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Sorghum Breeding

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Objectives

- Familiarize students with the Sorghum crop, its biology, classification system, adaptation and usage, production constraints, breeding institution working on the crop, and breeding method used to develop sorghum cultivars

Origin, Domestication and Diversification

Sorghum (*Sorghum bicolor* (L.) Moench) is an ancient crop that originated in North Eastern Africa. These places are also areas where greatest diversity of wild and cultivated species of sorghum are found to this day (Fig. 1). Domestication of sorghum probably took place in Ethiopia and some parts of Congo by selecting wild sorghum, approximately 5,000 years ago. India, Sudan and Nigeria are considered as secondary centers of origin. From these centers of origin, sorghum was probably distributed to other parts of the world (Acquaah, 2007). This early distribution and introduction of the crop helped generate further genetic diversity in other continents, such as Asia. The genus Sorghum has greatest genetic diversity ranging from 20 to 30 species. Cultivated sorghum along with the two perennial species [*Sorghum halepense* L (2n=40-forage sorghum) and *Sorghum propinquum* (Kunth)] are included in the genus sorghum. Based on morphological classification, all cultivated sorghums (*Sorghum bicolor* spp.) are grouped in five races along with ten intermediate races. The five races are:

- durra,
- kafire,
- guinea,
- bicolor, and
- caudatum.

Most of these races differ mainly in their panicle morphology, grain size and yield potential. Durra type of sorghum originated primarily in Ethiopia and the horn of Africa, and then spread to Nigeria and other parts of West Africa where it became popular. Kafir types of sorghum developed in the eastern and southern parts of Africa where they grow well. Guinea types developed in West and Central Africa and grow well in that region, while the bicolor type originated in East Africa but is less important to African production.

Fig. 1 Sorghum field showing genetic diversity in grain color. Photo by Teshale Mamo, Iowa State University.

Biology of the Crop

General Characteristics of The Development of the Sorghum Plant

Sorghum is an annual grass, and belongs to the graminae family. It reaches up to 5 m in height with one to several tillers, and these tillers emerge first from the base of the plant and sometimes later from the stem nodes. The tillers on stem notes form when growing conditions are favorable. These tillers form on upper or lower nodes and are undesirable because they form later and produce a small amount of grain that is unripe by harvest with higher moisture content. This can cause delayed harvest, as well as problems in storage, delivery and sales. Lower plant density (i.e. sparse planting) causes more tillering and higher plant density in field planting suppresses tillering. Tillering is suppressed when growing conditions are unfavorable.

Optimum temperature for germination ranges from 27-35^{O}C, and after germination the plant goes through root and leaves development rapidly. Sorghum has a fibrous root system which is mostly concentrated in the top 90 cm of the soil, but root growth can extend twice that depth under dry environments. Sorghum leaves are alternate with the leaf sheath and ranges from 15-35 cm in length. Total number of leaves on the plant varies between 7 to 24 depending on the variety and environmental conditions. Sorghum leaves have rows of motor cells along the midrib on the upper surface of the leaf which is unique characteristic of sorghum leaves as these cells can help the leaves to roll up rapidly during drought stress to minimize water loss from the leaves. In addition, morphological and physiological characteristics of sorghum such as extensive root system, wax on the leaves (minimize water loss) and the ability to stop growth during moisture stress and resume growth when moisture levels increase (from rain) are inherent characteristics of sorghum to adapt to drought conditions.

Growth Stages

The inflorescence or head of sorghum is called panicle that may be loose or dense. Under favorable conditions, initiation of panicle takes place after one third of the growth cycle. Each fully developed panicle can contain 800 to 3000 grains, each one usually enclosed by glumes. The color of the seed is variable. Sorghum flowers usually open during the night or early in the morning with those flowers at the top of the panicle opening first, and it takes 6 to 9 days for the whole panicle to flower. Sorghum is a self pollinated crop due to its flower structure but cross pollination (approximately 2-25 %) occurs naturally.

In general, once the sorghum seedling emerges, the plant goes through three distinct growth stages represented as growth stage I, II and III. The first growth stage (GS I) is recognized as vegetative growth. During this stage, the plant develops leaves, internodes and tillers. This stage helps the plant to prepare for grain formation and growth. At this stage the plant can tolerate drought stress, heat and freezing temperatures. The second growth stage (GS II) is the reproductive phase in which the panicle is developed and maximum number of seeds per plant are set. This growth stage starts with panicle initiation and it continues to flowering. It is reported that it is the most critical period that determines the level of grain production. This is the stage when the crop’s water requirement is high. Hence if severe moisture stress occurs at this stage, panicle initiation is hindered or delayed, leading to incomplete flowering, seed set and loss in grain yield. The third growth (GS III) is the grain filling period which starts with flowering and continues until the grain is filled with drymatter.

Photosynthesis, Photoperiod and Temperature

Sorghum is one of the C4 grasses with high photosynthetic efficiency. It is a short day plant requiring long nights before flower initiation (start of reproductive stage) (Craufurd et al., 1999). The optimum photoperiod for flower initiation ranges from 10 to 11 hours and a photoperiod beyond 12 hours can stimulate vegetative growth. Tropical cultivars are more photoperiod sensitive than short-season sorghum cultivars (quick mature).

Sorghum is a dry land crop requiring high temperature ranges from 27 to 30^{0}C for its growth and development (Craufurd et al., 1999). Increased day and night temperature beyond plant requirements can delay flower initiation and development of flower primordia, and this reduces yield. The sorghum plant can tolerate a temperature as low as 21^{o}C without significant effect on growth and yield.

General Classification

Classification by Utilization or Mode of Consumption

Grain sorghum is the most widely cultivated type of sorghum in the world, and it is the main staple food in dry land (semi-arid tropical region) areas of Africa and Asia. It is an important part of diet that is prepared in the form of boiled porridge, unleavened bread (pancake), popped (like maize), dumplings, beers and non-alcoholic fermented beverages. Sorghum grain is also used as animal feed, and the stems and leaves are used as green chopped animal feed, hay and pasture feed. It is grown as grain and fodder crop in the USA, Europe and Australia (Berenji and Dahlberg, 2004).

Human Food

In Africa and Asia, many people consume sorghum grain in unfermented and fermented pancake (breads), porridges, dumplings, snacks, and malted alcoholic and nonalcoholic beverages. White grain sorghum is mostly preferred for cooking while red and brown grain sorghum are preferred for beer making. In some parts of Africa, e.g., around Lake Victoria, where bird pressure is high, farmers may grow red and brown grain sorghum instead of white grain types, because these types of sorghum are rich in tannin and are bitter tasting thus preventing bird feeding and associated losses.

In the USA, sorghum is primarily grown as a fuel crop (for ethanol production) and there are few food products available to consumers; however several researchers have developed and introduced products from sorghum into the food market. In addition, several researchers have been working on health benefits associated with sorghum grain that might increase its use in the health food industry. For example, food products made from sorghum grain did not show toxicity to celiac patients (Ciacci et al., 2007), and several gluten-free sorghum products have been developed and are being popularized (Schober et al., 2005).

Animal Feed

In the United State, Central and Southern America, Europe, Australia and China, sorghum grain is mainly used as cattle, pig and chicken feeds. Similar to the use of silage corn, the sweet sorghum type is also used as cattle feed in Europe. The problem with sorghum as cattle feed is the presence of prussic acid (HCN) which causes death in cattle if the animal consumes fresh sweet sorghum. This problem is eliminated through cultivar choice and proper agronomic practices.

Renewable Energy

Sorghum is one of the crops that can be used for production of renewable fuels in temperate regions. It is unique among grasses in being used as feed stocks for renewable energy because it can be used in various forms for biofuel production. Starch and sugar are converted to ethanol, and lignocellulose (composed mainly of cellulose, hemicellulose and lignin - inedible parts of the plant) is converted to biogas, making sweet sorghum a unique biofuel crop that is also used as food and fodder.

Classification of Grain Sorghum by Intended Purpose

Sorghum is classified into four major groups based on the applications.

1. *Grain sorghum:* this group is used as staple food in the tropical areas of Africa and Asia and is often used as raw materials for making alcoholic beverages, sweets and glucose.
2. *Sweet sorghum:* this group is mainly produced for sugar production. This sugar is used as material to produce sweet syrup, which is similar to molasses.
3. *Broom sorghum:* this is recognized by long panicles with fine, elastic branches called fibers with the seed on their tip which is used as material to making brooms.
4. *Grass sorghum:* this is mainly grown for green feed and forage purpose.

Classification of Grain Sorghum by Agronomic Groups

Commercial grain sorghum is classified into seven groups.

1. *Kafir sorghum:* this group of sorghum is originally from South Africa. In this group, the stalk is thick and juicy, have large leaves, and the panicles are cylindrical in shape without awn. The seed are medium in size, color could be white, pink or red.
2. *Milo sorghum:* came from east Africa, has short, compact and oval panicles, with less juicy stems than kafir, and has light green leaves. The seed size is relatively large with either yellow or white seed color. The plant in this group has more tillers than kafir. The varieties in this group are more heat and drought tolerant than kafir.
3. *Hegari sorghum:* came from Sudan and is similar to kafir but has more nearly oval panicles. Plants in this group have more leaves than kafir, and the grain produces a sweeter juice which is desirable for forage. Seeds are chalky white in color.
4. *Feterita sorghum:* is originally from Sudan. Plants have few leaves and dry stems. Panicles are oval compact shape. Seeds are large in size and chalky white in color.
5. *Dura sorghum:* came from Mediterranean and Middle East regions. Plants have dry stems, flat seeds with pubescent glumes. The panicles in this group are erect but compact or loose. The varieties in this group are mainly grown in North Africa, India and the Near East.
6. *Shallu sorghum:* This group is from India, and plants have tall, slender and dry stalks. Panicles are loose, and seed color is pearly white. The varieties in this group are late maturing, thus requiring a relatively long growing period.
7. *Kaoliang sorghum:* This group is mainly grown in China and Japan. The varieties have slender, dry and woody stalks with sparse leaves. They have an open semi compact panicle. Seeds are small in size and white or brown in color and are bitter in taste.

Adaption and Economic Importance and Uses

Adaption

Sorghum is a small cereal crop adapted to wide range of environmental conditions, but is particularly adapted to a warm weather. Sorghum is mainly grown between 40^{o}N and 40^{o}S in arid, semi-arid tropics and subtropics, and it can also be grown at an altitude of up to 2300 m above sea level in the tropics with annual rainfall ranges from 300 -1200 mm. It is also widely grown in temperate regions mainly in South China and USA and some parts of Europe. Cold tolerant sorghums are also grown successfully in Central America.

Sorghum is a short day plant requiring 90 to 140 days to mature depending on climate and type of cultivar. Its genetic variation in response to photoperiod and temperature contribute to its adaptation to the wide range of growing environments. Sorghum's most outstanding characteristics are its heat and drought tolerance and it can also be grown on a wide range of soil types from vertisol (clay soil) in the tropics to light sandy soil. The soil pH requirement ranges from neutral to high pH (5.0 to 8.5) and it is tolerant to salinity compared with corn. Sorghum can be grown in poor soil and can produce grain where other crops fail to produce fruit.

Cropping System

Intercropping is a cropping system involving the growing of two or more crops in the same space and at the same time. It is a common practice among small scale farmers in the semi-arid areas of Africa and Asia in order to increase productivity per unit area of the land (Kidane et al., 1989). Sorghum is one of the important cereal crops being used for intercropping. It is commonly intercropped with a legume crop such as sorghum-chickpea, sorghum-common bean, sorghum-pigeon pea, sorghum-cowpea and sorghum-mung bean. It is also intercropped with other cereals such as sorghum-millet and maize-sorghum. Several researchers have reported that a significant yield was obtained from intercropping compared to pure stands. Sorghum yield was increased 8-34% in a sorghum-legume intercropping system compared to sole sorghum crop stand (Singh, 1977). In Ethiopia, sorghum-mung bean intercropping gave extra yield of 495 kg/ha of sorghum compared to sole sorghum crop (Kidane et al., 1989). Striga infestation on sorghum was reduced when mung bean was intercropped with sorghum. In general, intercropping of sorghum with legumes has a benefit in that the legume crop allows efficient use of both space and time to optimize effects (increased land productivity). Intercropping promotes diversification of crops so that the farmers can harvest two or more different crops from the same piece of land, and it provides better weed control and reduces diseases and pests incidence.

Production Constraints

Biotic Constraints

Diseases and pests are the main causes of significant yield losses in sorghum. The fungal disease **Smut**, caused by *Sphacelotheca* spp., may cause more yield losses than other fungal diseases and is widely important in the eastern, central and southern parts of Africa where sorghum is used as major staple food. The different types of smut are: loose smut, kernel smut, head smut and long smut. They are controlled by seed treatment with fungicides. Through breeding, use of resistant cultivars provide protection against this disease. **Rust**, which is caused by *Puccunia purpurea,* is another important fungal disease and is widely distributed in many parts of sorghum producing regions particularly in Africa. **Grain mold** is caused by several fungi, *Curvularia lunata*, *Fusarium spp*, and anthracnose (*Colletotrichum graminicola*) are the most important sorghum diseases that infect the grain during grain development and can cause severe discoloration of grain and loss of seed quality. Continued rainfall throughout grain maturity period increases the occurrence of grain mold and causes delayed harvest. Grain mold control measures include the use of resistant cultivars and adjustment of planting time to avoid long maturation period during prolonged rainy season. Downy mildew, ergot and bacterial streak are occasional important constraints.

Sorghum insect pests important in tropical Africa are stem borer (particularly, *Busseola fusca* and *Chilo partellus*) and shoot fly (*Antherigona soccata*). Yield losses due to these insect pests are significantly high and the problem is widespread in major sorghum producing African countries.

Other biotic constraints such as Striga, weeds, and quelea are also considered as major production contains. Striga is rated as causing high yield losses in all regions in Africa. In some countries, the yield losses were estimated to be more than 50%, particularly in Rwanda and Kenya (Wortman et al. 2009).

Abiotic Constraints

Abiotic stresses such as extreme drought (in all sorghum growing regions), saline soil (some parts of India and Middle East countries) and acidic soil (mostly in Latin America) are major production constraints.

International Breeding Center

Collections Diversity

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), a member of the Consultative Group on International Agricultural Research (CGIAR), based at Patancheru, India was established in 1972 with sorghum as one of its five mandate crops.

A total of 36,774 accessions have been collected from 90 countries (Reddy et al., 2008) and maintained in a gene bank, and these collections exhibit 80% of the diversity present in the crop.

ICRISAT coordinates all sorghum research programs in the semi-arid (dry land) tropics of the world. It has strong collaboration and active breeding programs covering over 55 countries in Asia and sub-Saharan Africa with a mission to reduce poverty, hunger, and environmental degradation in the dry land areas of the tropics. ICRISAT has been addressing national, regional and global concerns for sorghum improvement through developing sorghum cultivars with genetic resistance to major diseases and insect pests. ICRISAT is also developing intermediate breeding products such as a wide range of male sterile lines that are widely used by public and private breeding centers for hybrid cultivar development. ICRISAT is more involved in diversification of sorghum breeding populations through incorporation of major abiotic and biotic resistance traits that have not previously been used in sorghum improvement programs. The traits that are currently being given emphasis at the global level include tolerance to drought, heat, Aluminum toxicity, salt, head and stem pests, and grain molds. Earliness with high grain and biomass yield, and tillering capacity are also emphasized.

Additional Collections Locations

In addition to ICRISAT, large sorghum collections are held in temperate regions including USA (National seed storage lab) and China. Similarly, in tropical Africa, large sorghum germplasm collections are held in Zimbabwe (SADC/ICRISAT sorghum and millet improvement program, Matopos), Ethiopia (Institute of Biodiversity Conservation, Addis Ababa), Kenya (National gene bank, Crop Plant Genetic Center, KARI) and Uganda (Serere Agricultural and Animal Production Research Institute). All these accessions are a valuable genetic resource for further germplasm development efforts.

Breeding Methods and Strategies

Breeding Opportunities and Objectives

Sorghum (2n=2x=20) is predominantly a self-pollinated crop with out-crossing ranging from 2 to 25 %. It has a small genome size (730 Mbp) compared to maize or sugar cane. Sorghum genome is a fully sequenced and provides many useful opportunities to plant breeders and genomics researchers.

Breeding objectives of sorghum include: high grain and fodder yield potential, resistance to diseases (smut, rust, grain mold, bacterial blight, anthracnose, and downy mildew etc.), resistance to insect pests (stalk borer, shoot fly, and midge), resistance to drought and extremely acidic soil, wide adaptation and improved quality (for use in bread, porridge, snacks, and beverages).

In sorghum breeding programs, breeders are developing two kinds of cultivars: 1) open pollinated (OP) or pure line cultivars (mainly for developing countries), and 2) hybrid cultivars (mainly for industrialized countries where the seed system are well developed).

The breeding methods for open pollinated variety (OPV) is different from pure-line or hybrid cultivar development. Recurrent selection schemes are used for OPV, while breeding methods that we learned for self-pollinating crops are used to develop pure-lines. Hybrid development programs will also use pure-lines, however, they use three different kinds of pure-lines: A-line (cms line), B line (maintainer line) and R-line (restorer line) details presented in Breeding Methods module.

Open Pollinated and Pure Line Culitvars Development Methods

A. **Population improvement:** This is the most common type of breeding method being used in developing countries (Africa), and it includes a group of sorghum plants sharing a common gene pool. Sorghum population improvement program is mainly used for developing broad-based gene pools through recurrent selection methods. In population improvement, the recurrent selection methods are the most useful methods for improving quantitatively inherited traits by increasing frequency of genes that effect trait/traits under selection and to maintain genetic variability by recombining superior genotypes for further and continuous improvement. The method of population improvement is grouped into Intra-population improvement (practiced within specific population for its improvement), and Inter-population improvement methods (selection is based on the intercross performance between two populations). The most convenient population improvement methods in sorghum are mass selection, S1, and S2 progeny testing (ICRISAT annual report, 2010). Details of these methods are covered in **Breeding Methods**.
B. **Pedigree method (or another method applicable to self-pollinated crops):** In this method, sorghum breeders are hybridizing between desirable complementary parental lines (Fig. 2), followed by selection of desirable plants from segregating populations until homozygosity is achieved. It is applicable for improving specific trait such as disease and insect pest resistance, plant height, early maturity, etc. These methods will lead to the development of pureline cultivars.

Note: This method is used to develop B-line and R-lines for Hybrid development and production programs.

C. **Backcross breeding:** Backcross breeding in sorghum is used to transfer favorable single or few genes including resistance to diseases (grain mold, rust and smut), and resistance to insect pests (stalk borer and shoot fly) from donor genotype, which generally has poor agronomic performance, into elite genotype (recipient).

Note: This method is used to develop A-line version of B-lines for Hybrid development and production programs.

Fig. 2 A crossing block. Photo by Teshale Mamo, Iowa State Univeristy.

Hybrid Cultivar Development (Hybrid Breeding)

This method of hybrid cultivar development in sorghum closely resembles that of hybrid corn breeding. The two major differences are that (a) heterotic groups are not well defined in sorghum as in maize, so groups are based on fertility restorer genes, however more recently, reproductive groups are emerging with the differentiation and use of nuclear fertility genes. The other difference (b) is that sorghum utilizes cytoplasmic male sterility system (3-line system) to facilitate hybrid seed production unlike maize where manual detasseling, which works very well is employed (detassel female inbred line and allow male inbred line pollen to pollinate) to create hybrid seed on female ears.

Briefly, a plant breeder will develop B-line (maintainer) and R-line (restorer) under two separate reproductive groups (to maximize heterosis) using pedigree or Single Seed Descent approach or any other method suitable for a self-pollinating crop. Once new and superior B-lines are developed, backcross breeding is used to convert them to A-lines (CMS lines). As the backcross breeding program continues, general combining ability (GCA) or specific combining ability (SCA) may be assessed to decide which B-line conversion to continue and also to generate information on suitable R line parent in combination. The A-line is cytoplasmic male sterile and serves as the seed bearing parent. The B-line has recessive form of fertility restorer gene and is used as a maintainer for the A-line. The R line has the dominant form of fertility restorer gene in the nucleus and has the capacity to restore fertility in the A system and it is used as the pollen parent. For details, see the **Breeding Methods** e-module for diagram on fertility and restorer genes in cytoplasm and nucleus, respectively.

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