pests. Rodents are also major storage pests in tropical Africa.

The parasitic witchweed (*Striga* spp.) is a serious constraint to maize production in many parts of tropical Africa, especially *Striga hermonthica* (Delile) Benth. in West and Central Africa and *Striga asiatica* (L.) Kuntze in southern Africa. No single control measure is effective for this weed, and an integrated approach is recommended, involving planting maize seed that is free from *Striga* seeds, planting resistant cultivars, adequate fertilizer application (especially N), crop rotation (e.g. with cotton, soya bean or cowpea), and removal of *Striga* plants before they flower.

Harvesting

Maize is usually harvested by hand. Mechanical harvesting is practised on large farms. Indicators of maturity are yellowing of the leaves, yellow dry papery leaves around the cobs, and hard grains with a glossy surface. In the dry season, maize is often left in the field until the moisture content of the grain has fallen to 15–20%. In case of harvesting by hand, the cobs should be broken off with as little attached stalk as possible. Cobs may be harvested with the surrounding leaves still attached. These may be turned backward and used to tie several cobs together and hung up to dry. Alternatively, the leaves are completely removed from the cobs, which are then stored in cribs to dry.

Yield

Maize has the highest yield potential among the cereal crops. The current average world

yield of maize is 4.4 t/ha, but grain yields over 20 t/ha are possible. Average grain yields of maize in tropical Africa are about 1.25 t/ha, varying greatly from less than 1 t/ha for smallholders to about 6 t/ha in commercial farms. Yields higher than 10 t/ha have been recorded, but these are exceptional. In 2001 the average yields of maize in the different sub-regions of tropical Africa were: West Africa 1.3 t/ha, Central Africa 1.0 t/ha, East Africa 1.6 t/ha and southern Africa 1.4 t/ha.

Handling after harvest

The major post-harvest problems of maize in most production areas are reducing the moisture content of the grain to 12–15%, protection from insects and rodents, and proper storage. A high grain moisture content combined with high ambient temperatures can cause considerable damage, making the product unsuitable for consumption by humans and livestock. Maize grain for home consumption is either sun-dried for several days by hanging up whole cobs tied together by their leaves, or these are put in a well-ventilated store or crib. Shelling (the removal of grains from the cob) is usually carried out by hand, although mechanical shellers are available. The average shelling percentage is about 75%. The shelled grain is dried for a few days and then stored in bags, tins or baskets. The optimum moisture content for storage is 12–13%, but often it is not below 18%. Smallholder farmers generally select seed for the next crop from the last harvest. The selected cobs are stored at home in the surrounding leaves above the fireplace to prevent insect damage.

Genetic resources and breeding

The largest germplasm collections of maize are held in India (Indian Agricultural Research Institute, New Delhi, 25,000 accessions), Mexico (International Maize and Wheat Improvement Center (CIMMYT), Mexico City, 22,140 accessions), the United States (USDA-ARS North Central Regional Plant Introduction Station, Iowa State University, Ames, Iowa, 17,910 accessions) and China (Institute of Crop Germplasm Resources (CAAS), Beijing, 15,840 accessions). In tropical Africa substantial germplasm collections are held in Kenya (Kenya Agricultural Research Institute (KARI), National Agricultural Research Centre, Kitale, 1780 accessions), Malawi (Malawi Plant Genetic Resources Centre, Chitedze Agricultural Research Station, Lilongwe, 970 accessions), Rwanda (Institut des Sciences Agronomiques du Rwanda (ISAR), Butare, 580 accessions).

Breeding

Maize breeding in tropical Africa started with introduction of improved materials from Central and South America. Some of the cultivars were multiplied and distributed to farmers directly, while others were subjected to genetic improvement. Breeding for resistance to various diseases, such as rust, blight, smut and leaf spots, was a major objective. Many cultivars resistant to the prevalent diseases were released. At the initial stages of maize improvement in the region, composites (mixtures of genotypes from various sources that are

maintained by normal pollination) and synthetic cultivars (cultivars produced by crossing a number of genotypes in all possible combinations, with subsequent maintenance by open pollination) were developed for the farmers. F₁ hybrids (first generation progeny of crosses between genetically distinct parents) with greatly increased grain yield were produced in the United States and in some tropical African countries during the early part of the 20th century. Zimbabwe, for example, adopted hybrids at that time; most other tropical African countries could not produce hybrids because there were no seed companies that could produce and distribute hybrid seed in commercial quantities. Two international research institutes, IITA (International Institute of Tropical Agriculture) and CIMMYT, established breeding programmes in the region and greatly boosted the development of improved cultivars. With time, many African countries also established their own breeding programmes and developed maize cultivars for their special needs. Germplasm from CIMMYT and IITA has been widely used in these programmes. The demand for maize continued to increase, thus necessitating attempts to improve the yield of the cultivars grown by the farmers. Hybrid seed is commonly used in high-input farming with high fertilizer use and adequate facilities for seed production. In tropical Africa breeding methods such as recurrent selection, inbreeding and hybridization have been used in maize breeding. Seed companies are now being established in many of the countries, thereby making it possible to produce hybrid seed in commercial quantities. In low-input farming, composite or synthetic cultivars may be preferable, as they permit farmers to save seed from one crop to the next, while their wider genetic base provides a better adaptation to variable growth conditions. Emphasis in maize breeding is on incorporation of resistance to biotic and abiotic stresses. Several open-pollinated cultivars and F₁ hybrids that are resistant to one or more stress factors, including *Striga*, diseases, insect pests, drought and low soil N, are now available for farmers in tropical Africa. 'Obatanpa', a Quality Protein Maize (QPM) with higher contents of tryptophan and lysine, developed by maize breeders in Ghana, is widely grown in West and Central Africa, and also in some East and southern African countries. Compared to other crops, the adoption level of improved maize cultivars is relatively high in tropical Africa. It has been estimated that 35–50% of the maize area in tropical Africa is planted with improved open-pollinated cultivars and F₁ hybrids, but large differences exist between countries.

A range of techniques is available for in-vitro regeneration of maize, using callus tissue, cell suspensions, excised plant parts and immature embryos. Genetic transformation of maize is possible using *Agrobacterium* -mediated and biolistic methods, but the efficiency of the latter is relatively low. Genetic transformation of maize is now routinely and commercially employed, although genotype-independent techniques are not yet available. In 2001 the world area under transgenic maize was estimated at 9.8 million ha, and maize was only second to soya bean in area planted to transgenic crops. The main transgenic maize types planted are Bt maize (maize that possesses genes from *Bacillus thuringiensis* conferring resistance to the European maize borer, *Ostrinia nubilalis*), herbicide-tolerant maize or types with both traits. Bt maize has been commercially released in South Africa. CIMMYT is working on Bt maize for tropical Africa, especially to control stem borers. Industrial and academic research is testing transgenes capable of improving grain quality, e.g. by increasing the lysine content. Maize was one of the earliest crops to be subjected to molecular mapping; the first molecular map was reported in 1986. Many genetic linkage maps have been constructed since then, using mainly RFLP, SSR and SNP markers; maps

have been integrated into a high-density linkage map. Quantitative trait loci (QTLs) for a wide range of traits have been localized, including grain yield, resistance to diseases and pests, drought tolerance, and oil and protein contents of the grain. Genome sequencing of maize is difficult because of its large size (2500 Mbp), complexity and highly repetitive character.

Prospects

Maize will continue to play a large and important role in Africa's food production. It is the principal staple food in large parts of East and southern Africa. Although less important in West and Central Africa, it is a major source of energy in these regions, especially in parts of Côte d'Ivoire, Ghana, Benin and Nigeria. Of the cereals, maize gives the highest yield per man-hour invested; it is usually the first crop to be harvested for food during the hunger period of the year; it is easy to grow as sole crop or intercropped with other crops; it is easy to harvest, it does not shatter and is not liable to bird damage. Many maize technologies have been developed in national and international research stations in Africa but most of these are yet to be adopted by the farmers. This has led to a large yield gap between the researchers' and the farmers' fields. High-quality seed is in short supply because most countries, especially in West and Central Africa, do not have adequately organized seed sectors. Farmers also need improved access to fertilizers, crop protection chemicals and other inputs. Cultivars and cropping techniques that fit well into the prevailing cropping systems are now being developed in collaboration with farmers in what is called participatory plant breeding.

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MILLET (*Pennisetum glaucum* (L.) R.Br.)

Family

Poaceae (Gramineae)

Chromosome number

$2n = 14$

Origin and geographic distribution

Pearl millet was domesticated in the Sahel 4000–5000 years ago from *Pennisetum violaceum* (Lam.) Rich. It spread to East Africa and from there to southern Africa, and, about 3000 years ago, to the Indian subcontinent. It reached tropical America in the 18th century and the United States in the 19th century. Pearl millet is commonly grown as a grain crop in the semi-arid regions of West Africa and the driest parts of East and southern Africa and the Indian subcontinent. It is also grown as a fodder crop, e.g. in Brazil, the United States, South Africa, and Australia.

Uses

Pearl millet is the staple food for over 100 million people in parts of tropical Africa and India. Decorticated and pounded into flour it is consumed as a stiff porridge ('tô') or gruel in Africa, or as flat unleavened bread ('chapatti') in India. In Africa there are various other

preparations such as couscous, rice-like products, snacks of blends with pulses, and fermented and non-fermented beverages. In several Indian preparations parched seeds are used. The stems are widely applied for fencing, thatching and building, as fuel and as a poor-quality fodder. Split stems are used for basketry. A dye for leather and wood is obtained from red- and purple-flowered types. In African traditional medicine the grain has been applied to treat chest disorders, leprosy, blennorrhoea and poisonings, and the ground grain as an anthelmintic for children. A root decoction is drunk to treat jaundice; the vapour of inflorescence extracts is inhaled for respiratory diseases in children. In some areas the grains are used in rituals. Outside Africa and India pearl millet is mostly grown as a green fodder crop for silage, hay making and grazing. Following the discovery that pearl millet can suppress root-lesion nematodes (*Pratylenchus penetrans*) it is increasingly being used as an alternative to soil fumigation in tobacco and potato cropping in Canada.

Production and international trade

Production statistics often combine data on all millet species. Estimates based on total millet production (FAO statistics) and relative importance of pearl millet in different countries indicate an annual grain production of about 18 million t from a planted area of 26.5 million ha mostly in the dry regions of Africa (60% of area and 58% of production) and the Indian subcontinent (38% of area and 41% of production). Production statistics over the past 10 years show a 20% increase in area planted in Africa, with a 12% increase in yield. Most of the area increase is in Burkina Faso, Chad, Mali, Niger and Nigeria, but yield levels increased only in the latter two countries. During the same period, the area planted to pearl millet in India declined by 16%, but yield levels increased by 30%. Negligible quantities are traded internationally.

Properties

Whole dried grain of pearl millet contains per 100 g edible portion: water 12.0 g, energy 1428 kJ (341 kcal), protein 10.4 g, fat 4.0 g, carbohydrate 71.6 g, fibre 1.9 g, Ca 22 mg, P 286 mg, Fe 20.7 mg, β -carotene traces, thiamin 0.30 mg, riboflavin 0.22 mg, niacin 1.7 mg and ascorbic acid 3 mg (Leung, Busson & Jardin, 1968). The content of essential amino acids per 100 g food is: tryptophan 189 mg, lysine 332 mg, methionine 239 mg, phenylalanine 467 mg, threonine 374 mg, valine 535 mg, leucine 927 mg and isoleucine 397 mg (FAO, 1970). From a nutritional viewpoint pearl millet is better than maize and sorghum. Compared to that of other millets, the protein of pearl millet is rich in tryptophan.

Description

Robust annual grass up to 4 m tall, with basal and nodal tillering; root system extremely profuse, sometimes the nodes at ground level produce thick, strong prop roots; stem slender, 1–3 cm in diameter, solid, often densely villous below the panicle, nodes

prominent. Leaves alternate, simple; leaf sheath often hairy; ligule short, membranous, with a fringe of hairs; blade linear to linear-lanceolate, up to 1.5 m × 8 cm, often pubescent, margins minutely toothed, somewhat rough. Inflorescence a cylindrical, contracted, stiff and compact panicle, suggesting a spike, up to 200 cm long; rachis cylindrical, bearing densely packed clusters of 1–5(–9) spikelets, subtended by a tuft (involucre) of up to 90 bristles about as long as spikelets, but in some cultivars with a few stiff bristles up to 2 cm long. Spikelets obovate, 3–7 mm long, usually 2-flowered; glumes 2, lower one c. 1 mm long, upper one c. 2.5 mm; lower floret male or sterile, upper one bisexual; lemma ovate, pubescent on margins; palea almost as long as lemma; lodicules absent; stamens 3, anthers 2–5 mm long, tipped with brush-like bristles; ovary superior, obovoid, smooth, with 2 hairy stigmas, connate at the base. Fruit a free-threshing caryopsis (grain), globose to cylindrical or conical, 2.5–6.5 mm long, variously coloured, from white, pearl-coloured or yellow to grey-blue or brown, occasionally purple, hilum marked by a distinct black dot at maturity.

Other botanical information

Pennisetum comprises about 80 species and occurs throughout the tropics. Pearl millet is not closely related to most other *Pennisetum* species, although it hybridizes easily with elephant grass (*Pennisetum purpureum* Schumach., a tetraploid with $2n = 28$). *Pennisetum glaucum* belongs to a complex of 3 taxa that hybridize freely and are sometimes considered as subspecies of *Pennisetum glaucum*. However, as long as the complicated taxonomy of pearl millet has not been fully cleared up, it is preferable to keep these taxa separate:

– *Pennisetum glaucum*: cultivated types, with persistent, stiped involucres; the dense inflorescences and non-shattering habit are conspicuous.

– *Pennisetum sieberianum* (Schltdl.) Stapf & C.E.Hubb. (synonyms: *Pennisetum stenostachyum* (A.Braun & Bouché) Stapf & C.E.Hubb., *Pennisetum dalzielii* Stapf & C.E.Hubb., *Pennisetum americanum* (L.) Leeke subsp. *stenostachyum* (A.Braun & Bouché) Brunken): weedy types, resulting from introgression between wild *Pennisetum violaceum* and cultivated *Pennisetum glaucum* and ranging in morphology between wild and cultivated types; in the latter case they are termed ‘shibras’ and they look much like *Pennisetum glaucum* cultivars, but differ in having deciduous shortly stiped involucres, and spikelets which shatter before harvest; bristles numerous, longer than spikelets; widespread in the Sahel and also found, though less frequently, in East and southern Africa.

– *Pennisetum violaceum* (Lam.) Rich. ex Pers. (synonyms: *Pennisetum fallax* (Fig. & De Not.) Stapf & C.E.Hubb., *Pennisetum americanum* (L.) Leeke subsp. *monodii* (Maire) Brunken): wild, variable type, with deciduous sessile involucres which always contain a single spikelet; bristles numerous, longer than spikelets; distributed from the West African Sahel region to Eritrea in very dry locations, independent of farming; sometimes harvested as a wild cereal in times of scarcity.

Although many intermediate cultivars occur, 4 cultivar groups (originally described as races) can be distinguished in cultivated *Pennisetum glaucum*, based

mainly on grain shape and partly on distribution:

- Typhoides Group; grain obovoid, circular in cross-section, 2.5–5.5 mm × 1.5–3 mm × 1–2.5 mm, inflorescence cylindrical or ellipsoidal, usually less than 0.5 m long; it is the most primitive, the most variable and most widely distributed group, occurring all over the pearl millet range in Africa and India, and is probably ancestral for the other groups.
- Globosum Group: grain globose, more than 2.5 mm in diameter, inflorescence cylindrical, often longer than 1 m; most common in the Sahel region west of Nigeria.
- Leonis Group: grain oblanceolate in outline, circular in cross-section, 4–6.5 mm × 2–2.5 mm × 2–2.5 mm, apex acute, inflorescence cylindrical; this is the smallest group and is grown in Mauritania, Senegal and Sierra Leone.
- Nigritarum Group; grain obovoid but angular in cross-section, 3–5 mm × 1.5–2.5 mm × 1.5–2 mm, inflorescence cylindrical; most common in semi-arid regions from Nigeria to Sudan.

Agronomically two main groups of cultivars are recognized in West Africa, based on growth duration : short-duration Gero (or Souna) cultivars and long-duration Maiwa (or Sanio) cultivars. Gero cultivars are less photoperiod-sensitive, are more widely grown and exhibit more genetic diversity than Maiwa cultivars, in which flowering date is strongly controlled by daylength. Maiwa types are grown in regions where the rainy season is longer and where sorghum is the major cereal, but on poorer, more drought-prone soils. Certain Maiwa millets are transplanted from nurseries into the field and are known as Dauro millet.

The improved cultivars and dwarf single-cross hybrids grown in India are stronger tillering, early (80 days) to very early (65 days) maturing and less photoperiod-sensitive than African cultivars

Growth and development

Pearl millet cultivars vary in time to maturity from 55–280 days, but mostly from 75–180 days. Time to flower initiation is the main factor determining the life cycle of a cultivar. Floral initiation is weakly to strongly controlled by photoperiod, with short days accelerating flower initiation. Photoperiod response allows crop cycle length to be adjusted by time of planting, needed when rains begin late, to ensure that flowering and grain production occur at the same optimum time each year for a specific latitude. In short-duration, photoperiod-insensitive cultivars the developmental stages (from germination to flower initiation, to flowering and to maturity) are of approximately equal duration.

Field establishment of pearl millet is affected by its relatively small seed size, especially in crusting soils. Other factors that influence stand establishment include high soil surface temperatures at emergence (as high as 50–55°C), sand storms and early season moisture stress. During early development the roots grow more than the above-ground parts. Pearl millet produces an extensive and dense root system, which may reach a depth of 1.2–1.6 m, exceptionally 3.5 m. Basal tillering occurs 2–6 weeks after sowing, and when planted in widely spaced pockets up to 40 tillers

may be produced, especially on long-season cultivars. Secondary tillering from the upper nodes of stems is a common response to drought, or to damage to the stem or inflorescence. These aerial tillers produce 2–3 leaves and a small inflorescence within 10–20 days; they may contribute 15% and occasionally up to 50% of grain yield. It takes 15–20 days from inflorescence differentiation to flowering. Pearl millet has a protogynous breeding system, which encourages but does not enforce cross-pollination; 10% or more inbreeding may occur, depending on overlap in flowering between florets within an inflorescence and among tillers. Pearl millet cultivars are therefore heterogeneous and heterozygous random mating populations, which exhibit substantial inbreeding depression. Heavy rainfall, low temperature and moisture stress reduce seed set. The grain-filling period normally takes 22–25 days. The harvest index of landraces is low (0.15–0.20), attaining 0.35 in improved cultivars, and up to 0.45 in dwarf hybrids.

Pearl millet is characterized by the C₄ photosynthetic pathway. Vesicular-arbuscular mycorrhizae (e.g. *Gigaspora* and *Glomus* spp.) and nitrogen-fixing bacteria (e.g. *Azospirillum* spp.) are commonly found associated with pearl millet roots, which may assist with the uptake of water, N and P

Ecology

In West Africa, from the oases of the Sahara desert (under irrigation) to the northern Sahel (characterized by 250 mm annual rainfall), pearl millet cultivars are grown that are photoperiod insensitive and mature in 55–65 days. In the 250–400 mm rainfall zone, where very high temperatures are common, especially at planting time, it is the dominant cereal. The optimum temperature for germination of pearl millet seeds is 33–35°C; no germination occurs below 12°C. The optimum temperature for tiller production and development is 21–24°C, and for spikelet initiation and development about 25°C. Extreme high temperatures before anthesis reduce pollen viability, panicle size and spikelet density, thus reducing yield. Pearl millet is tolerant of various soil conditions, especially of light and acid soils. Its large and dense root system allows it to grow on soils with a low nutrient status. Pearl millet does not tolerate waterlogging. Once established, the crop is fairly tolerant of salinity.

Propagation and planting

Propagation of pearl millet is by seed, usually sown directly in the field. Transplanting is carried out on a very limited scale in India and West Africa (Dauro millet). The 1000-seed weight is 2.5–16 g. In Africa short-duration cultivars are sown early, after the first 20 mm rain of the season and land preparation is limited to a light hoeing. Land preparation for long-duration cultivars, which are sown later, is done more thoroughly. Pearl millet is usually sown directly in pockets (hills) in rows at plant distances of 45 cm × 45 cm to 200 cm × 200 cm depending on the cropping system (intercrop or sole crop). The pockets are opened with a hoe or a stick, a pinch of seeds is thrown in, and the hole is covered by soil using the foot. At the first weeding the crop is thinned to 2 or 3 plants per pocket. Farmers tend to adjust plant density based on average rainfall and soil fertility; it generally ranges

from 20,000–50,000 plants per ha in pure stands. Seed rates vary accordingly from 2–5 kg per ha. Pearl millet is often intercropped with one to several crops, including cowpea, sorghum and groundnut.

Management.

Pearl millet frequently needs 2–3 weedings, which are done mostly by hand. With short-duration cultivars in Africa, weeding coincides with land preparation and planting of later crops. Manual weeding places severe demands on available labour and limits the area that can be managed properly. In a few regions animal-drawn implements are used for weeding. Pearl millet is highly responsive to increased soil fertility, but under traditional rainfed farming conditions the application of manure and chemical fertilizers is limited. Because of the depleted fertility status of most pearl millet soils some phosphorus and potassium is needed for an optimal response to nitrogenous fertilizers. As fertilizers increase water use of the crop, plant populations and average seasonal water availability also need to be considered when making fertilizer recommendations. A pearl millet crop yielding about 3.1 t grain per ha in the West African savanna was recorded as removing 132 kg N, 28 kg P, 65 kg K and 31 kg Ca per ha from the soil.

Diseases and pests.

Green ear caused by downy mildew (*Sclerospora graminicola*), grain smut (*Tolyposporium penicillariae*), rust (*Puccinia substriata* var. *penicillariae*) and ergot (*Claviceps fusiformis*) are important diseases of pearl millet, both in Africa and in Asia. Sources of resistance against all four have been identified and are being incorporated into new cultivars, except for resistance to ergot which is polygenic and recessively inherited. Birds are the major pest in pearl millet, especially *Quelea* spp. Bird scaring for several weeks before the harvest is essential. Farmers in West Africa often do not harvest a larger area than they can protect from birds. Cultivars with long, hard bristles are less vulnerable than those without. Stem borer (*Coniesta ignefusalis*), millet head miner (*Heliocheilus albipunctella*) and millet midge (*Geromyia penniseti*) are locally important. Other pests are white grubs, grasshoppers, locusts, and various Lepidoptera. Pearl millet is sometimes seriously attacked by adapted strains of the root parasite *Striga hermonthica* (Delile) Benth. in West Africa.

Harvesting.

Pearl millet is harvested by hand, either by picking the panicles or by harvesting whole plants. In cultivars where tillers ripen unevenly, several pickings are required. Cultivars with long panicles are favoured for ease of harvest, bundling and transport.

Yield

Grain yields range from 250 kg/ha in the driest areas to 500–1500 kg/ha in the main

production areas. Average yields in Africa and India are about 670 and 790 kg/ha, respectively. Under optimal conditions hybrids may reach grain yields of 5 t per ha in 85 days and yields of 8 t per ha have even been obtained. In landraces the above-ground dry matter yield may be 3–10 t/ha. In hybrids bred specifically for forage dry matter yields in a season range from 10–20 t/ha.

Handling after harvest

A harvested pearl millet crop is dried in the sun for a few days. In Africa whole panicles are commonly stored in elevated granaries, built of mud or plant materials and covered with thatch. Sometimes they are stored in pits. Ash or neem (*Azadirachta indica* A.Juss.) leaves may be put in layers to reduce insect attack. Threshing is normally done manually when grain is needed. If dry and protected from insects, seed can be stored adequately at room temperature for several years. Pearl millet flour, unless dry-milled and well-packed, has poor storage quality because of rancidity due to the high oil content.

Genetic resources and breeding

Landraces of pearl millet have evolved over thousands of years through natural and human selection. Selection at different latitudes and in different agro-climatic zones for crop duration, yield, adaptability to nutrient-poor soils, resistance to drought and diseases, and grain type has resulted in local cultivars with a large range of morphological diversity and photoperiod sensitivity. Continual introgression with wild and weedy relatives in West Africa has further contributed to the crop's genetic diversity. Genetic variation is conserved and evaluated at the Coastal Plains Experiment Station, Tifton (Georgia, United States) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Hyderabad (India), where the world collection of over 24,000 entries is housed. The International Plant Genetic Resources Institute (IPGRI) supports a programme, started in Burkina Faso, to improve the description and evaluation of material at the time and location of collection. One particular germplasm source, the 'Iniadi' cultivar from northern Togo and Ghana, has had a profound effect on pearl millet breeding. Selections from it have been successful as cultivars in northern India, Namibia and Botswana, and it has been extensively used in all breeding programmes.

Breeding

Both improved open-pollinated types and hybrids have been developed in pearl millet ; cytoplasmic male sterility is available for the commercial production of hybrid seed. Cultivar breeding of pearl millet started in Africa in the 1950s and traditional cultivars are still widely used. Breeding work by the Indian Council of Agricultural Research and ICRISAT has been most successful in developing cultivars that were rapidly adopted by farmers. The discovery of cytoplasmic male sterility in 1958 in the forage breeding programme at Tifton (Georgia, United States) led to the production of early-maturing, semi-dwarf grain hybrids in India, which covered 3 million ha by 1970. Despite the occurrence of

disease epidemics, some 50% of the Indian pearl millet crop on family farms now consists of hybrids and improved cultivars, and yields have increased by 40% since 1965. Early breeding work in West Africa by the Institut de Recherches Agronomiques Tropicales et de Cultures Vivrières (IRAT) and the East African Agriculture and Forestry Research Organization (EAAFRO) produced improved local cultivars, but adoption was negligible. Since the early 1980s ICRISAT, working with a broader germplasm base and in conjunction with national agricultural research programmes in West, East and southern Africa, has produced better cultivars. In 8 countries in West Africa 24 cultivars (11 for the Sahel zone and 13 for the Sudan Zone) have been released and in East and southern Africa 19 new cultivars are available for 8 countries with adoption rates of up to 50% (Namibia, Zimbabwe). Work at ICRISAT is focused on the identification of stable stress tolerance, wide adaptability and high yield potential. Sources of tolerance of the major diseases have been identified and are being incorporated into new cultivars. Two further cytoplasmic male sterility systems (A4 and A5), which have superior attributes both for hybrid breeding and seed production, have been discovered. These allow access to different heterotic patterns and more rapid development of new hybrids, particularly topcross hybrids which are most suited to the higher disease pressures in Africa. On average, single-cross hybrids (male-sterile \times inbred restorer) give about 20% more grain yield than open-pollinated cultivars of similar maturity. Topcross hybrids (male-sterile \times open-pollinated cultivars) benefit from the adaptability and durable disease resistance of the open-pollinated type, and give 10–15% more yield. The pearl millet genome has now been well mapped, and marker-assisted selection is being used to improve downy mildew and rust resistance. Transgenic pearl millet plants with various marker genes have been obtained using particle bombardment. Forage breeding work, mainly in the United States, Australia, Brazil and southern Africa, has also produced pearl millet hybrids. Interspecific hybrids between pearl millet and elephant grass (*Pennisetum purpureum*) are available; these are vigorous, variable, triploid and sterile, but selections are easily vegetatively propagated and used as a persistent perennial forage by small farmers in South-East Asia, East and southern Africa and South America. In the United States dwarf plant stature and synchronous maturity of tillers, in addition to earliness and tolerance of diseases have been successfully incorporated into pearl millet to convert it to a new feed grain crop suitable for mechanical cultivation. Commercial production of grain pearl millet for poultry feed has commenced in Georgia (United States).

Prospects

Pearl millet has great potential because it has one of the highest rates of dry matter gain among the C₄-cycle cereals, a very flexible breeding system and a large amount of genetic variability in the primary gene pool yet to be used. The results of pearl millet breeding work in India, where gains from breeding have been 1–2% per year over the last 35 years, demonstrate what can be achieved in Africa. Half of the millet area in India is now planted to improved cultivars, including hybrids. Proven breeding techniques and wider use of genetic resources will continue to produce better cultivars.

In Africa small and seasonably variable grain markets, lack of credit and bulk grain storage have constrained farmers from making the monetary investments which will increase production. However, the growing urban demand for pearl millet flour, and food products

like couscous allow farmer cooperatives in Niger, Mali and Senegal to make contracts before planting directly with urban grain processors, for the supply of grain meeting given standards, including grain type and colour, milling quality, flavour and freedom from impurities. In Senegal the cultivar is also specified. This enables subsistence farmers to benefit from seed of improved cultivars, and from purchased inputs such as fertilizer. Better cultivars, produced by certified seed farmers, are being marketed in Namibia, Nigeria and Senegal. Many production technologies have been researched and tested both for family farmers and larger-scale pearl millet cultivation, including improved cultivars, better crop management, soil improvement and moisture conservation techniques for the major pearl millet producing regions in Africa. If reliable grain markets are established, pearl millet production in Africa can follow the example of India, and increase substantially on existing land.

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SORGHUM (*Sorghum bicolor* (L.) Moench)

Family

Poaceae (Gramineae)

Chromosome number

$2n = 20$

Origin and geographic distribution.

The greatest diversity in both cultivated and wild types of *Sorghum* is found in north-eastern tropical Africa. The crop may have been domesticated in that region, possibly Ethiopia. Various hypotheses have been put forward as to when the crop was domesticated, from as early as 5000–3000 BC to around 1000 BC, but the latter period is more widely accepted now. From north-eastern Africa sorghum was distributed all over Africa and along shipping and trade routes through the Middle East to India. From India it is believed to have been carried to China along the silk route and through coastal shipping to South-East Asia. From West Africa sorghum was taken to the Americas through the slave trade. It was introduced into the United States for commercial cultivation from North Africa, South Africa and India at the end of the 19th century. It was subsequently introduced into South America and Australia. It is now widely cultivated in drier areas of Africa, Asia, the Americas, Europe and Australia between latitudes of up to 50°N in North America and Russia and 40°S in Argentina. Sorghum types exclusively cultivated for the dye in the leaf sheaths can be found from Senegal to Sudan.

Uses

Sorghum is an important staple food, particularly in semi-arid tropical regions of Africa and Asia, and an important feed grain and fodder crop in the Americas and Australia. In the simplest food preparations, the whole grain is boiled (to produce a food resembling rice), roasted (usually at the dough stage), or popped (like maize). More often the grain is ground or pounded into flour, often after hulling. Sorghum flour is used to make thick or thin porridge, pancake, dumplings or couscous, opaque and cloudy beers and non-alcoholic fermented beverages. In Africa sorghum grain is germinated, dried and ground to form malt, which is used as a substratum for fermentation in local beer production. White grain is generally preferred for cooking while red and brown grains are normally used for beer making. Where bird pressure is high, e.g. around Lake Victoria, red and brown types rich in tannin may be grown for food instead of white types. In China sorghum is extensively distilled to make a popular spirit and vinegar. Sorghum grain is a significant component of cattle, pig and chicken feeds in the United States, Central and South America, Australia and China, and is becoming important in chicken feed in India. It requires grinding, rolling, flaking or steaming to maximize its nutritional value.

Several non-edible sorghum cultivars are exclusively grown for the red dye present in the leaf sheaths and sometimes also in adjacent stem parts. In Africa this dye is used particularly for goat-skin leather (e.g. in Nigeria), but also for mats, textiles, strips of palm leaves and grasses used in basketry and weaving, ornamental calabashes, wool (e.g. in Sudan), as a body paint and to colour cheese and lickstones for cattle (e.g. in Benin). A similar dye can be extracted from the grain refuse (glumes and grain wall) of several red sorghum cultivars grown for food or for beer-making. In Nigeria the red sorghum dyes were traditionally used by the Bunu, Aworo, Igbira and Okpella people for a fabric called 'abata', used as a funeral hanging, decorated with patterns made by thick threads added to the weft of the fabric. The fabrics in which the dominant colours were derived from sorghum were known as 'ifala'. Sorghum is also used to provide the violet colours decorating the masks worn during certain dances by Yoruba people in southern Benin and in south-western Nigeria. In Côte d'Ivoire sorghum and other tannin-rich dyes are used in combination with mud to create the patterns of the painted cloths produced in the Korhogo region. The dye was formerly exported to Morocco where it was used in the leather industry. In China sorghum types with red panicles and leaf sheaths were also used for dyeing. In the 19th century red sorghums were exported to Europe where the dye was known as 'carmin de sorgho'. It was extracted by squeezing out the juice, which was then fermented. Used with wool or silk mordanted with tin or chrome, the result was a colourfast red-brown that was once known as 'rouge badois'. 'Durra red', a similar product, was imported from India into the United Kingdom where the dye was known as 'Hansen brown' or 'Meyer brown'. Recently the use of sorghum dye in hair dyeing products has been patented.

The stems of sweet sorghum types are chewed like sugar cane and, mainly in the United States, a sweet syrup is pressed from them. In North America and eastern Europe special types with very long, fibrous and few-seeded inflorescences, known as 'broomcorn', are grown to make brooms. Sorghum plant residues are used extensively as material for roofing, fencing, weaving and as fuel. The stems can be used for the production of fibre board. Danish scientists have made good panelling using stem chips of sorghum. The stover remaining after harvesting the grain is cut and fed to cattle, sheep and goats, or may be grazed. Some farmers grind harvested stover and mix it with sorghum bran or salt to feed livestock. Sorghum is also grown for forage, either for direct feeding to ruminants or for preservation as hay or silage. Sorghum flour is used to produce an adhesive in the manufacture of plywood. Sweet sorghum is suitable for the production of alcohol, while the bagasse is a suitable source of paper pulp for the production of kraft paper, newsprint and fibre board. Sorghum has various applications in African traditional medicine: seed extracts are drunk to treat hepatitis, and decoctions of twigs with lemon against jaundice; leaves and panicles are included in plant mixtures for decoctions against anaemia. The Salka people in northern Nigeria use sorghum in arrow-poisons. The red pigment is said to have antimicrobial and antifungal properties and is also used as a cure for anaemia in traditional medicine.

Production and international trade.

Sorghum grain is the fifth most important cereal in the world after wheat, rice, maize and barley. In Africa it comes second after maize in terms of production. According to FAO

estimates, the average world production of sorghum grain in 1999–2003 amounted to 57.7 million t/year from 42.6 million ha. The production in sub-Saharan Africa was 19.0 million t/year from 22.8 million ha. The main producing countries are the United States (12.0 million t/year in 1999–2003 from 3.2 million ha), India (7.6 million t/year from 9.8 million ha), Nigeria (7.6 million t/year from 6.9 million ha), Mexico (6.0 million t/year from 1.9 million ha), Sudan (3.4 million t/year from 5.3 million ha), Argentina (3.0 million t/year from 630,000 ha), China (3.0 million t/year from 840,000 ha), Australia (1.9 million t/year from 690,000 ha), Ethiopia (1.4 million t/year from 1.2 million ha) and Burkina Faso (1.3 million t/year from 1.4 million ha). In sub-Saharan Africa annual production increased from around 10 million t from 13 million ha in the early 1960s to about 20 million t from 25 million ha in the early 2000s.

Almost all sorghum traded on international markets is for use as livestock feed. Average world exports of sorghum in 1998–2002 amounted to 6.3 million t/year, almost all from the United States (5.6 million t/year). The main importers are Mexico and Japan. In tropical Africa most sorghum is grown for home consumption (except for beer production). In southern and eastern Africa malting sorghum for beer brewing has developed into a large-scale commercial industry, using about 150,000 t of sorghum grain annually. In Uganda commercial production of lager beer using sorghum instead of barley is becoming a great success (annual requirement of sorghum is 3000 t) and is very promising for other African countries. In Nigeria sorghum malting has become a major industry for lager and stout beer brewing and for malt beverages, using about 15,000 t of sorghum annually. In South Africa an instant breakfast cereal is made from sorghum that is similar in quality but much cheaper than wheat or maize products. Annual production is 12,000 t and is increasing steadily. In West Africa small tied bundles of 4–6 leaf sheaths of sorghum dye cultivars are offered for sale on local markets (in the 1990s the price was about 150 CFA). In 1993 in Burkina Faso, the red pigment was successfully extracted chemically from sorghum leaf sheaths and offered for sale as dry powder on the world market.

Properties.

The composition of sorghum grain per 100 g edible portion is: water 9.2 g, energy 1418 kJ (339 kcal), protein 11.3 g, fat 3.3 g, carbohydrate 74.6 g, Ca 28 mg, P 287 mg, Fe 4.4 mg, vitamin A 0 IU, thiamin 0.24 mg, riboflavin 0.14 mg, niacin 2.9 mg and ascorbic acid 0 mg. The essential amino acid composition per 100 g edible portion is: tryptophan 124 mg, lysine 229 mg, methionine 169 mg, phenylalanine 546 mg, threonine 346 mg, valine 561 mg, leucine 1491 mg and isoleucine 433 mg. The principal fatty acids are per 100 g edible portion: linoleic acid 1305 mg, oleic acid 964 mg and palmitic acid 407 mg (USDA, 2004). Sorghum grain is first limiting in lysine, then in methionine and threonine. Much of the protein in sorghum is prolamine (39–73%), which is poorly digestible. As a result,

maximum available protein in sorghum grain is usually 8–9%. The tannin content of sorghum also affects its nutritional value. High- and low-tannin sorghum types are distinguished. High-tannin sorghum types (sometimes called ‘brown sorghums’, although the grain may also be white, yellow or red) have less nutritional value but have agronomic advantages, including resistance to birds, insects, fungi and decreased sprouting in the panicle. Sorghum types without a pigmented grain wall (‘white sorghums’) do not contain condensed tannins and have a nutritional value similar to that of maize. Decortication, parboiling, malting or steeping in alkali solutions significantly reduce the tannin content of sorghum grain. In general the endosperm accounts for 82–84% of the grain weight, the germ for 9–10% and the grain wall for 6–8%. The starch granules in the endosperm have a diameter of (4–)15(–25) μm . The starch normally contains 70–80% amylopectin and 20–30% amylose, although some types contain 100% amylopectin and others up to 62% amylose. The gelatinization temperature ranges from 68–75°C. Sorghum grain does not contain gluten and cannot be used for leavened products unless mixed with wheat. The composition of the green plant varies according to age and cultivar but it normally contains 78–86 g of water per 100 g of fresh material. On a dry basis it contains per 100 g: protein 12 g, carbohydrate 40–50 g and fibre 20–30 g. The glycoside dhurrin occurs in the aerial parts of most sorghum. Dhurrin is hydrolyzed to hydrocyanic acid (HCN), which is highly toxic and can kill grazing animals. It is particularly concentrated in the young leaves and tillers and in plants that are suffering from drought. HCN content usually declines with age, reaching non-toxic levels 45–50 days after planting, and HCN is destroyed when the fodder is made into hay or silage.

The red pigment in sorghum dye cultivars is composed of anthocyanic compounds, particularly rich (95%) in the stable apigeninidin chloride (3-deoxyanthocyanidin) and tannins of the condensed proanthocyanidins group (producing phlobaphen reds). The red pigment in the sorghum leaf sheath makes up to over 20% of the dry weight. The role of the non-pathogenic fungus *Bipolaris maydis* in the production of apigeninidin in these cultivars deserves further research. Used without a mordant, the dye obtained from sorghum gives a dark red that is fairly colourfast and still much used in eastern Africa, particularly Sudan and Ethiopia, for dyeing leather, cotton and the grasses and reeds used for woven matting. Black colours are obtained with natron salt and iron mordants. From red sorghum grain the pigments apigenin, quercimeritrin, kaempferol glucosides, apigenidin glucosides, apigeninidin, luteolinidin and 7-O-methyl-luteolin-glucoside have been isolated. From the stem of red sorghum cultivars the constituents of the red dye were the anthocyanidin apigeninidin (17%) and the flavonoids luteolin (9%) and apigenin (4%). The anaemia curing property of the red pigment has been confirmed in tests with rats.

Description.

Annual grass up to 5 m tall, with one to many tillers, originating from the base or stem nodes; roots concentrated in the top 90 cm of the soil but sometimes extending to twice that depth, spreading laterally up to 1.5 m; stem (culm) solid, usually erect. Leaves alternate, simple; leaf sheath 15–35 cm long, often with a waxy bloom, with band of short white hairs at base near attachment, reddish in dye cultivars, auricled; ligule short, c. 2 mm long, ciliate on upper free edge; blade lanceolate to linear-lanceolate, 30–135 cm \times 1.5–13 cm, initially

erect, later curving, margins flat or wavy. Inflorescence a terminal panicle up to 60 cm long; rachis short or long, with primary, secondary and sometimes tertiary branches, with spikelets in pairs and in groups of three at the ends of branches. Spikelet sessile and bisexual or pedicelled and male or sterile, with 2 florets; sessile spikelet 3–10 mm long, with glumes approximately equal in length, lower glume 6–18-veined, usually with a coarse keel-like vein on each side, upper glume usually narrower and more pointed, with central keel for part of its length, lower floret consisting of a lemma only, upper floret bisexual, with lemma cleft at apex, with or without knee and twisted awn, palea, when present, small and thin, lodicules 2, stamens 3; ovary superior, 1-celled with 2 long styles ending in feathery stigmas; pedicelled spikelet persistent or deciduous, smaller and narrower than sessile spikelet, often consisting of only two glumes, sometimes with lower floret consisting of lemma only and upper floret with lemma, 2 lodicules and 3 stamens. Fruit a caryopsis (grain), usually partially covered by glumes, 4–8 mm in diameter, rounded and bluntly pointed.

Other botanical information.

Sorghum comprises 20–30 species. *Sorghum bicolor* belongs to section *Sorghum*, together with the 2 perennial species *Sorghum halepense* (L.) Pers. and *Sorghum propinquum* (Kunth) Hitchc. At present, *Sorghum bicolor* is mostly considered as an extremely variable crop-weed complex, comprising wild, weedy and cultivated annual types (classified as subspecies) which are fully interfertile. The cultivated types are classified as subsp. *bicolor* (synonyms: *Sorghum ankolib* Stapf, *Sorghum caudatum* Stapf, *Sorghum cernuum* Host, *Sorghum dochna* (Forssk.) Snowden, *Sorghum durra* (Forssk.) Stapf, *Sorghum membranaceum* Chiov., *Sorghum nigricans* (Ruiz & Pav.) Snowden, *Sorghum subglabrescens* (Steud.) Schweinf. & Asch., *Sorghum vulgare* Pers.) and they are subclassified into different races on the basis of grain shape, glume shape and panicle type. Five basic races and 10–15 hybrid combinations of 2 or more of these races are recognized and grouped into subsp. *bicolor*. A classification into cultivar groups would, however, be more appropriate. The 5 basic races are:

- Bicolor: the most primitive cultivated sorghum, characterized by open inflorescences and long clasping glumes that enclose the usually small grain at maturity. Cultivars are grown in Africa and Asia, some for their sweet stems to make syrup or molasses, others for their bitter grains used to flavour sorghum beer, but they are rarely important. They are frequently found in wet conditions.
- Caudatum: characterized by turtle-backed grains that are flat on one side and curved on the other; the panicle shape is variable and the glumes are usually much shorter than the grain. Cultivars are widely grown in north-eastern Nigeria, Chad, Sudan and Uganda. The types used for dyeing also belong here and are known as ‘karan dafi’ by the Hausa people in Nigeria.
- Durra: characterized by compact inflorescences, characteristically flattened sessile spikelets, and creased lower glumes; the grain is often spherical. Cultivars are widely grown along the fringes of the southern Sahara, western Asia and parts of India. The durra type is predominant in Ethiopia and in the Nile valley in Sudan and Egypt. It is the most specialized and highly evolved of all races and many useful genes are found in this type. Durra cultivars range in maturity from long to short-season. Most of them are drought resistant.

– Guinea: characterized by usually large, open inflorescences with branches often pendulous at maturity; the grain is typically flattened and twisted obliquely between long gaping glumes at maturity. Guinea sorghum occurs primarily in West Africa, but it is also grown along the East African rift from Malawi to Swaziland and it has also spread to India and the coastal areas of South-East Asia. Many subgroups can be distinguished, e.g. with cultivars especially adapted to high or low rainfall regimes. In the past the grain was often used as ship's provisions because it stored well.

– Kafir: characterized by relatively compact panicles that are often cylindrical in shape, elliptical sessile spikelets and tightly clasping glumes that are usually much shorter than the grain. Kafir sorghum is an important staple across the eastern and southern savanna from Tanzania to South Africa. Kafir landraces tend to be insensitive to photoperiod and most commercially important male-sterile lines are derived from kafir type sorghum. Hybrid races exhibit various combinations and intermediate forms of the characteristics of the 5 basic races. Durra-bicolor is found mainly in Ethiopia, Yemen and India, guinea-caudatum is a major sorghum grown in Nigeria and Sudan, and guinea-kafir is grown in East Africa and India. Kafir-caudatum is widely grown in the United States and almost all of the modern North American hybrid grain cultivars are of this type. Guinea-caudatum with yellow endosperm and large seed size is used in breeding programmes in the United States. The wild representatives are classified as subsp. *verticilliflorum* (Steud.) Piper (synonyms: *Sorghum arundinaceum*(Desv.) Stapf, *Sorghum bicolor* (L.) Moench subsp. *arundinaceum* (Desv.) de Wet & J.R.Harlan): tufted annual or short-lived perennial, with slender to stout culms up to 4 m tall; leaf blade linear-lanceolate, up to 75 cm × 7 cm; panicles usually large, somewhat contracted to loose, up to 60 cm × 25 cm, branches obliquely ascending, spreading or pendulous. Wild types extend across the African savanna and have been introduced into tropical Australia, parts of India and the New World. The weedy plants are usually considered as hybrids between subsp. *bicolor* and subsp. *verticilliflorum*, and named subsp. *drummondii* (Steud.) de Wet (synonyms: *Sorghum × drummondii* (Steud.) Millsp. & Chase, *Sorghum atherimum* Stapf, *Sorghum sudanense* (Piper) Stapf); they occur in Africa wherever cultivated sorghum and its wild relatives are sympatric because they cross freely. These weedy plants occur in recently abandoned fields and field margins as a very persistent weed; stem up to 4 m tall; leaf blade lanceolate, up to 50 cm × 6 cm; panicle usually rather contracted, up to 30 cm × 15 cm, often with pendulous branches. A well-known forage grass, 'Sudan grass', belongs to this complex.

Growth and development.

The optimum temperature for sorghum seed germination is 27–35°C. Seedling emergence takes 3–10 days. Panicle initiation takes place after approximately one third of the growth cycle. By this stage the total number of leaves (7–24) has been determined and about one-third of total leaf area has developed. Rapid leaf development, stem elongation and internode expansion follow panicle initiation. Rapid growth of the panicle also occurs. By the time the flag leaf is visible, all but the final 3 to 4 leaves are fully expanded and light interception is approaching its maximum; lower leaves have begun to senesce. During the boot stage, the developing panicle has almost reached its full size and is clearly visible in the leaf sheath; leaf expansion is complete. The peduncle grows rapidly and the panicle

emerges from the leaf sheath. Flowering follows soon after panicle emergence, with the interval largely determined by temperature. Individual panicles start flowering from the tip downwards and flowering may extend over 4–9 days. Sorghum is predominantly self-pollinating; cross-pollination may range from 0–50%, but is on average about 5–6%. Grain filling occurs rapidly between flowering and the soft dough stage, with about half the total dry weight accumulating in this period. Lower leaves continue to senesce and die. By the hard dough stage, grain dry weight has reached about three-quarters of its final level. At physiological maturity, determined by the appearance of a dark layer at the hilum (where the grain is attached to the panicle), maximum dry weight has been achieved. Moisture content of the grain is usually between 25–35% at this stage. The time taken between flowering and maturity depends on environmental conditions but normally represents about one-third of the duration of the crop cycle. Further drying of the grain takes place between physiological maturity and harvest, which usually occurs when grain moisture content has fallen below 20%. Leaves may senesce rapidly or stay green with further growth if conditions are favourable. Early maturing sorghum cultivars take only 100 days or less, whereas long-duration sorghum requires 5–7 months. Sorghum follows the C₄-cycle photosynthetic pathway.

Ecology

Sorghum is primarily a plant of hot, semi-arid tropical environments that are too dry for maize. It is particularly adapted to drought due to a number of morphological and physiological characteristics, including an extensive root system, waxy bloom on leaves that reduces water loss, and the ability to stop growth in periods of drought and resume it when the stress is relieved. A rainfall of 500–800 mm evenly distributed over the cropping season is normally adequate for cultivars maturing in 3–4 months. Sorghum tolerates waterlogging and can also be grown in areas of high rainfall. It tolerates a wide range of temperatures and is also grown widely in temperate regions and at altitudes up to 2300 m in the tropics. The optimum temperature is 25–31°C, but temperatures as low as 21°C will not dramatically affect growth and yield. Sterility can occur when night temperatures fall below 12–15°C during the flowering period. Sorghum is susceptible to frost, but to a lesser extent than maize and light night-frosts during ripening cause little damage. Sorghum is a short-day plant with a wide range of reactions to photoperiod. Some tropical cultivars fail to flower or to set seed at high latitudes. In the United States, Australia and India the existence of mild photoperiod-sensitive to virtually insensitive cultivars has been recorded.

Sorghum is well suited to grow on heavy Vertisols commonly found in the tropics, where its tolerance of waterlogging is often required, but is equally suited to light sandy soils. The best growth is achieved on loams and sandy loams. Sorghum tolerates a range of soil pH from 5.0–8.5 and is more tolerant of salinity than maize. It is adapted to poor soils and can produce grain on soils where many other crops would fail.

In the floodplains of the Senegal and Niger rivers and in parts of Chad and Cameroon sorghum is sown in the early dry season when the water recedes, and the crop survives on residual moisture ('culture de décrue').

Propagation and planting

Sorghum is normally grown from seed. The 1000-grain weight is 13–40 g. Seed dormancy is not common in cultivated sorghum. A fine seedbed is preferable but is often not achieved. The seed is usually sown directly into a furrow following a plough, but can also be broadcast and harrowed into the soil. Optimum plant spacing depends on soil type and availability of moisture. In low-rainfall areas a population of 20,000 plants/ha is normal, in high-rainfall areas 60,000 plants/ha. For favourable conditions, spacings of 45–75 cm between rows and 15–25 cm within the row, resulting in 80,000–180,000 pockets per ha, are normal; for drier or less fertile conditions rows 1 m apart, or broadcasting at 6 kg seed per ha. A planting depth of 2.5–5 cm is common, and up to 25 seeds may be sown per pocket. Occasionally, seedlings are grown in a nursery and transplanted into the field early in the dry season, e.g. on the floodplains round Lake Chad in Africa ('sorgho repiqué'). Sweet sorghum in the United States is also sometimes transplanted. Sorghum can also be propagated vegetatively by splitting tillers from established plants and transplanting them, a practice that is often used by small farmers to fill gaps. Sorghum may be harvested more than once as a ratoon crop, e.g. in locations with a bimodal rainfall pattern. Sorghum is often grown in intercropping systems with maize, pearl millet, cowpea, common bean, groundnut and bambara groundnut; in India also with pigeonpea. Dye cultivars are never grown in large quantities. Farmers usually grow a few plants in or around their normal sorghum field or near the house.

Management

Sorghum does not compete well with weeds during the early stages of growth, and it is recommended that weeding be done early during the seedling stage. In tropical Africa weeding is commonly done once or twice with a hoe but sometimes animal-drawn or tractor-drawn cultivators are used. Where couch grass (*Cynodon dactylon* (L.) Pers.) is a problem more frequent weeding is necessary. Sorghum may be weeded by a combination of inter-row cultivation with animal-drawn implements and hand weeding within rows. Chemical weed control is almost non-existent among small farmers. Thinning can be carried out at the same time as hand weeding, or at intervals during the crop cycle, particularly where thinnings are used to feed livestock. Subsistence farmers rarely apply fertilizer, but application of farmyard manure or ash is common. In South Africa and the United States high doses of fertilizers are used in the production of sorghum. In tropical Africa sorghum is grown mainly as a rainfed crop, but it is grown under irrigation in Sudan. It is grown in rotations with maize, pearl millet, finger millet, cotton and other crops. It is often planted late in the rotation, as it tolerates low soil fertility. Under certain conditions decomposing roots of sorghum have an allelopathic effect on the subsequent crop, including sorghum.

Diseases and pests

Common seed and seedling rot diseases in sorghum are caused by soil- and seed-borne *Aspergillus*, *Fusarium*, *Pythium*, *Rhizoctonia* and *Rhizopus* spp. They are controlled by treatment of the seed with fungicides. Anthracnose (*Colletotrichum graminicola*) is common in hot and humid parts of Africa. Control measures include the use of resistant

cultivars and crop rotation. Downy mildew (*Peronosclerospora sorghi*) may cause serious yield losses; the use of resistant cultivars and seed treatment are recommended. Smuts (*Sporisorium* spp.) are important panicle diseases. Loose and covered kernel smut are controlled by seed treatment with fungicides; head smut and long smut by using resistant cultivars and cultural practices such as crop rotation and removal of infected panicles. Grain mould is caused by a complex of fungal pathogens (predominantly *Cochliobolus lunatus* (synonym: *Curvularia lunata*), *Fusarium* spp. and *Phoma sorghina*) that infect the grain during development and can lead to severe discoloration and loss of quality. It is most severe in seasons when rains continue through the grain maturity stage and delay the harvest. Control measures include adjustment of the sowing date to avoid maturation during wet weather, and the use of resistant cultivars.

Important pests of sorghum in tropical Africa are shoot fly (*Atherigona soccata*) and stem borers (particularly *Busseola fusca*, *Chilo partellus* and *Sesamia calamistis*). Shoot fly larvae attack shoots of seedlings and tillers, and cause 'dead hearts'. Stem borers cause damage in all crop stages. Damage by both shoot fly and stem borers can be reduced by early, non-staggered planting and seed or soil treatment with insecticides. Resistance to shoot fly is associated with low yield. Foliage pests include army worms (*Spodoptera* and *Mythimna* spp.); they are controlled by contact insecticides. Larvae of the sorghum midge (*Stenodiplosis sorghicola*, synonym: *Contarinia sorghicola*) feed on the young grains in the panicle. Damage can be limited by sowing early-maturing cultivars and avoiding staggered planting. Head bugs (*Eurystylus* and *Calocoris* spp.) suck on developing grains, resulting in yield loss, grain deformation and discoloration and infection by moulds. Guinea type sorghum is generally less affected.

In practice, control methods of diseases and pests are mainly preventative or cultural, including selection of optimum planting dates, seed treatment and crop rotation. Early sowing is particularly important as a mechanism to avoid large insect populations at times when plants are most susceptible to damage. High levels of host plant resistance are available for sorghum midge, but only low levels of resistance for the other pests. Chemical control of diseases and insect pests is rarely practised in tropical Africa.

Birds, especially *Quelea quelea*, cause important yield losses. Control measures include the choice of suitable planting dates, timely harvesting, bird scaring and the destruction of roosting and nesting sites. Brown sorghum is less preferred by birds than the tannin-free white sorghum.

Sorghum is very susceptible to damage by storage pests, the main ones being rice weevil (*Sitophilus oryzae*), flour beetle (*Tribolium castaneum*) and the grain moth (*Sitotroga cerealella*). Damage can be minimized by drying grain adequately before storage. Cultivars with hard grain also suffer less damage.

The parasitic weed *Striga* (especially *Striga hermonthica* (Del.) Benth., but also *Striga asiatica* (L.) Kuntze, *Striga densiflora* Benth. and *Striga forbesii* Benth.) has become a major constraint to sorghum cultivation, particularly in Africa, where severe infestations can lead to grain losses of 100% and land being abandoned. *Striga* can be controlled by cultural methods such as rotation with trap crops or with crops that are not susceptible (e.g. groundnut, cotton or sunflower), rigorous removal of the weeds before flowering and application of nitrogen fertilizer and herbicides. A few sorghum cultivars that are resistant or tolerant to *Striga* have been identified

Harvesting

Sorghum is usually harvested when the grain moisture content has fallen below 20%, and the grain has become hard. Harvesting is done by hand using a knife to cut the panicles, which are temporarily stored in sacks before being taken to the threshing floor for further drying to a moisture content of 12–13%. Alternatively, the whole plant is cut or pulled up and the panicle removed later. Combine harvesting is possible, but many small farmers cannot afford to buy the machinery. In South Africa combine harvesting is more common. For dye production, leaf sheaths are harvested when the plant comes to maturity, about 4–6 months after sowing. They can be used immediately or dried and stored.

Rainfed forage sorghum is usually cut only once, soon after flowering. Forage sorghum crops grown under more favourable conditions, often with irrigation and high levels of fertilizer, can be harvested and then left to regrow (ratoon).

Broomcorn is harvested by hand as mechanical harvesters are not available. Sweet sorghum is harvested when the seed is in the soft dough stage when the sugar content of the stalk is highest.

Yield

Average sorghum grain yields on farmers' fields in Africa are as low as 0.5–0.9 t/ha because sorghum is often grown in marginal areas under traditional farming practices (low inputs, traditional landraces). Under favourable conditions sorghum can produce grain yields up to 13 t/ha. In South Africa, with intensive agricultural practices and improved cultivars, average commercial yield was 2.3 t/ha in 2001. In China, where sorghum is grown with high levels of inputs, yield averages 3.6 t/ha and in the United States 3.8 t/ha.

Forage yields from single-cut cultivars and hybrids can reach 20 t/ha of dry matter. Multi-cut cultivars and hybrids usually give only slightly higher total yields but produce better quality forage. Sweet sorghum yields about 1000 l syrup per ha in the United States.

Average broomcorn yields are 300–600 kg/ha, enough to make 350–800 brooms.

Handling after harvest

The harvested grain of sorghum is usually sun-dried, often in the panicle. Panicles, particularly those to be retained for seed, may be stored hanging from the ceiling of kitchens over cooking fires where the smoke helps to deter insect attack. Alternatively, the heads may be threshed after drying and the grain stored in granaries, above or below ground, designed to prevent insect attack.

Traditional food preparation of sorghum is quite varied. The whole grain may be ground into flour or decorticated before grinding to either a fine particle product or flour which is then used in various food products. To prepare porridge, water is boiled and sorghum flour is gradually added until the desired consistency of the paste is reached. Regular stirring is needed to mix the contents thoroughly. Another simple form of sorghum food preparation is

to boil the grain before or after decorticating. To make beer, sorghum grain is germinated, dried, pounded into flour and mixed with water and left to ferment in a warm place for some days. To make the non-fermented drink 'mageu' in Botswana and South Africa, milled sorghum malt is mixed with water and kept at room temperature for 2–3 days. Occasional stirring may be necessary.

In a traditional method of dyeing hides with sorghum dye in West Africa, a watery extract of wood ashes, preferably from the wood of *Anogeissus leiocarpa* (DC.) Guill. & Perr., is prepared and allowed to stand for 3–4 hours. The major active compound of the lye is potassium- or sodium carbonate. The red leaf sheaths are pulverized and placed in a large vessel in which the dyeing is carried out. From time to time a little lye is added and diluted with plain water as desired, obtaining a crimson liquid. The tanned hide that has been dressed with oil is folded with the tanned side outwards, the hide is immersed for about two minutes in the dye bath, wrung out and shaken. Alternatively, the dye liquid is painted on the tanned surface with the fingers or a brush. The hide is then rinsed in cold water acidulated with lime juice or tamarind pulp. After the hide has been dried, the process is completed by rubbing the hide with a smooth stone on a wooden block. It is estimated that 1.25 l of dye bath is sufficient for about 6 skins of medium size. Another recipe uses about 30 leaf-sheaths of sorghum, about half a spoonful of soda, a handful of 'sant' pods (*Acacia nilotica* (L.) Willd. ex Delile) or 2 handfuls of chips of mangrove bark, 2 spoonfuls of palm oil and 1.5 l of water. These are all mixed together and boiled, the juice of 5 or 6 limes added, and the liquid is left to simmer for 2 hours. It is then ready for application on the skin by brushing or rubbing.

To obtain a dye of constant high quality, a laboratory extraction technique has been designed in Burkina Faso. Sorghum leaf sheaths are crushed into fine particles, a solvent is added in an acid or basic medium (both give similar results) and a red liquid is produced. By addition of an acid the dyestuff is precipitated and is centrifuged off. The end product is a fine, burgundy-red powder with an apigeninidin concentration of 50–60%, ready for use as a dye. Pure apigeninidin can be obtained by further processing of the powder.

Forage sorghum can be fed to livestock while still green or can be stored in various ways for later use. The forage is often dried and stacked or can be made into silage. Stover left after harvest of grain is often grazed by animals.

Genetic resources and breeding

A major collection of sorghum germplasm is maintained and distributed to interested researchers by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India. The collection extends to over 36,000 accessions from all the major sorghum-growing regions of the world (90 countries). Large germplasm collections of sorghum are also held in the United States (Southern Regional Plant Introduction Station, Griffin, Georgia, 30,100 accessions; National Seed Storage Laboratory, Fort Collins, Colorado, 10,500 accessions) and China (Institute of Crop Germplasm Resources (CAAS), Beijing, 15,300 accessions). In tropical Africa large germplasm collections of sorghum are held in Zimbabwe (SADC/ICRISAT Sorghum and Millet Improvement Program, Matopos, 12,340 accessions), Ethiopia (Institute of Biodiversity Conservation (IBC), Addis Ababa, 7260 accessions), Kenya (National Genebank of Kenya, Crop Plant Genetic Resources Centre, KARI, Kikuyu, 3410 accessions) and Uganda (Serere Agricultural and Animal

Production Research Institute, Serere, 2635 accessions).

Breeding

The main objectives in sorghum breeding include high grain yield, white grain for human consumption with improved nutritional value and processing quality, and red or brown grain for feed purposes and brewing. In many countries the emphasis is on producing cultivars which combine high grain yield with high stover yields because of the importance of the residues as animal feed. Incorporation of resistance to major yield-limiting diseases and pests, and tolerance of abiotic stresses are also of high priority. Resistance to grain moulds and other diseases as well as to insect pests such as head bugs and sorghum midge has been identified. High-yielding improved cultivars of sorghum are available in most of the main producing countries. These include cultivars and hybrids produced using cytoplasmic male sterility. Compared to traditional landraces they have a weak photoperiodic response and they are less hardy, less tall, with a lower grain quality but a higher yield potential. *Striga*-resistant cultivars have been released in Africa and India, e.g. 'Framida' in Ghana and Burkina Faso. Cultivars resistant to grain mould have also been released. Special cultivars with high biomass production and good forage quality are bred for animal feed. Modern sorghum cultivars predominate in the Americas, China and Australia, but in Africa they occupy probably less than 10% of the area under sorghum. In India about 50% of the sorghum area is sown to modern cultivars and 50% to traditional landraces.

The sorghum genome is relatively small (about 760 Mbp) compared to that of maize (about 2500 Mbp), and construction of a physical genome map is in progress. Several genetic linkage maps have been developed, mainly based on RFLP markers. Various genes have been tagged, e.g. genes associated with head smut resistance, leaf blight resistance and shattering. Many QTLs have been mapped, including those associated with plant height, tillering, seed size, drought resistance and rust resistance. In-vitro plant regeneration has been achieved from calli derived from young leaf bases, shoot apices, immature inflorescences and immature embryos. Protocols have been developed for the production of stably transformed sorghum plants using microprojectile bombardment or *Agrobacterium*-mediated transformation, but the efficiency is generally low, especially with the former technique.

Prospects

Sorghum is a hardy, drought-tolerant crop with a high potential yield, which plays an important role in tropical Africa and elsewhere, especially as source of food and fodder, but also for a range of other uses, including as a source of dye. Sorghum has lost part of its traditional area in tropical Africa to maize, which yields better in more favourable environments, is less liable to bird damage and easier to process. It is to be expected, however, that sorghum will remain an important food security crop in less favourable environments in tropical Africa. Important problems in sorghum cultivation to be addressed by research and breeding activities are the large yield losses caused by parasitic weeds (especially *Striga hermonthica*), anthracnose, downy mildew, grain moulds, sorghum midge and stem borers. Improved sorghum cultivars are not widely grown in tropical Africa, and

the improvement of seed supply systems should accompany sorghum improvement programmes in this region. Demand for sorghum for non-traditional uses is likely to increase. In particular, the use of sorghum as a feed grain, already well established in many industrialized countries, is likely to become more common in developing countries. However, sorghum faces strong competition from maize in the international feed grain market. Similarly, as increased affluence results in increased demand for meat and dairy products, the use of sorghum as a forage crop in intensive production systems in many tropical regions is likely to expand. The use of sorghum as a raw material for industrial processes will also increase. Research should focus on innovations that are likely to reduce the costs of production of sorghum. This should include research to increase yield levels of available cultivars, and to improve agronomic practices. Emphasis should be placed on enhancing resistance to the main biotic and abiotic stresses and on production of cultivars richer in high quality proteins.

Sorghum dye may profit from the trend of increasing use of natural colourants in foods and cosmetics. Rising harvesting costs of broomcorn in North America and Europe may offer possibilities for expanding this commodity in Africa.

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