Botany, Taxonomy and Breeding

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Abstract

Sorghum is one of the most important cereal crops grown in the semi-arid tropics (SAT) of Asia, Africa, and the Americas for its food, feed, fodder, and fuel value. Sorghum production is constrained by several biotic and abiotic stresses. Genetic enhancement of sorghum for grain and stover yield, nutritional quality, and plant defense traits (abiotic and biotic) that stabilize the crop performance requires thorough knowledge of crop botany, diversity, and genetics so as to deploy appropriate crop-breeding strategies. Sorghum is one of the well-understood species in terms of botany, floral biology, and genetic diversity. Both cultivated and wild forms are available in sorghum, which are well distributed in Africa, its center of origin, and in the rest of the world. This chapter describes the botany, floral biology, and classification of sorghum and their implications to the breeding methods to be used. Also this chapter presents how the understanding of botany and taxonomy can be effectively used for improving sorghum yield and nutritional quality traits.

1 Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is a self-pollinating, diploid ($2n = 2x = 20$) species belonging to the Poaceae family with a genome size of 730 Mb, about 25 % the size of maize. It is a C_4 plant with higher photosynthetic efficiency and higher abiotic stress tolerance (Nagy et al. 1995; Reddy et al. 2009) adapted to a range of environments around the world. Its small genome makes sorghum an attractive model for studying the functional genomics of C_4 grasses. Drought tolerance makes sorghum especially important in dry regions such as northeast Africa (its center of diversity), India, and the southern plains of the United States (Paterson et al. 1995, 2009). Genetic variation for micronutrient concentration and its ability to absorb, translocate, and accumulate higher micronutrients in grain makes it an important model for biofortification research (Ashok Kumar et al. 2012). Its high level of inbreeding makes it an attractive association genetics system.

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Sorghum is among the climate-resilient crops that can better adapt to climate changes (Reddy et al. 2011). This chapter deals with the botany, floral biology, and taxonomy of sorghum and their implications for sorghum improvement methods and their utilization in improving sorghum yield and nutritional quality.

Sorghum is among the top 10 crops that feed the world. It is the dietary staple of more than 500 million people in over 30 countries, primarily in the developing world. It is grown on ~40 m ha in more than 90 countries in Africa, Asia, Oceania, and the Americas. The top 10 sorghum producers globally are the United States, India, Mexico, Nigeria, Sudan, Ethiopia, Australia, Brazil, China, and Burkina Faso (Rakshit et al. 2014). Sorghum accounts for 6 % of the global coarse cereals production in the world and is particularly well suited to hot and dry agroecologies in the world. Global sorghum productivity is low (1.4 t ha^{-1}) with wide variation in different parts of the world (Reddy et al. 2011). Although productivity is high in the Americas, China, and Australia, it is low in India, Nigeria, and Sudan.

Broadly, the world sorghum economy consists of two distinct production systems: a traditional, subsistence, smallholder farming production system where most of the production is consumed directly as food (mainly in Africa and Asia) with limited or no marketable surplus, and a modern, mechanized, high-input, large-scale sector where output is used largely as animal feed (mainly in the developed countries and in Latin America). The future of the sorghum economy is linked with its contribution to food security in Africa, income growth and poverty alleviation in Asia, and the efficient use of water in drought-prone regions in much of the developed world.

Sorghum is one of the cheapest sources of energy and micronutrients, and a vast majority of the population in sub-Saharan Africa and India depend on it for their dietary energy and micronutrient requirement. Sorghum provides more than 50 % of the dietary micronutrients, particularly Fe and Zn, to the low-income group, particularly in rural India where both physical and economic access to nutrient-rich foods is limited (Kumar et al. 2011). Thus, sorghum is a unique crop with multiple uses as food, feed, fodder, fuel, and fiber. Different utilizations of sorghum have been detailed in Chap. 1. Sorghum is generally grown in the rainy season (spring) but in India and in some parts of Africa it is grown in both rainy and post-rainy seasons (Reddy et al. 2009). In some parts of the world sorghum is grown in the summer season particularly for forage production.

2 Taxonomy and Classification

Sorghum exhibits various morphophysiological forms and large variation for floral morphology resulting in classification to various basic and intermediate races. Taxonomically it was first described by Linnaeus in 1753 under the name *Holcus*. Originally he delineated several species of Holcus, some of which have been later moved to the tribe Avenae, where the generic name Holcus now belongs. In 1794, Moench distinguished the genus *Sorghum* from genus *Holcus* (Celarier et al. 1959; Clayton et al. 1961). Subsequently, several authors have discussed the systematics, origin, and evolution of sorghum since Linnaeus (de Wet and Huckabay 1967; de Wet and Harlan 1971; Dahlberg 2000). Sorghum is classified under the family Poaceae, tribe Andropogoneae, subtribe Sorghinae, genus *Sorghum* Moench (Clayton and Renvoize 1986). Some authors further divided the genus into five subgenera: *sorghum*, *chaetosorghum*, *heterosorghum*, *parasorghum*, and *stiposorghum* (Garber 1950; Celarier 1959). Variation within these five subgenera except the subgenera *sorghum* has been described (Celarier 1959). *Sorghum bicolor* subspp. *bicolor* contains all of the cultivated sorghums. Doggett (1988) described them as annual plants, with stout culms up to 5 m tall, often branched, and frequently tillering.

Harlan and de Wet (1972) developed a simplified classification of cultivated sorghum that proved to be of real practical utility for sorghum researchers. They classified *Sorghum bicolor* (L.) Moench, subspp. *bicolor* into five basic and ten hybrid races as depicted below.

Basic races	Intermediate/hybrid races
1. Race *bicolor* (B) 2. Race *guinea* (G) 3. Race *caudatum* (C) 4. Race *kafir* (K) 5. Race *durra*(D)	6. Race *guinea-bicolor* (GB) 7. Race *caudatum-bicolor* (CB) 8. Race *kafir-bicolor* (KB) 9. Race *durra-bicolor* (DB) 10. Race *guinea-caudatum* (GC) 11. Race *guinea-kafir* (GK) 12. Race *guinea-durra* (GD) 13. Race *kafir-caudatum* (KC) 14. Race *durra-caudatum* (DC) 15. Race *kafir-durra* (KD)

The descriptors for five basic races (Fig. 1) in sorghum are as given below.

1. **Bicolor**: Grain elongate, sometimes slightly obovate, nearly symmetrical dorsoventrally, glumes clasping the grain, which may be completely covered or exposed as much as one-fourth of its length at the tip, spikelets persistent.
2. **Guinea**: Grain flattened dorsoventrally, sublenticular in outline, twisting at maturity nearly 90° between gaping involute glumes that are nearly as long as to longer than the grain. They are easily distinguishable by the presence of open glumes.
3. **Caudatum**: Grain markedly symmetrical, the side next to the lower glume flat or in extreme cases somewhat concave, the opposite side rounded and bulging, the persistent style often at the tip of a beak pointing towards the lower glume, glumes half the length of the grain or less.
4. **Kafir**: Grain approximately symmetrical, more or less spherical, glumes clasping and variable in length.
5. **Durra**: Grain rounded obovate, wedge-shaped at the base and broadest slightly above the middle; glumes very wide, the tip of a different texture from the base and often with a transverse crease across the middle.

All 15 races of cultivated sorghum can be identified by mature spikelets alone, although head type is sometimes helpful. This classification is clear and simple and practically all of the variation in cultivated sorghum can be accounted for by the five basic races and their intermediate combinations. The intermediate races involving guinea, for example, have glumes that open partially and seeds that twist noticeably, but not as much as in pure guinea. Intermediate races involving caudatum have asymmetrical seeds, but the character is not as fully expressed as in pure caudatum. Other intermediate combinations can be recognized in a similar manner. The method is so sensitive that even three-way and possibly four-way combinations can also be recognized, but these are usually products of modern plant breeding and not part of the variation of indigenous varieties. If they occur in significant numbers, they could be best treated as subraces of the main races.

In sorghum the degree of expression of these characteristics and their combinations determine the race, for the most part without equivocation. Identification can be made easily in the field or in the laboratory from head or even spikelet specimens. In addition to the basic and intermediate races described above, some of the commercial grain sorghum types are utilized in sorghum improvement programs, the characteristics of which are given in Table 1. They denote only commercial grain sorghum types and cut across intermediate/basic races. The Biodiversity International (formerly International Plant Genetic Resources Institute, IPGRI) Advisory Committee on Sorghum and Millets Germplasm has accepted this (de Wet and Harlan 1972) classification, and recommended this to describe sorghum germplasm (IBPGR/ICRISAT 1980). The amount of genetic variability available in sorghum is immense. Much of the genetic variability is available in areas of origin of the crop (Africa) and regions of early introduction (Asia). In Africa, genetic variability is available in both cultivated species and wild progenitors of the crop (Gebrekidan 1981). De Wet and Harlan (1972) reported on the distribution of both wild relatives and the major cultivated races of the

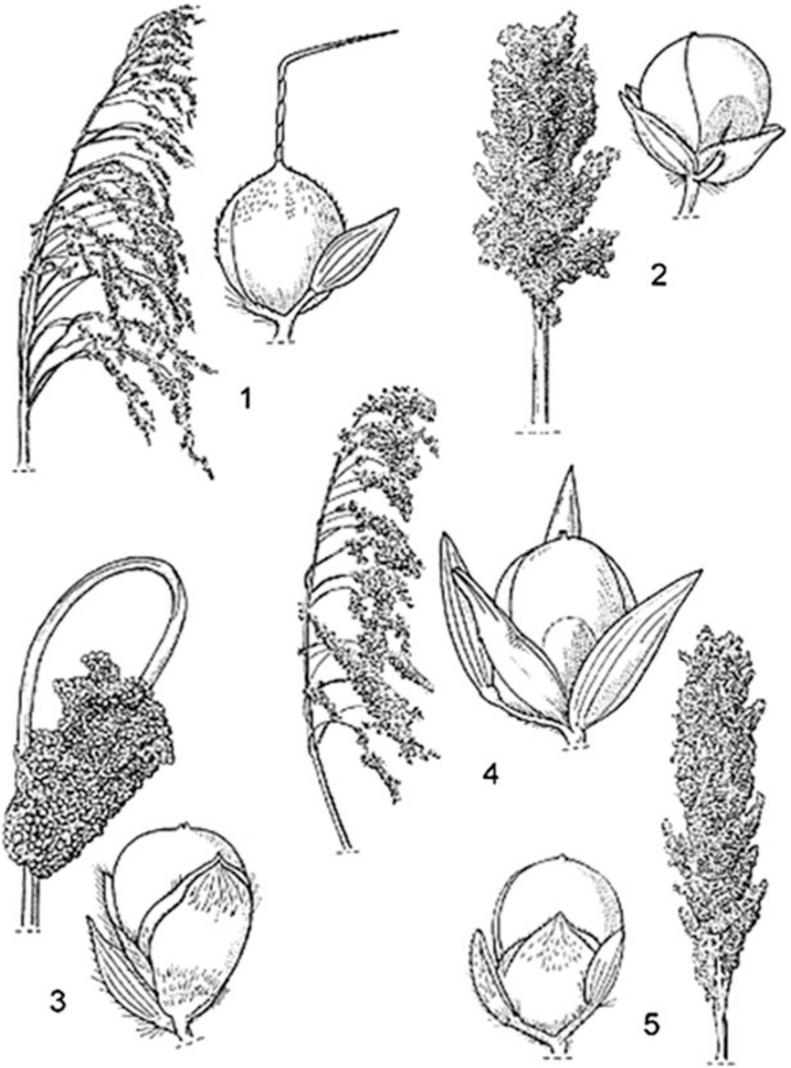

Fig. 1 Panicles and spikelets of the five basic races in sorhgum: (1) bicolor; (2) caudatum; (3) durra; (4) guinea; and (5) kafir. *Source* PROSEA

crop in Africa. However, this natural genetic diversity is subjected to a range of threats from natural selection and destruction of habitats and often merely expedient agricultural practices of mankind. Landraces and wild relatives of cultivated sorghum from the centers of diversity have been rich sources of resistance to new pathogens, insect pests, and other stresses such as high temperature and drought, as well as sources of traits to improve food and fodder quality, animal feed, and industrial products. Preventing the vulnerability of landraces and wild relatives of cultivated sorghum from extinction, following the release of varieties and hybrids, collection and conservation of sorghum germplasm was accelerated about four decades ago. Since then, germplasm collection and conservation have become integral components of several crop improvement programs at both national and international levels (Rosenow and Dalhberg 2000). The gene bank at ICRISAT holds ~38,000 global collections of sorghum germplasm which represent 80 % of the genetic variability in sorghum. All this germplasm is

Table 1 Characteristics of commercial grain sorghum types used in sorghum improvement programs

Grain sorghum type	Brief morphological description	Geographical location
Durra	Hairy rachis, flattened kernels, and dry stalks	Mediterranean, Near East, Middle East
Shallu	Partly pubescent involute glumes, cone-shaped lax panicles, corneous kernels, dry and nonsweet stalks	India, tropical Africa
Guineense	Involute and nearly glabrous glumes and compact panicles	Central and Western Africa
Kafir	Awnless, compact cylindrical panicles and juicy nonsweet stalks	South Africa
Kaoliang	Stiff stalks, thick hard rind, stiff spreading and few panicle branches, and dry and nonsweet stalks	Eastern Asia
Milo	Yellow midrib, transverse wrinkle of the glumes, compact, awned panicles, large round kernels	East Africa
Feterita	Large kernels, brown testa, and dry and nonsweet stalks	Sudan
Hegari	Rounded kernels, brown testa midcompact ellipsoid and branched panicles, and white kernels with a bluish-white appearance	Sudan

well characterized and conserved using short-term and long-term conservation practices. To make the germplasm accessions more useful for crop improvement research, core collections representing ~10 % of the total collections were developed by Dahlberg et al. (2004) and mini-core collections, representing ~1 % of the total collections, were developed by Upadhyaya et al. (2009) in sorghum. Details on the genetic resources of sorghum have been elaborated in Chap. 4.

3 Floral Biology, Reproduction, and Implications for Crop Improvement

Sorghum is an annual/perennial grass adapted to a range of climates spread between 40°S and 40°N latitudes and therefore is widely distributed across various continents. The adaptation features are slightly different for tropical and temperate environments (Vanderlip and Reeves 1972; Rao et al. 2004). The photoperiod insensitivity and dwarfism predominate the temperate adaptation to facilitate mechanized harvesting whereas sorghums grown in the tropics are mostly tall and photoperiod sensitive barring the improved hybrids (Thurber et al. 2013). Sorghum has a well-developed root system and in addition to its subterranean root system, sorghum forms strong aerial roots permeating through the soil and ensuring better stability. The stem is strong, hard, smooth, and divided by nodes and grows up to 1–1.8 m, but sweet sorghums and high biomass sorghums are taller (2.5–4 m). Sorghum leaves are 7 and 28 in number arranged alternating to opposite sides with parallel venation. The leaves are 50–100 mm wide and 0.5–0.8 m long depending upon the genotype. Leaves and stems are often covered with a wax layer which is an adaptation mechanism to tolerate drought and insect attacks. The panicle varies from loose to compact; in some varieties the panicle remains surrounded by sheath, although this is not desirable from an economic yield point of view. In some genotypes the peduncle is recurred resulting in a pendant head referred to as “goose neck”. The sorghum panicle consists of spikelets in pairs, sessile and pedicillate types; the sessile is hermaphrodite and fertile and the other pedicillate contains only anthers (Aruna and Audilakshmi 2008). The grain is caryopsis; the endosperm is starchy; the embryo consists of plumule, coleoptiles, and radical coleorhizae referred to as scutellum.

Sorghum is a short-day plant, and blooming is hastened by short days and long nights. Delayed flowering can be typically observed when winter-season adapted cultivars are grown in the spring season. However, varieties differ in their photoperiod sensitivity (Quinby and Karper 1947) and it has implications in sorghum improvement. In traditional varieties, the reproductive stage is initiated when day lengths return to 12 h. Sorghum follows a predictable pattern of growth from planting through physiological maturity. The duration between growth stages is closely dependent upon the air temperatures and relative maturity of the cultivar. The number of days required for a cultivar to reach maturity depends primarily on location, date of planting, and climatic temperature. For a given cultivar, days to 50 % flowering may vary depending on growing conditions, because daily minimum and maximum temperatures vary from year to year and between locations. The use of cumulative growing degree unit (GDU) gives a better idea from planting to successful growth stages until maturity in sorghum. The GDU (°C) for short-season sorghum cultivars was 1467 whereas for long-season cultivars it may go up to 1849 °C (https://www.uaex.edu/publications/pdf/mp297/MP297.pdf verified on June 20th, 2016). Usually, the floral initial (primary branch primordial differentiation on the floral apex) is 15–30 cm above the ground when the plants are about 50–75 cm tall (House 1980). Floral initiation marks the end of the vegetative phase. The time required for transformation from the vegetative primordial to reproductive primordial is largely influenced by the genotype and the environment. The grand growth period in sorghum follows the formation of a floral bud and consists largely of cell enlargement. In general, sorghum hybrids take less time to reach panicle initiation, more days to expand the panicle, and a longer grain-filling period than their corresponding parents (Maiti 1996). This enabled exploitation of heterosis through hybrids' development and their commercialization.

3.1 Mode of Reproduction and Artificial Hybridization

Sorghum is a self-pollinated crop with the natural cross-pollination from 0.6 to 15 % depending on the genotype, panicle type, and wind direction and velocity (House 1980). The inflorescence is a raceme, consisting of one to several spikelets. The spikelets usually occur in pairs, one being sessile and the second borne on a short pedicel, except the terminal sessile spikelet, which is accompanied by two pedicelled spikelets. The sessile spikelet contains a perfect flower whereas the pedicillate spikelet possesses only anthers but occasionally has a rudimentary ovary and empty glumes.

In sorghum anthesis starts with the exsertion of the complete panicle from the boot leaf. Flowers begin to open two days after complete emergence of the panicle. The sorghum head begins to flower at its tip and anthesis proceeds successively downward. Anthesis takes place first in the sessile spikelets. It takes about 6 days for completion of anthesis in the panicle with maximum flowering at 3 or 4 days after anthesis begins. Anthesis takes place during the morning hours, and frequently occurs just before or just after sunrise, but may be delayed on cloudy damp mornings. Maximum flowering is observed between 06:00 and 09:00 h. Because all heads in a field do not flower at the same time, pollen is usually available for a period of 10–15 days. At the time of flowering (anthesis), the glumes open and all three anthers fall free, while the two stigmas protrude, each on a stiff style. The anthers dehisce when they are dry and pollen is blown into the air. Pollen in the anthers remains viable several hours after shedding. Flowers remain open for 30–90 min. Dehiscence of the anthers for pollen diffusion takes place through the apical pore. The pollen drifts to the stigma, where it germinates; the pollen tube, with two nuclei, grows down the style, to fertilize the egg and form a $2n$ nucleus (Aruna and Audilakshmi 2008). Stigmas get exposed before the anthers dehisce subjecting them to cross-pollination.

Pollination for crossing purposes should start soon after normal pollen shedding is completed during the morning hours.

Sorghum is a breeder-friendly crop as it is amenable for crossing and selfing quite easily. For selfing, after panicle exsertion, bagging should be done by snipping off the flowered florets at the tip. Crossing is done by emasculation of selected panicles and dusting of pollen from identified plants. Hand emasculation is most commonly practiced in sorghum. Because of this ease in crossing, hybridization is most commonly followed in sorghum for trait improvement. For effective results in artificial hybridization the pollen is collected in pollen bags and thoroughly dusted on the emasculated or male-sterile panicles.

4 Sorghum Improvement Methods

The crop improvement methods depend on the pollination control mechanisms and cultivar options. As mentioned earlier, sorghum is a breeder-friendly crop. One can employ the breeding methods that can be used to improve both self- and cross-pollinated crops with ease in sorghum. This is the reason why one can find sorghum pure line varieties, hybrids, and populations as cultivar options in different parts of the world. However, sorghum hybrids are superior to pure lines and populations for yield and other important agronomic traits. The discovery of cytoplasmic-nuclear male sterility in sorghum helped to produce hybrid seeds on a mass scale using a three-line system (A, B, and R) for commercial cultivation of hybrids (Stephens and Holland 1954a, b).

4.1 Pure Line Selection

Pure line selection is the most common method of crop breeding particularly in self-pollinated crops. Pure line selection is practiced under two situations: (i) when there is a need to develop a variety from a landrace population, and (ii) while developing a variety from a segregating population. For example, in sorghum, for post-rainy season adaptation in India, the local landraces from the state of Maharashtra were collected and single plant selections were made for a couple of generations and the performance for grain and stover yields of the selected lines was compared. The line showing better performance than the check variety for yield traits across locations was released for commercial cultivation (Audilakshmi and Aruna 2008). In the case of segregating populations, the individual plants are heterozygous in the beginning as they are the products of crossing between two homozygotes and attain homozygosity in successive generations upon self-pollination. Individual plant selections have to be carried out for at least five to six generations to achieve the desired level of homozygosity of a pure line. A higher number of plants (3000–10,000) of segregating population are evaluated and selection is practiced to obtain the desired plants.

4.2 Mass Selection

Mass selection differs from pure line selection, wherein a number of desirable plants (instead of only one) are selected and compositing is done on the harvested seed to produce the next generation (Allard 1960). This method has a few drawbacks. It is not known whether the plants being grouped are homogeneous and some of them if heterogeneous would segregate further in following generations, and repeated selection would be required (Sharma 1988). Mass selection is generally practiced to purify a variety. A large number of single plants are selected from an impure variety population, each line progeny tested, and similar type progeny bulked to form the pure seed lot. The success of the method depends upon high heritability, that is, the presence of additive gene action and minimal influence of genotype × environment interaction on the expression of the selected trait. Mass selection is relatively less used in sorghum except for the improvement of plant height or grain size.

4.3 Hybridization-Based Methods

The term hybridization refers to the crossing of two genetically different individuals as it combines the traits of two varieties and provides an opportunity to select plants with desirable features of both parents through recombination in the segregating progeny. As the natural variability for most traits is limited or already exploited, there is a need to create new variability by making artificial hybrids to make any further dent in developing improved varieties through selection in the segregating populations. As most of the traits of interest in sorghum are quantitatively inherited, sorghum breeders generally use the pedigree method of selection in segregating populations. In the pedigree method, the records of the ancestry or pedigree of each progeny is maintained and it is easy to trace back the parentage and selection. With the pedigree system, the F_2 generation represents the first and the maximum opportunity for selection. Selection for superiority is based on the vigor and other agronomic features of progeny (families). In F_2, selection is limited to individuals. In F_3 and subsequent generations, until a reasonable level of genetic homozygosity is reached, selection is practiced both within and between families. Of the >700 sorghum female parents (A-/B-pairs) developed by ICRISAT for various traits of global importance (Table 2), more than 600 parents are used in crossing to develop them using the pedigree method (Reddy et al. 2007).

Bulk population breeding is an economic method of obtaining homozygous lines in self-fertilized crops. However, it is not widely used in sorghum. The backcross method is widely used in sorghum improvement particularly for disease resistance, transferring male sterility to the identified maintainer lines by test crossing. Similarly, it is the most sought-after method for transferring quantitative trait loci (QTLs) for shoot-fly resistance and stay-green traits (Kumar et al. 2011).

The choice of parents for hybridization programs is crucial for their success and requires careful and critical evaluation of potential parents for various attributes such as yielding ability, disease resistance, adaptation, quality of the produce, and morphological features relevant to crop management practices. Inasmuch as new strains are intended to have superior yield potential to the existing varieties, one of the parents used in the crossing program is invariably the adapted variety of the area. The other parent is primarily chosen for complementing the specific weakness of the variety, which needs to be replaced. The general combining ability of a parent is likely to be reflected adequately in the parental performance of the trait. In addition to selection of the parents on the yield performance and general and specific combining abilities in the partial diallel crosses or line × tester crosses, it is desirable to analyze the potential parents for important traits such as panicle length, number of primary/secondary branches, grain per primary branch, and grain size (Audilakshmi and Aruna 2008).

Population improvement is another important method for sorghum improvement, which includes: (i) the development of broad genetic-based gene pools, and (ii) its improvement through recurrent selection methods. In sorghum a single gene in recessive homozygous condition confers male sterility and eight different genes reported in sorghum are involved in control of genetic male sterility. Using these genes, population improvement methods can be successfully deployed in sorghum which provides a long-term breeding strategy to derive diverse and broad genetic-based superior varieties/hybrid parents (Reddy et al. 2008). More than 50 sorghum hybrid parents (A-/B-pairs) at ICRISAT were developed using population improvement methods.

Heterosis breeding is most important as hybrids are the cultivar options in sorghum wherever they are available. Although heterosis was demonstrated as early as 1927 in sorghum (Conner and Karper 1927), its commercial exploitation was possible only after the discovery of a stable and heritable cytoplasmic-nuclear male sterility (CMS) mechanism (Stephens and Holland 1954a, b). This CMS system has been designated as A1 (milo). Since then a large number of hybrids have been developed and

Table 2 Details of the sorghum trait-specific (milo) and non-milo hybrid parents (A-/B-pairs) developed at ICRISAT–Patancheru using diverse sorghum basic and intermediate races

ICSA numbers	Traits	No. of lines
1–103	High yielding	77*
88001–88026	”	15*
89001–89004	”	4
90001–90004	”	4
91001–91010	”	10
94001–94012	”	12
201–259	Downy mildew resistant	59
260–295	Anthracnose resistant	36
296–328	Leaf blight resistant	33
329–350	Rust resistant	22
351–408	Grain mold resistant	58
409–436	Shoot-fly resistant (rainy)	28
437–463	Shoot-fly resistant (postrainy)	27
464–474	Stem borer resistant (rainy)	11
475–487	Stem borer resistant (postrainy)	13
488–545	Midge resistant	58
546–565	Head bug resistant	20
566–599	Striga resistant	34
600–614	Acid soil tolerant lines	15
615–637	Early-maturity lines	23
638–670	Durra (large grain) lines	33
671–674	Tillering lines	4
675–687	Stay-green lines	13
688–738	Non-milo (A_2) cytoplasmic lines	51
739–755	Non-milo (A_3) cytoplasmic lines	17
756–767	Non-milo (A_4) cytoplasmic lines	12
24001–24005	High yielding	5
25001–25005	High yielding	5
28001–28006	High yielding	6
29001–29006 and 29017	Shoot-fly resistant (rainy)	7
29007–29016	Grain mold resistant	10
11001–11040	High yielding	40
13001–13030	High yielding	30
14001–14035	Sweet sorghum	35
14036–14039	Shoot-fly resistant (rainy)	4
14040–14042	Grain mold resistant	3
14043–14044	High yielding	2
Total		**836**

*The number of lines being maintained

released/marketed for commercial cultivation in Asia, the Americas, Australia, and Africa. The hybrids have contributed significantly to the increased grain and forage yields in several countries. Grain productivity increased by 47 % in China and by 50 % in India from the 1960s to the 1990s (FAO 1960–1996), which corresponds well with the adoption of hybrids in these countries. Adoption of the first commercial hybrid (CSH 1) in India over much of the rainy season sorghum area while local varieties were confined to fairly narrow specific environmental niches stands testimony to the wide adaptability of hybrids over varieties (House et al. 1997). Currently, over 95 % of the sorghum area is planted to the hybrids in the United States, Australia, and China. In India, over 85 % of the rainy season sorghum area is planted to hybrids (Reddy et al. 2006).

5 Taxonomy and Sorghum Improvement

Sorghum improvement deals with production of new crop cultivars that are superior to existing cultivars for traits of interest. Availability of genetic variability for these traits, knowledge about their heritability and inheritance, and availability of effective phenotyping methodologies are fundamental for success of any crop improvement program. In fact, the efficiency of phenotyping and its robustness decides the success of the crop improvement program in terms of producing a tangible product or technology. As indicated above, in sorghum, a large collection of germplasm is available at ICRISAT (~38,000 accessions) and other places with characterization information on various morphological, agronomic, and adaptive traits. These germplasm lines predominantly consist of the intermediate races of sorghum with a good number of basic races. Inheritance of major traits is well studied and phenotyping techniques developed for efficient selection/screening for major traits of interest. There is continuous exchange of material and information across research groups. As a result, a large number of sorghum cultivars were developed and commercialized around the world for traits of interest. For example, during the period 1976–2010, a total of 242 sorghum cultivars were released in 44 countries using the ICRISAT-bred sorghum material by private and public sector organizations (Kumar et al. 2011), which increased to 268 cultivars by 2016. The list is quite exhaustive if we consider cultivars developed by the national programs of all sorghum-growing countries. Focused sorghum improvement programs backed by the germplasm sources, information on heritability and gene action for traits of interest, phenotyping tools, established selection procedures, massive adaptive trials in partners' locations, and, above all, collaborative research contributed to the large-scale development and commercialization of improved cultivars. In the majority of cases of cultivar development conventional methods were used. Various basic races and the phenotyping tools employed in sorghum improvement programs for various traits of global importance are discussed hereunder. Cultivated sorghum can be grouped differently based on adaptation, usages, and so on.

5.1 Adaptation

Sorghum is produced in the rainy (hot) season in most parts of the world for various uses—food, feed, fodder, and industrial starch, among others—whereas in India it is grown in both rainy and post-rainy (cold) seasons. Limited sorghum area (mostly forages) is grown in summer seasons but it is very small compared to the global area of 40 m ha.

5.1.1 Rainy Season Sorghum

This is the most important adaptation globally spanning from May/June to August/September with more than 30 m ha sorghum area across continents. A variety of sorghums belonging to different races (basic or hybrid/intermediate), different cultivar types (mostly hybrids and varieties), and different grain color (red, brown, white, etc.) types are grown for a variety of end uses in more than 90 sorghum-growing countries. For a plant breeder, the target materials and criteria for selection depend on the prevailing seed systems and the utilization pattern of the crop and consumer preference. For example, medium tall (1.5–1.8 m) dual-purpose hybrids with bold white grains are preferred in India for both food and feed use whereas grain types with red pericarp are preferred for food and brewing purposes in East Africa, and tall, long-duration photoperiod-sensitive guinea sorghums are preferred in West Africa for food. In contrast, short (0.8–1.3 m) hybrids are preferred in the United States, South America, and Australia for mechanical harvesting of sorghum for use as animal feed. Plant height, pigmentation, time to flowering, crop duration, panicle exsertion, panicle size, glume coverage, grain number, grain size and color, and grain thresh ability are major selection criteria in addition to the grain yield. In dual-purpose types, apart from grain yield, stover yield and quality are also important selection criteria. A plant breeder needs to select appropriate germplasm and breeding methods keeping the end product in mind; the maturity duration of the cultivar should correspond with the length of the growing period in the target area with the grain development stage preferably coinciding with the dry period to get the best quality grain. The important biotic constraints in rainy season sorghum include shoot-fly, stem borer, midge, grain mold, striga, and among abiotic constraints, drought predominates (Reddy et al. 2010). An overview of broad adaptation of basic races showed that the *guinea* race and intermediate races involving the *guinea* race are predominant in Western and Central Africa; the *caudatum* race per se and in combination with others as intermediate races in North Eastern Nigeria, Chad, Sudan, Uganda, Western Ethiopia, and rainy season adaptation in India; and the *durra* race along with intermediate races in Ethiopia and other Eastern and Southern Africa including post-rainy season adaptation in India and the *kafirs* in Southern Africa, Tanzania, and Northern Nigeria (Upadhyaya et al. 2014).

5.1.2 Post-rainy Season Sorghum

It is a unique adaptation to India with approximately 4.5 m ha where the crop is grown from September/October to January/February taking advantage of residual and receding moisture in black soils. The Deccan plateau in India encompassing the states of Maharashtra, Karnataka, Andhra Pradesh, and Telangana is the major post-rainy sorghum growing region. The post-rainy sorghum grain is preferred for food use in India owing to its bold globular lustrous nature. However, no differences were observed between the flatbreads made from rainy (but matured under rain-free condition) and post-rainy sorghums in a sensory evaluation involving traditional sorghum-eating populations (ST Borikar, personal communication). The stover from the post-rainy crop is the most important animal feed particularly in the dry periods. In addition to the traits mentioned under rainy season adaptation, photoperiod sensitivity, temperature insensitivity, and grain luster are the major selection criterion. Varieties are the cultivar choice but there is good scope for hybrid development using the white-grained rainy season adapted lines as female parents and landrace restorers as pollinators. Although terminal drought is the major production constraint, shoot-fly, aphids, and charcoal rot play havoc with post-rainy season production (Kumar et al. 2011). The *durras* possess the typical grain traits preferred by post-rainy sorghum farmers; that is why almost all major cultivars in post-rainy sorghums belong to this race, with characteristic low diversity.

5.2 Yield and Yield Attributes

Grain yield obviously is the most important trait in sorghum breeding as in other major food crops; however, stover yield is equally important in sorghum particularly in countries like India. Breeding for grain yield improvement is carried out by selecting genotypes directly for grain yield and for component traits. For higher yield, genotypes with a plant height of around 150 cm are desirable, which are amenable to mechanical harvesting with medium maturity duration (100–120 days). Longer duration types give higher yields but the length of the growing period (LGP) in most sorghum growing areas does not allow for breeding long duration types, with the exception of West Africa. If we reduce the crop duration, it is likely that the yield goes down. Therefore, the breeder first has to fix the plant height and maturity duration for a given environment. However, in the context of climate change, longer duration types need to be maintained in the breeding program considering the fact that when temperatures increase by 2 °C, the longer duration types behave as medium duration types and produce higher yields than other types (Reddy et al. 2011). Another important consideration is photoperiod sensitivity. Photoperiod insensitivity is the ability of a genotype to mature at any given period in the calendar year irrespective of its planting date. It is feasible to identify the photoperiod-sensitive genotypes by planting them at different dates (at 15- or 30-day intervals) and recording the days for 50 % blooming in the genotypes. The genotypes that take less time for flowering when planted late can be considered photoperiod sensitive. In sorghum improvement programs in West Africa and in post-rainy sorghum improvement in India, photoperiod sensitivity is a key trait, although *guinea* types are predominant in West Africa and *durras* predominate in post-rainy sorghum in India. Among the component traits, long panicles, higher number of primary and secondary branches, bold grains, large number of grains per panicle, and higher 100-seed weight contribute to higher grain yield and most of these traits have high heritability enabling the plant breeder to improve for these traits through selection. The gap between flag leaf sheath and panicle base should be minimal to have good grain filling and the glume coverage on grains is to be less for higher threshability. Grain size can be visually judged and grain color can be selected as per the consumer/market preference in the given adaptation (Reddy et al. 2009; Rosenow and Dalhberg 2000). If there is no stringent grain quality preference, use of *caudatums* gives the best yields owing to their high per se performance and higher combining ability in hybrid combinations.

5.2.1 Grain and Stover Yield

In addition to sorghum grain, its stover has high feed value. In areas where sorghum stover is important as animal feed, breeding dual-purpose types is the best choice. Heterosis for grain and stover yield is high in sorghum and therefore hybrid development should be targeted. A heterosis of 30–40 % for grain yield is reported compared to the best varieties (Kumar et al. 2011). Development of hybrid parents is critical for exploiting heterosis and therefore genetic and cytoplasmic diversification of hybrid parents is a major breeding objective. Population improvement is also being followed for improving the grain and stover yields. In general, *caudatums* show higher yield and higher combining ability and therefore are widely exploited in developing hybrid parents in sorghum.

Quality of grain and stover is as important as grain yield in sorghum. This is more so in the case of post-rainy season sorghum where consumers prefer bold, lustrous white-grain types, which is generally available only in landrace varieties (Reddy et al. 2009). The grain luster is visually scored on a scale 1–3 where 1 = lustrous and 3 = dull among the white-grained types. The genetic base of these *durra* landraces is narrow and therefore it is more challenging to improve for post-rainy season adaptation. Similarly, heterosis is low when both parents are derived from landraces (*durra* × *durra*). A more practical method for developing post-rainy season hybrids is by using rainy season adapted lines (mostly *caudatum* types) as females and landrace varieties (*durras*) as pollinators. While improving the stover yield, one has to keep in the mind the stover digestibility and protein content in addition to the stover yields. The stover yields have to be recorded on oven-dried samples after harvesting the grains and for stover quality; indirect selection for stover digestibility using near-infrared reflectance spectroscopy (NIRS) is the most practical method for assessing feed quality of stovers.

5.2.2 Plant Height and Maturity

Plant height is a major consideration in sorghum improvement and in fact it is one the criteria for classifying sorghums as grain sorghums, dual-purpose sorghums, forage sorghums, and high biomass sorghums. In sorghum, four loci are known to be involved in the control of plant height. These genes are assigned the symbols *Dw1*, *Dw2*, *Dw3*, and *Dw4* (House 1980). Tallness is partially dominant to dwarfness. The zero dwarf type (dominant [*DW*-] at all loci) may reach a height of 4 m. The change from four to three dominant genes may result in a height change of 50 cm or more. If genes at one or more of the loci are recessive, the difference in height resulting from the recessive condition at an additional locus may have a smaller effect in reducing plant height. The difference between a 3-dwarf (recessive genes [*dw dw*] at three loci) and a 4-dwarf type may be only 10 or 15 cm (Rosenow and Dalhberg 2000). Breeders have to keep in mind these facts while selecting genotypes with appropriate height. For example, farmers in India prefer to use two gene dwarfs that result in a height of 1.7–2.0 m as they wish to have fodder along with grain and the plant height is directly proportional to the height (Quinby 1974). The plant height is always recorded from the base of the plant to the tip of the panicle. Plant height and days to flowering data give an idea about the genotype in terms of suitability for various uses. In practical sorghum breeding, the plant height should be less than 150 cm in grain sorghums, up to 170 cm in dual-type sorghums, more than 200 cm in forages, and 300 cm or more in the case of high biomass sorghums.

In sorghum, Quinby (1974) identified factors at four loci that influence maturity, *Ma1*, *Ma2*, *Ma3*, and *Ma4*. Generally, tropical types are dominant (*Ma*-) at all four loci, and a recessive condition (*mama*) at any one of them will result in more temperate zone adaptation that takes more time for maturity. Most sorghum improvement programs target medium maturity types (crop duration less than 120 days) as they yield high; however, the targeted maturity is to be decided based on the length of the growing period of the target area. In general, sorghum takes 35–40 days from flowering to maturity. The grain is to be harvested at physiological maturity stage. The hilum turns dark at physiological maturity and this is an important criterion for harvesting (Rosenow and Dalhberg 2000). There are some racial differences in maturity of the crop. Certain *guinea* race sorghums take up to 180 days for maturity. However, one can find large variation for maturity in any given race.

5.3 Nutritional Quality Traits

Sorghum is one of the major food crops in the world and has a predominant role in meeting the dietary energy and micronutrient requirements particularly in the low-income group populations; improving sorghum nutrition quality is of paramount importance (Parthasarathy Rao et al. 2006). There is a conscious focus on improving the nutritional quality of sorghum.

5.3.1 Protein and β-Carotene Contents

Protein content is more intensively studied in sorghum wherein high genetic variability is reported. Gains in protein content were reported by various authors (Virupaksha and Sastry 1968; Ramesh and Hudda 1994; De Mesa-Stonestreet et al. 2010). The best method for measuring protein content is through the Micro-Kjeldahl method or Technicon autoanalyzer (TAA) method (Johnson and Craney 1971; Jambunathan 1983). Sorghum is a good source of protein vis-à-vis other cereals and there exists large variability for protein content in sorghum although there is no correlation between protein content and races in sorghum. Sorghum is not a good source of β-carotene, like other cereal staples. In a study on a limited number of germplasm lines, hybrid parents in sorghum did not show appreciable variability for β-carotene content in sorghum (Reddy et al. 2005). A similar case with yellow endosperm lines is reported wherein the β-carotene content did not exceed 1.1 ppm (Reddy et al. 2005). For phenotyping this trait, spectrophotometry followed by high-performance liquid chromatography (HPLC) gives more accurate information.

5.3.2 Grain Fe and Zn Concentration

Sorghum is a good source of grain Fe and Zn although we cannot attribute the variability found in sorghum for grain Fe and Zn to any given basic or intermediate races (Table 3). Large-scale screening of sorghum core germplasm accessions, hybrid parents, and commercial hybrids showed high genetic variability for grain Fe and Zn concentrations (7–70 ppm) and most of this variation is heritable (Reddy et al. 2005; Kumar et al. 2012). Significant positive association exists between grain Fe and Zn concentrations ($r^2 = 0.6–0.8$) and it is possible to improve both traits simultaneously (Kumar et al. 2009). Additive gene action plays a significant role in conditioning the grain Zn concentration whereas both nonadditive and additive gene actions condition the grain Fe concentration (Ashok Kumar et al. 2013a, b). The Fe and Zn concentrations can be estimated using inductively coupled plasma optical emission spectrometry or atomic absorption spectrometry (Houk 1986). This is a precise but destructive and laborious method. The most rapid and low-cost method for assessing grain Fe and Zn concentrations is by using the X-ray fluorescence spectrometry (XRF) method which is nondestructive and can be used routinely to screen the breeding materials. There is high correspondence between the values obtained by both methods, indicating that XRF can be used for assessing grain Fe and Zn concentrations particularly for discarding the poor lines in the breeding material (Ashok Kumar et al. 2015).

Table 3 Mean performance of selected sorghum germplasm lines evaluated for grain Fe and Zn concentration at ICRISAT–Patancheru during the 2007 and 2008 post-rainy seasons

IS No./pedigree	Race	Origin	Days to 50 % flowering	Plant height (m)	Glume coverage (%)	Grain yield (t ha^{-1})	Grain size (g 100^{-1})	Iron (mg kg-1)	Rank	Zinc (mg kg-1)
5427	Durra	India	65	2.0	54	2.0	2.8	61	1	57
5514	Guinea-bicolor	India	68	1.7	71	1.4	3.0	56	2	45
55	Durra-caudatum	US	71	1.0	75	1.3	2.6	54	3	38
3760	Caudatum-bicolor	USSR	68	1.9	67	2.2	2.2	53	4	37
3283	Bicolor	US	66	1.8	71	1.9	2.7	50	5	42
17580	Caudatum	Nigeria	66	1.9	79	1.6	2.1	50	6	41
15952	Guinea	Cameroon	81	2.4	38	2.5	3.4	49	7	41
3813	Durra	India	79	2.2	83	1.4	1.7	49	8	38
15266	Caudatum	Cameroon	70	1.4	54	2.7	2.7	49	9	44
2939	Kafir	US	69	2.0	63	3.6	3.9	48	10	37
4159	Durra	India	65	1.9	50	1.5	3.3	48	11	38
3929	Kafir-durra	US	75	2.0	79	2.2	2.1	48	12	40
3443	Guinea-caudatum	Sudan	68	1.7	63	3.3	3.5	47	13	39
3925	Durra-caudatum	US	78	2.0	67	2.4	2.0	47	14	39
5460	Durra-bicolor	India	66	1.5	79	1.4	2.7	47	15	46
12452	Caudatum-bicolor	Sudan	64	1.9	79	3.2	4.3	47	16	33
2801	Caudatum	Zimbabwe	71	1.8	71	2.3	3.1	46	17	45
2536	Kafir-caudatum	US	72	1.8	83	2.3	2.4	45	18	37
5429	Durra	India	66	1.7	79	2.8	3.0	44	19	30
356	Durra	US	84	1.1	46	2.2	2.7	44	20	33
2265	Durra-bicolor	Sudan	75	2.2	71	1.8	1.7	44	21	41
12695	Bicolor	South Africa	68	1.9	100	2.8	2.6	44	22	39
5538	Durra	India	65	1.4	33	1.7	2.2	44	23	37

(continued)

Table 3 (continued)

IS No./pedigree	Race	Origin	Days to 50 % flowering	Plant height (m)	Glume coverage (%)	Grain yield (t ha^{-1})	Grain size (g 100^{-1})	Iron (mg kg-1)	Rank	Zinc (mg kg-1)
5476	Durra	India	69	1.5	75	2.1	2.7	41	24	36
16337	Caudatum	Cameroon	80	1.7	38	2.4	3.0	41	25	34
5853	Guinea-durra	India	65	1.7	29	2.4	5.9	41	26	32
14318	Bicolor	Swaziland	79	2.1	79	2.2	2.3	39	29	38
10674	Durra-caudatum	China	65	2.1	46	1.9	4.0	39	30	38
22215	Durra-bicolor	USSR	80	2.1	71	2.9	2.4	26	31	21
Controls										
ICSR 40			70	1.2	33	3.3	3.2	40	27	24
296B			86	1.1	29	2.7	2.8	40	28	24
Mean			71	1.76	63	2.26	2.9	46		37
SE +			0.96	0.12	7.30	0.26	0.2	3		3
CV (%)			2.32	11.51	20.06	20.12	10.4	10		13
CD (5 %)			2.68	0.33	20.44	0.74	0.5	8		8

6 Conclusion

The botany and taxonomy of the genus *Sorghum* were well studied and exploited in improving the sorghum for various traits of interest. The classification of sorghum and the adaptation of various basic and intermediate races in sorghum to different geographies still hold. However, it is increasingly realized in most of the sorghum improvement programs that the *caudatums* and *durras* were extensively used in hybrid development programs and it is important to bring in the *guineas* to further increase the variability so as to increase the yield. A classic example is that at the ICRISAT gene bank, the largest number of sorghum germplasm accessions (53.21 % of total accessions) belong to races *durra* (21.28 %), *caudatum* (20.19 %), and their intermediate races *durra–caudatums* (11.74 %). Therefore, their utilization is also very high in the ICRISAT sorghum improvement program for hybrid parents' development. However, considering that sorghum yield is reaching a plateau in most breeding programs and that grain mold resistance is low, it is high time to bring *guineas* into the crossing program to break the yield barriers and increase grain mold resistance.

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