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Sorghum, *Sorghum bicolor* (L.) Moench

P. Sanjana Reddy

ICAR-Indian Institute of Millets Research, Hyderabad, India

1.1 Introduction

Sorghum, *Sorghum bicolor* (L.) Moench, is known under a variety of names: 'great millet' and 'guinea corn' in West Africa, 'kafir corn' in South Africa, 'dura' in Sudan, 'mtama' in Eastern Africa, 'jowar' in India and 'kaoliang' in China (Purseglove, 1972). It is the fifth most important cereal crop grown in the world. It is mostly cultivated by subsistence farmers in the semi-arid tropics of Africa, Asia and Latin America. It is an important staple food crop in the semi-arid areas of Asia and Africa, thus contributing to the vital share of energy, proteins, vitamins and minerals for millions of poor people of these regions, whereas it is used as animal feed in the Americas, China and Australia. In India, the rainy-season sorghum grain is used mainly as animal/poultry feed, while the post-rainy-season sorghum grain is used primarily for human consumption. The crop residue (stover) after the harvest is a valuable source of fodder and fuel in India and Africa. Sorghum also has great potential to supplement fodder resources in India because of its wide adaptation, rapid growth, high green- and dry fodder yields with high ratoonability and drought tolerance (Reddy, Ramesh *et al.*, 2004). Grain sorghum grown primarily for food uses can be divided into milo, kafir, hegari, feterita and hybrids (Purseglove, 1972). There are other classes of sorghums such as sorghos, grass sorghums, broomcorn sorghum and special- purpose sorghum. The crop is grown under harsh environments where other crops fail to grow. The produce is mostly consumed locally and the surplus usually does not have assured price.

1.2 Origin and Taxonomy

Mann *et al.* (1983) hypothesised that the origin and early domestication of sorghum took place approximately 5000 years ago in northeastern Africa. Wendorf *et al.* (1992) reported new evidence that places the origin and domestication at 8000 years before present (BP) in the Egyptian–Sudanese border. Thus, there seems to be no argument against the African origin of sorghum (Kimber, 2000), which is also supported by the largest diversity of the cultivated and wild sorghum in Africa (de Wet, 1977; Doggett, 1988). The great diversity of *S. bicolor* has been created through disruptive selection

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(i.e. selection for extreme types) and by isolation and recombination in the extremely varied habitats of northeast Africa and the movement of people carrying the species throughout the continent (Doggett, 1988). In the Indian Subcontinent, evidence for early cereal cultivation was discovered at an archaeological site in the western parts of Rojdi (Saurashtra) dating back to about 4500 BP (Damania, 2002). The Indian Subcontinent is considered to be the secondary centre of origin of sorghum (Vavilov, 1992).

In 1753, Linnaeus described three species of cultivated sorghum in his *Species Plantarum*, viz., *Holcus sorghum*, *Holcus saccaratus* and *Holcus tricolor*. In 1794, Moench distinguished the genus Sorghum from the genus Holcus, and in 1805, Pearson suggested the name *Sorghum vulgare* for *Holcus sorghum* (L.). In 1961, Clayton proposed the name *Sorghum bicolor* (L.) Moench as the correct name for cultivated sorghum and this is currently being used. Detailed classification of sorghum is given by Snowden (1936). Other classifications proposed since then have been the modifications or adaptations of the Snowden system. Harlan and de Wet (1972) published a simplified classification of sorghum. They divided cultivated sorghum into five basic groups or races: *bicolor*, *guinea*, *caudatum*, *kafir* and *durra*. The wild type and shattercane are considered as the two other spikelet types of *S. bicolor*. Based on the polymorphism of 11 enzymes, sorghum is classified into three enzymatic groups. The first group includes mainly *guinea* varieties of West Africa; the second Southern African varieties of all five races; and the third *durra* and *caudatum* types of Central and East Africa (Ollitrault *et al.*, 1989).

Sorghum is classified under the family *Poaceae*, tribe *Andropogoneae*, subtribe *Sorghinae* and genus *Sorghum* Moench (Clayton and Renvoize, 1986). Garber (1950) and Celarier (1959) divided the genera sorghum into five subgenera: sorghum, chaetosorghum, heterosorghum, parasorghum and stiposorghum. *Sorghum bicolor* was further broken down into three subspecies: *S. bicolor* subsp. *bicolor*, *S. bicolor* subsp. *drummondii* and *S. bicolor* subsp. *verticilliflorum*. The cereal sorghums were found to consist of four wild races and five cultivated races (Harlan *et al.*, 1976). The four wild races of *Sorghum bicolor* that include *arundinaceum*, *virgatum*, *aethiopicum* and *verticilliflorum* are placed in *S. bicolor* subsp. *verticilliflorum*, formerly subspecies *arundinaceum*. Cultivated sorghums are placed under *S. bicolor* subsp. *bicolor* and are represented by diverse agronomic types such as grain sorghum, sweet sorghum, sudangrass and broomcorn (Berenji and Dahlberg, 2004). The cultivated races that are presently conceived are *bicolor*, *guinea*, *kafir*, *caudatum* and *durra*. Intermediates that are caused by hybridisation of these races exhibit characters of both parents (Smith and Frederiksen, 2000). Additionally, there are two weedy sorghums widespread in the temperate zone, viz., Johnsongrass and spontaneous sorghum (shattercane).

1.3 Germplasm Resources and Utilisation

Sorghum genetic resources are conserved at many research centres across the world. At the global level, sorghum germplasm collections consist of approximately 168500 accessions (Reddy *et al.*, 2006). The major organisations/countries which maintain sorghum genetic resources are the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India, the National Plant Germplasm System (NPGS) in United States, Ethiopia, Sudan, South Africa, India and China, primarily because of the large crop improvement programmes (Rosenow and Dahlberg, 2000). ICRISAT with a collection of 37949 accessions from 92 countries (about 22% of global total) represents the major diversity centres of sorghum. The Indian National Gene Bank holds about 19844 accessions of sorghum (Radhamani *et al.*, 2011).

The promising germplasm lines after evaluation can be directly released as varieties. About 31 sorghum germplasm accessions supplied from the ICRISAT gene bank have been directly released as cultivars in 17 countries. Notable among these is IS 18758, a popular landrace from Ethiopia belonging to the hybrid race *guinea-caudatum* WG *zera zera*. It has been released as a variety in Burundi (as Gambella 1107) and Burkina Faso (as E 35-1) (Reddy *et al.*, 2006). The landrace IS 1054 belonging to the race *durra* and subrace *cernuum* is a ruling post-rainy-season-adapted variety released as M 35-1 in peninsular India. Another landrace, IS 33844, selected from a germplasm collection from Ghane Gaon (in Sholapur, Maharashtra), belonging to the race *durra*, was released in Maharashtra, India. The highly popular high-biomass-yielding forage sorghum variety UP Chari-1, released in India, is a landrace (IS 4776). Germplasms with one or more outstanding traits but with poor agronomic performance are considered for registration, which is an instrument of soft protection. About 47 sorghum germplasm accessions are registered for various traits with NBPGR, India (Table 1.1) (Radhamani *et al.*, 2011).

Developing the core and mini-core collections (10 and 1%, respectively, of the entire collection), representing the total genetic diversity, is the best strategy to promote utilisation of germplasm. A core collection consisting of 2247 accessions has been developed and is being maintained at ICRISAT, Patancheru, India (Grenier *et al.*, 2001). The hierarchical cluster analysis of data of the core collection evaluated 11 qualitative

Table 1.1 Sorghum germplasm registered for potential valuable traits.

Trait	**No. of accessions registered**
Resistant to yellow sugarcane aphid, *Melanaphis sacchari*	1
Cytoplasmic-nuclear male sterility (CMS), thermo-sensitive with high yield and long panicle	1
Roti and dough quality, high protein (9.63%), stover quality, shoot fly and anthracnose resistant	1
Low hydrocyanic acid (HCN) and multiple resistance	1
Drought tolerant	1
Converted male and female parents of dual-purpose sorghum hybrid, SPH 1148 with high yield	2
Shoot fly resistance and high grain yield	2
Sweet sorghum MS line	15
Medium dwarf sweet sorghum male sterile line with yellow grain colour	2
Grain mould resistance	13
Shoot fly tolerance with multiple resistance to leaf diseases and also agronomic superiority and yield	1
Medium early duration male sterile line	2
Resistance to multiple foliar diseases	4
Good flaking quality	1

Source: Adapted from Radhamani *et al.*, 2011.

and 10 quantitative traits in 21 clusters. From each cluster, about 10% or minimum of one accession was selected to form a mini core that comprised 242 accessions (Upadhyaya *et al.*, 2009).

1.4 Genetics and Cytogenetics

Excellent reviews on the genetics of various traits are found in Doggett (1988), Murty and Rao (1997) and Rooney (2000). Quinby and Karper (1954) have shown that four recessive non-linked brachytic dwarfing genes control height. Quinby *et al.* (1973) have shown that the duration of growth and floral initiation is controlled by four loci; involving both dominant and recessive alleles. Most tropical landraces/varieties are dominant at all four loci, but a recessive allele at Mal locus will cause them to be less photoperiod-sensitive and apparently less responsive to temperature variations. The genetics of resistance to most diseases caused by fungi, bacteria and virus are, in general, simple inheritance of dominant alleles. The genetics of resistance to major diseases of sorghum is given in Table 1.2. Grain mould resistance on the other hand, is complex.

In contrast to diseases, the genetics of insect resistance is complex. Four insects are recognised as important pests throughout Asia, Africa and India: shoot fly; stem borer (*Chilo* spp. and *Busseola* spp.); midge; and head bug (*Calocoris* spp.). Rana *et al.* (1980) reported that the F_1 is almost intermediate between the two parents for shoot fly resistance, however, resistance was found to be partially dominant under low to moderate shoot fly pressures. Resistance to stem borer is conferred by both tolerance and antibiosis, with primary damage explained by additive (A) and A × A interactions, with secondary damage controlled by A and non-additive gene interactions (Rana and Murty, 1971; Jotwani, 1976). Resistance to both midge and head bug are predominantly under the control of additive gene action (Sharma *et al.*, 1994; Ratnadass *et al.*, 2002).

Two types of male sterility are widely used in sorghum improvement programmes: (i) genetic male sterility (GMS) and (ii) cytoplasmic nuclear male sterility (CMS). Genetic male sterility is expressed in sorghum in many ways with several sources of male sterility identified. In all the cases, a recessive allele in homozygous condition (designated with alleles, ms_1–ms_7 and *al*) confers male sterility. Genetic male sterility is

Table 1.2 Genetics of disease resistance in sorghum.

Disease	Genetic nature	Number of alleles
Kernel smut	Incomplete, dominant	3
Head smut	Dominant	—
Milo disease	Susceptibility is partially dominant	1
Anthracnose	Dominant, cytoplasm not significant	1
Rust	Dominant	1
Leaf blight	Susceptibility (in sudangrass) is dominant	1
Staygreen trait (charcoal rot tolerance)	Dominant at least with E 36-1 hybrids	—
Downy mildew	Dominant	>2

Source: From House, 1985; Reddy *et al.*, 1992; Reddy and Singh, 1993; Reddy and Stenhouse, 1993.

discussed in detail in Doggett (1988), Murty and Rao (1997), and Rooney (2000). The discovery of the male sterility resulting from the interaction of cytoplasmic and nuclear genes by Stephens and Holland (1954) laid the foundation and revolutionised the development of hybrid cultivar and hybrid seed production technology. The original source of the cytoplasm was the milo race, which induced male sterility in the nuclear background of the *kafir* race, and is designated as A_1 cytoplasm. Since then, several sources and types of male-sterile inducing cytoplasms (A_1–A_6) have been discovered. In all these cytoplasms, a single/oligo recessive gene in the nucleus and sterile cytoplasm induces male sterility. These male-sterile cytoplasms are differentiated based on the inheritance patterns of their fertility restoration, which is unclear, but dependent on the specific cytoplasm and nuclear combinations. Fertility restoration is controlled by single gene in some combinations (e.g. A_1) but is controlled by two or more oligogenes when the same nuclear genotype interacts with a different cytoplasm (Schertz, 1994).

1.4.1 Cytogenetics

Sorghum bicolor has a haploid chromosome number of 10, and it is classified as a diploid ($2n = 2x = 20$). Most species within *Sorghum* are diploid ($2n = 20$), but several species, most notably *S. halapense*, are tetraploid ($2n = 4x = 40$). Euploid variants such as haploids, triploids and tetraploids occur naturally and can be induced. Autotetraploid sorghums have an increased grain size, which sparked interest in their development for grain production (Doggett, 1962). The initial limitation in autotetraploid development was the high level of sterility observed, however selection for improved fertility was successful, with resulting fertility levels near that of diploids (Doggett, 1962; Luo *et al.*, 1992). However, further research in this direction stalled, resulting in the non-realisation of tetraploid sorghum for grain production. Aneuploids are organisms with more or less than an integral multiple of the haploid chromosome number. The most common form of aneuploidy observed in sorghum is trisomy, followed by translocation. Apomixis in sorghum occurs when the embryo forms by apospory from a somatic cell in the nucellus with up to 25% of the progeny developed apomictically, however, this can occur at a significantly higher percentage (Hanna and Schertz, 1970; Rao and Murty, 1972; Murty and Rao, 1977). In most cases, apospory is the primary mechanism of apomixis in sorghum, although diplospory may occur (Murthy *et al.*, 1979). Apomixis provides a mechanism to perpetuate a high-performing hybrid through self-pollination. Obligate apomixis is necessary to develop such a system, but all the reports of apomixis in sorghum involve only facultative apomixes, and efforts to increase the frequency of apomicts have not been successful (Reddy *et al.*, 1980). To utilise facultative apomixis, the use of ‘vybrids’ has been proposed (Murthy, 1986).

1.5 Reproductive Biology

The inflorescence of sorghum is the panicle/raceme. Sorghum spikelet development is basipetal – those in the upper region of the panicle develop earlier than those in the lower. The tertiary rachis consists of one or several spikelets. One spikelet of a raceme is always sessile and the other pedicellate, except the terminal sessile spikelet, which is accompanied by two terminal pedicellate spikelets. The number of sessile spikelets in a single inflorescence of cultivated sorghum varies from 2000 to 4000. At flowering, they are green but then change shades, becoming straw- or cream-coloured buff, yellow, red, brown, purple or almost black at maturity. There are two glumes. The lower glume is enclosed by the upper glume with its membranous margin. The lower glume is usually flat and conforms more or less to the shape of the spikelet. The upper glume is more convex or boat-shaped. The seed may be enclosed by the glume or may protrude from it either partially or completely. There are two lemmae. The lower lemma is elliptical or oblong and equal in length to the glume. The upper lemma is short, ovate and may be awned. There are two lodicules and a palea. The spikelet has two pistils and three stamens. The stigma is fluffy, attached to a short style extending to the ovary. The anthers are attached to long, thread-like filaments (House, 1985). The pedicellate spikelets are narrower and may be smaller or longer or of the size of the sessile spikelets. They are male or neutral, or may rarely have a rudimentary ovary. The lemmae are short and the upper lemma rarely has an awn. Three stamens and two lodicules are found between the lemma and the palea.

Floral initiation in cultivated sorghum starts 30–40 days after germination. About 6–10 days before flowering, the boot forms a bulge in the sheath of the flag leaf. Sorghum usually flowers in 55–70 days in warm climates (House, 1985), depending on the genotype. Two days after the emergence of the inflorescence from the boot, the flowers begin to open. The flowering starts in the sessile spikelets at the tip of the inflorescence and progresses towards the bottom over 4 or 5 days. It takes 6 days for the whole inflorescence to complete flowering. The maximum flowering takes place on the third or fourth day. At flowering, the glumes open, and the three anthers fall free, while the two stigmas protrude, each on a stiff style (House, 1985). As the stamens emerge out of the opening glumes, they rotate and spread outward. The filaments elongate rapidly and the anthers become pendent. When flowering of the sessile spikelets is halfway through on the inflorescence, the pedicellate spikelets start opening from the tip and proceed downwards completing flowering earlier than the sessile spikelets in the inflorescence. The time taken from the commencement of glume-opening to completion of its closing is about 1–2 hours, which varies from cultivar to cultivar. Flowering starts at midnight and continues up to 10 a.m. depending on the genotype and climate. The maximum anthesis is between 6 a.m. and 8 a.m.. Wet and cool weather delays flowering. The anthers dehisce when they are dry, and the pollen grains are ejected into the air and onto the stigma. Sorghum is primarily self-pollinated (cross-pollination is only 2–10%). The florets of some of the very long glumed types do not open for outcrossing to take place, a phenomenon called *cleistogamy*. After pollination the glumes close, though the empty anthers and stigmas still protrude. The pollens retain their viability for 5 h at room temperature. The stigma remains receptive for 10 days. Under normal conditions stigma fertilisation takes place in 2 h. Organ differentiation occurs the following 12 days, and the embryo continues to grow until the seed is mature (Schertz and Dalton, 1980). Seed development is in three stages: milk stage, early or soft-dough stage, and late or hard-dough stage. The sorghum seed is a free caryopsis, also called grain. Seeds are spherical in shape, but somewhat flat on one side with the embryo at the base. They are red, brown, white, yellow or cream coloured with a dull or pearly lustre. The endosperm is usually white, sometimes yellow. The grain matures in 30–35 days after fertilisation. At physiological maturity, a dark brown callus tissue is formed at the base where the seed is attached to the spikelet. This callus tissue stops the translocation of nutrients from the plant to the seed. At physiological maturity, the seed contains 25–30% moisture and is fully viable. For safe storage, seed moisture should be brought down to 10–12%.

1.6 Production Constraints

The yield and yield stability of sorghum are constrained by a diverse array of insect pests, which vary according to the location of cultivation. Foliage pests in the United States include green bug (*Schizaphis graminum*), yellow sugarcane aphid (*Sipha flava*), chinch bug (*Blissus leucopterus*), fall armyworm (*Spodoptera frugiperda*), corn leaf aphid (*Rhopalosiphum maidis*), and Banks grass mite (*Oligonychus pratensis*). Other foliage pests are shoot fly (*Atherigona soccata*), spotted stem borer (*Chilo partellus*), and sugarcane aphid (*Melanaphis sacchari*) (Peterson *et al.*, 1997). Midge (*Contarinia sorghicola*) is a serious head pest common in India, Eastern Africa and Australia, with head bug (*Eurystylus oldi*) being another important pest in India and Western and Central Africa.

Sorghum is host to a large number of pathogens, including fungi, bacteria, viruses and nematodes. These pathogens, individually or in combination, may result in significant economic losses to grain and forage production. Important among diseases include grain mould caused by a complex of fungi in all sorghum growing regions of the world, anthracnose in Western and Central Africa (WCA) and Northern India. Apart from this, *Striga* is an important parasitic weed causing immense losses in all regions in Africa.

Drought stress is a major constraint to sorghum production worldwide. Although sorghum possesses excellent drought resistance compared to most other crops, improving its drought resistance would increase and stabilise grain and food production in low-rainfall, harsh environmental regions. (Rosenow *et al.*, 1997). Soil acidity (and associated Al^{3+} toxicity mostly in Latin America) and salinity (mainly in some parts of India and the Middle East countries) are probably the most important constraints to sorghum productivity in tropical environments, with an estimated 72.4 billion ha (18%) of the worlds soils classed as acidic, and 0.9 billion ha classed as saline and sodic (Vose, 1987; Gourley, Watson, Schaffert *et al.*, 1997). These problematic soils are major constraints for the resource-poor tropical farmers in developing countries.

1.7 Breeding Objectives

The identification of geographic functional regions with a set of constraints has resulted in the gradual shift in breeding strategy from initial wide adaptability to specific adaptations, and to trait-based breeding for threshold traits through the 1980s and 1990s (Reddy, Ramesh *et al.*, 2004). For example, improved post-rainy-season sorghums in India would require in addition to higher grain and fodder yields, tolerance to drought, shoot fly and lodging and grain quality (semi-corneous endosperm grains) suitable for making ‘roti’ (unleavened bread). On the other hand, in the northern Guinea zone of WCA, improved sorghum lines should have longer maturity, and hard grains with stable resistance to *S. hermonthica*, anthracnose, grain mould, stem borer and head bug. Also, grain quality evident traits such as soft endosperm grains are preferred in Eastern Africa for food product preparations such as injera and kisra and hard endosperm grains preferred in Western Africa for tô preparation are important (Reddy and Stenhouse, 1994).

1.7.1 Grain Sorghum

The main breeding objective in any breeding programme is yield. Poor productivity for grain yield of unimproved sorghum cultivars is related to their low harvest index; numerous biotic stresses including diseases, insect pests, and *Striga*; and abiotic stress factors such as heat, drought and problematic soils. All these factors cannot be addressed with the same priority at any given time by breeding. The relative impact of production constraints on yield loss is the primary criterion in research prioritisation. However, when it comes to genetic enhancement, the probability of success can be affected by a complex interplay of several factors, such as availability of genetic resources, inheritance and stability of the traits desired to be improved, simplicity and effectiveness of screening techniques (reliability and cost-effectiveness), access to test environments and availability of technical manpower and material resources, that also become determinants, sometimes of overriding importance. Breeding for high and stable grain yield with an improved harvest index continues to be the top priority in all sorghum programmes worldwide and it requires exploitation of the available germplasm as it provides vast genetic variability for yield components and adaptation traits, of which only a fraction, even from the cultivated types, has been utilised, understanding of the inheritance of most of the characters and designing suitable and simple evaluation procedures.

1.7.1.1 Breeding for Yield

Breeding methods used for genetic improvement of sorghum are similar to those employed for self-pollinated crops. The main methods used are pureline selection, pedigree breeding, back cross-breeding, random mating populations utilising genetic male sterility and hybrids involving cytoplasmic genetic male sterility. The discovery of genetic male sterility in sorghum opened up opportunities for recombination. Of the several genes reported to induce genetic male sterility, only two alleles were widely used in population improvement, as they are stable over a range of environments (Murty and Rao, 1977; Reddy and Stenhouse, 1994a). This, in combination with various mating systems and reciprocal recurrent selection methods in exploiting additive (A), A×A and some epistatic genetic variations led many breeders to propose/take up the population improvement methods in the 1960s (Comstock and Robinson, 1952; Doggett, 1972; Eberhart, 1972; Maunder, 1972). These breeding enhancements led to the development of several populations in East and West Africa supported by funding from the International Development Research Council (IDRC) (Doggett, 1972; Gardner, 1972). About 19 populations have been developed at ICRISAT–Patancheru using ms_3 and ms_7 genes into which 501 diverse germplasm accessions were introgressed. However most of the sorghum cultivars released globally was derived from the pedigree breeding programme rather than from the population improvement programmes. Pedigree selection is more appropriate for a short specific adaptation and targeted genepool approach is appropriate for a programme that aims at broad geographic mandate (Reddy, Ramesh *et al.*, 2004). Recurrent selection and pedigree breeding are the two most common methods used in the genetic improvement. Random mating is achieved through the application of genetic male sterility. At least seven recessive genes for male sterility have been identified in sorghum, but ms_3 has been used in nearly all the population improvement programmes, because it was the first to be discovered that had few disadvantageous pleiotropic effects. Both varieties and hybrids are commercially grown. The highest-yielding hybrids have about 15–30% grain yield advantage over the best varieties of comparable maturity. A variety in sorghum is an advanced generation progeny (generally F6–F7 or S5–S6) that is highly homozygous and homogeneous. Thus, a sorghum variety has a stable genotypic structure, with little chance of significant genetic change over time except that due to outcrossing or spontaneous mutation. Commercial hybrids are produced using CMS lines and currently, only one CMS system, designated A1, is predominantly used worldwide (Schertz *et al.*, 1997). All the commercial grain hybrids are single-cross hybrids. Three-way hybrids can be produced, but they are less likely to be adopted in sorghum, because sorghum growers are relatively more conscious of the morphological uniformity of single-cross hybrids, and the seed yield advantage of the male-sterile F1s over male-sterile inbreds is much less.

The 1960s were marked by the ready accessibility of germplasm from the developed world to the developing world, and the beginning of the development of hybrid sorghums using cytoplasmic-nuclear male sterility (Reddy and Stenhouse, 1994a). The development and commercial cultivation of hybrid sorghums led to the improvement in grain yield by over 300% from 1950 to 1990 in the United States. Later improvements were in terms of smaller yield increments, and enhanced disease and insect resistance and grain quality (Rooney and Smith, 2000). Introduction of several seed parents of hybrid grain sorghum from the United States paved the way for hybrid development in Australia with several hybrids being released during 1960s. Tropical germplasm is an important source of dominant alleles for yield and plant height, while temperate germplasm has dominant alleles for earliness/maturity. The use of tropical×temperate crosses has produced several high-yielding varieties with desirable plant height (2–2.5 m) and maturity (100–110 days) (Rao and Rana, 1982). The type of restorer line used in breeding significantly impacts on heterosis, or vigour, in the resulting hybrids. *Guinea* restorer lines contributed to the highest heterosis and grain yield *per se* in hybrids, followed by *caudatum* restorer lines. However, accompanying problems such as clasping of glumes to the grain in hybrids of *caudatum–kafir* male-steriles and *guinea* restorers need to be addressed (Reddy and Prasada Rao, 1993). To circumvent the problem of negative correlation of grain size with number of grains and its associated problem of germination, some breeding programmes have successfully minimised the negative correlation and optimised the grain size by selecting seed parents of hybrids with the highest grain number within some pre-judged minimum range, then selecting the male parents (R-lines) with large grains (without regard for numbers).

1.7.1.2 Breeding for Abiotic Stress Resistance

Drought is the most devastating production constraint that can occur at any crop growth stage. Drought tolerance in sorghum is specific to the growth stage, that is, sorghum genotypes with good tolerance during one of the developmental stages might be susceptible to drought during the other growth stages, making it a complex character to work with. Drought is highly specific and that breeding for drought resistance therefore depends upon the stage of the crop at which the drought occurs, inferring that breeding for the traits that contribute to specific drought resistance should be carried out to realise further productivity gains in the target regions (Reddy, 1986). The mechanisms of drought tolerance in sorghum can be described as escape, avoidance and tolerance (Reddy *et al.*, 2009). Early maturity is a well-known 'drought-escape' mechanism through which the crop completes its life cycle before the onset of severe moisture deficits, and is often associated with reduced yield potential. Short-duration sorghums have lower evapo-transpiration rates due to smaller leaf area and smaller root density compared to those of long-duration ones (Blum, 1979). To some extent, yield loss can be overcome by increasing the plant density. Drought avoidance is a mechanism for avoiding lower water status or to maintain a relatively higher level of hydration in tissues during drought by maintaining cell turgor and cell volume either through aggressive water uptake by an extensive root system (Manschandi *et al.*, 2006; Hammer *et al.*, 2009), or through reduction of water loss from transpiration and other non-stomatal pathways (Ludlow and Muchow, 1990) such as through the plant cuticle. Most cultivated dryland sorghum genotypes show epicuticular wax values close to the maximum (Jordan *et al.*, 1983). Plants avoid low Leaf Water Potential (LWP) by one or more mechanisms, such as a change in rooting pattern, an increased root growth for maximising water uptake or an adjustment in leaf area for optimisation of the use of absorbed water for the production of dry matter (Seetharama *et al.*, 1982). Sufficient genetic variability was recorded for the root attributes, transpiration efficiency and transpiration regulation (Hammer *et al.*, 1997; Kholová *et al.*, 2010), and canopy development (Borrell, Hammar and Henzell, 2000; Kim *et al.*, 2010). Drought tolerance is a mechanism by which plant maintains metabolism even at low water potential. Dehydration results in irreversible disruption of cellular organisation and metabolism and most crop plants belong to the dehydration-intolerant category. Severe dessication represents a small proportion of the total instances of drought. However, enhancement of dehydration tolerance, which results in continued leaf growth and decreased senescence during mild or moderate drought, could have a positive effect on agricultural production. This trait is considered as the most difficult to improve through conventional plant breeding. Characterisation of the target production region is the first and the crucial step in undertaking a genetic improvement programme aimed at improving yield and yield stability in drought-prone environments (Robertson, 1988).

Thus, while breeding for drought resistance and yield potential, emphasis should be given for traits such as emergence under crust, seedling drought recovery, and grain yield under drought-prone and yield-potential areas for early stage drought; for drought recovery and grain yield under drought-prone and yield-potential areas under mid-season drought; and stay-green, non-lodging and grain yield under drought-prone and yield-potential areas for terminal drought (Reddy, 1986).

1.7.1.2.1 Drought Tolerance

Drought stress is a major constraint to sorghum production worldwide. Although sorghum possesses excellent drought resistance compared to most other crops, improving its drought resistance would increase and stabilise grain and food production in the low-rainfall and harsh environmental regions of the world (Rosenow *et al.*, 1997). Drought resistance is the phenotypic expression of a number of morphological characteristics and physiological mechanisms including drought escape, dehydration avoidance and dehydration tolerance (Ludlow, 1993). Therefore, drought resistance in sorghum is a complex trait affected by several interacting plant and environmental factors.

The response of sorghum to soil moisture stress is largely determined by the stage of growth at which moisture stress occurs, with two distinct responses to drought stress identified. The pre-flowering (mid-season) drought response is expressed when plants are stressed during panicle differentiation prior to flowering, while the post-flowering drought response is expressed when moisture stress occurs during the grain filling stage (Rosenow and Clark, 1995). Two further responses were described by ICRISAT – where emergence under crust and high temperature prevailed in drought-prone environments, and wherein the lines with long mesocotyl emerge earlier than others; and early stage (120-day-old seedlings) drought recovery where distinct differences among the genotypes were observed (Reddy, 1985).

Symptoms of pre-flowering drought stress susceptibility include leaf rolling, uncharacteristic leaf erectness, leaf bleaching, leaf tip and margin burn, delayed flowering, poor panicle exsertion, panicle blasting and floret abortion and reduced panicle size. Tolerance to pre-flowering drought stress is indicated by the alternative condition in each instance. Since the panicle is directly affected, severe pre-flowering stress can result in drastic reductions in grain yield. Research at ICRISAT–Patancheru, India, screened and identified progenies with high levels of pre-flowering stress recovery which were further selected for grain yield alternatively under mid-season drought and yield potential environments in India. When tested in drought-prone environments in Africa, these lines had greater stability and grain and biomass yield than other varieties. Similarly, promising lines with resistance to seedling emergence under crust and high temperature were also identified (ICRISAT, 1982; 1986; 1987).

Symptoms of post-flowering drought stress susceptibility include premature plant (leaf and stem) death or plant senescence, stalk collapse and lodging, charcoal rot (*Macrophomina phaseolina*) and a significant reduction in seed size, particularly at the base of the panicle. Tolerance is indicated when plants remain green and fill grain normally. Such green stalks also have good resistance to stalk lodging and to charcoal rot. Such cultivars are referred to as having ‘stay-green’ trait.

Stay-green is an important post-flowering drought-resistance trait, with genotypes possessing stay-green ability maintain a greater green leaf area under post-flowering drought than their senescent counterparts (Rosenow *et al.*, 1997). Recent studies have shown that leaves stay green not only because of small sink demand, but also due to higher leaf nitrogen status and transpiration efficiency resulting in maintenance of photosynthetic capacity and ultimately, higher grain yield and lodging resistance (Borrell and Douglas, 1997; Borrell *et al.*, 1999; Borrell, Hammar and Douglas, 2000; Borrell and Hammer, 2000). Greater green leaf-area duration during grain fill appears to be a product of different combinations of three distinct factors, green leaf area at flowering; time of onset of senescence and subsequent rate of senescence, all of which are independently inherited and easily combined in breeding programmes (Van Oosterrom *et al.*, 1996; Borrell, Hammar and Henzell, 2000). Stay-green hybrids produce significantly greater total biomass after anthesis, retain greater stem-carbohydrate reserves, maintain greater grain-growth rates and have significantly greater yields under terminal drought stress than related but senescent hybrids (Henzell *et al.*, 1997; Borrell *et al.*, 1999; Borrell, Hammar and Douglas, 2000). Excellent sources of resistance to both pre- and post-flowering drought have been identified, and although high levels of both types of resistance are generally not found in the same genotype, some genotypes possess good levels of resistance to both types (Rosenow *et al.*, 1997).

Several physiological traits such as heat tolerance, desiccation tolerance, osmotic adjustments, rooting depth and epicular wax are known to improve drought resistance (Downes, 1972; Sullivan, 1972; Sullivan and Ross, 1979; Turner, 1979; Jordan and Monk, 1980; Kramer, 1980; Jordan and Sullivan, 1982; Peacock and Sivakumar, 1987; Levitt, 1992; Krieg, 1993; Ludlow, 1993; Van Oosterrom *et al.*, 1996; Henzell *et al.*, 1997). Although screening techniques based on these traits for drought resistance have been reported, little if any progress using specific physiological traits has been documented, partly because interaction of various physiological mechanisms involved in drought tolerance is still poorly understood (Christiansen and Lewis, 1982; Garrity *et al.*, 1982; Seetharama *et al.*, 1982; Blum, 1983; Jordan *et al.*, 1983; Ejeta, 1987; Bohnert *et al.*, 1995). It appears that individual physiological traits identified to date are not sufficiently related to overall drought response or field performance to merit selection based on them (Rosenow *et al.*, 1997).

Field nurseries in dry environments have been used to screen pre- and post-flowering drought response in several countries around the world including Mexico, Sudan and Australia (Ejeta, 1987; Rosenow *et al.*, 1997). Soil type affects screening, with sandy soil or shallow soil best suited for pre-flowering evaluation, and heavier, deeper soils best for evaluating post-flowering stress (Rosenow *et al.*, 1997).

The stay-green trait has been successfully used in Australia to develop post-flowering drought-stress resistance and lodging resistance in parental lines and in commercial hybrids. Conventional breeding for stay-green is primarily based on two sources, B35 and KS19 of Ethiopian and Nigerian origin, respectivley (Henzell *et al.*, 1984; 1992; Henzell and Hare, 1996; Rosenow *et al.*, 1997; Mahalakshmi and Bidinger, 2002). KS19 has been commercially used primarily in the breeding programme of Queensland Department of Primary Industries and Fisheries (QDPIF) while B35 is widely used in both public and private sector breeding programmes in the United States (Henzell and Hare, 1996). B35 has provided the major and best sources of stay-green used in QDPIF programme, and produced the key line QL41 with high levels of stay-green expression. Crosses between QL41 and sorghum midge-resistant lines formed the basis of the female stay-green and midge-resistant genepool in the QDPIF programmes, although less progress has been made in developing such germplasm in the male population (Rosenow *et al.*, 1983; Henzell *et al.*, 1997). Because of this precise requirement for the trait expression, field environments do not offer ideal conditions for selection and therefore, identification of QTL conferring stay-green trait and the molecular markers tightly linked to these QTL will provide powerful tools to enhance drought resistance (Henzell and Hare, 1996; Crasta *et al.*, 1999; Xu *et al.*, 2000).

1.7.1.2.2 Tolerance to Soil Acidity

Tolerance to soil acidity and Al^{3+} toxicity in sorghum is controlled by a few dominant genes under additive and non-additive actions, with heterosis also observed (Flores *et al.*, 1991; Adamou *et al.*, 1992; Zake *et al.*, 1992; Maciel, Andrade Lima de, Duncan *et al.*, 1994; Gourley, Watson, Schaffert *et al.*, 1997). Soil acidity stress factors vary with location, soil depth, rainfall, temperature, effective cation exchange capacity (ECEC), natural content of essential elements, level of toxic ions, p-fixation capacity and amount and quality of organic matter (OM) (Gourley, Watson, Schaffert *et al.*, 1997). These factors combined with a poor correlation of results obtained in nutrient culture for acidity tolerance in field or greenhouse studies are the causes of complexity of breeding for tolerance to soil acidity (Horst, 1985; Marschner, 1991). Nevertheless, much progress has been made since EMBRAPA sorghum for tolerance to acid soils and International Sorghum and Millets (INTSORMIL) sorghum acid-soil breeding project were initiated in Columbia in 1981 (Schaffert *et al.*, 1975).

Many sorghum lines have been identified with good levels and substantial genetic variability in Al^{3+} toxicity tolerance (Andrade Lima de *et al.*, 1992; Maciel, Andrade Lima de, Santos *et al.*, 1994; Gourley, Watson, Schaffert *et al.*, 1997). More than 6000 sorghum genotypes from the world collection were screened at Quilichao, Colombia, with around 8% found to tolerate 65% Al^{3+} saturation, with a few of these genotypes able to produce greater than 2 t/ha of grain (Gourley, 1988). Many of these highly tolerant genotypes from the world collection originated in acid-soil areas in Nigeria, Uganda or Kenya and were classified as *caudatum* or *caudatum*-hybrid races. The open-panicled *Guinea* race and the hybrid *Guinea bicolor* lines had a higher overall percentage of acid-tolerant sorghum entries than those of other races and hybrids evaluated (Gourley, 1988).

The INTSORMIL and EMBRAPA projects used pedigree-breeding methods to identify Al-tolerant plants, and screened the F_2 plants at 65 and 45% Al saturation, respectively. The resulting tolerant lines had yields between 2.6 and 4.6 t/ha, with the INTSORMIL lines shorter and earlier than the EMBRAPA lines (Gourley, Watson, Schaffert *et al.*, 1997). About 170 grain sorghum inbreds with tolerance to Al saturation levels of tropical acid soils developed by pedigree breeding have been released as germplasm by Mississippi Agricultural and Forestry Experiment Station (MAFES) (Gourley, Watson, Goggi *et al.*, 1997).

ICRISAT and Centro International de Agriculture Tropical (CIAT) screened large numbers of grain sorghum lines (male-sterile, restorer and forage lines) over four consecutive seasons under varied Al^{3+} concentrations, and identified high-yielding male-sterile lines (MS), restorer lines (R) and forage sorghums tolerant to Al^{3+} that have been distributed to various agencies in the region (ICRISAT, NARS, CIAT, 1997). Evaluation of these high-yielding breeding materials in multiple locations resulted in the identification of many male-sterile lines (MS), restorer lines (R), maintainer lines (B), and forage lines with wide adaptability (regression coefficient between 0 and 1) (Reddy *et al.*, 1998; Reddy and Rangel, 2000).

Four of the nearly 200 sorghum hybrids evaluated at Matazul (60% Al^{3+} and 4.6% organic matter), were found to have outstanding tolerance to soil acidity, and they were also less susceptible to leaf diseases, were greener at the time of maturity, and also taller than the control Real 60 (ICRISAT, 2000). Hybrids therefore hold promise for improving the sustainability of the acid savannas (Reddy, Prakasha Rao *et al.*, 2004).

1.7.1.2.3 Soil Salinity Tolerance

While there are several studies on the assessment of variability for salinity tolerance in sorghum, studies on genetic basis of this variation is rather limited (Azhar and Mc Neilly, 1989; Haggag *et al.*, 1993; de la Rosa Ibarra and Maiti, 1994; Fernandes *et al.*, 1994; Igartua *et al.*, 1994; Jiqing Peng *et al.*, 1994; Maiti *et al.*, 1994; Richter *et al.*, 1995). The genetic control of salinity tolerance appears to be complex with both additive and dominant gene effects important in controlling the expression of salt tolerance, however, the effect of dominant genes appear to be most important (Igartua *et al.*, 1994). The relatively high heritability for salt tolerance suggests the possibility of rapid improvement in salinity tolerance using high selection pressures in F_2 populations (Azhar and McNeilly, 1989).

Early screening for salt–stress-tolerant sweet sorghum genotypes can be done *in vivo* by: (i) growing the seedlings on sand in polystyrene containers, and (ii) growing the seedlings in spectrophotometer cuvettes (Montemurro *et al.*, 1994). Genotypic response to salt stress is similar in both the methods, and classification of sweet sorghum genotypes for salt tolerance was effectively demonstrated. A third method was suggested by Hassanein and Azab (1990), where seeds of sorghum genotypes were grown in water (control) and NaCl solution (ECE = 12, 16 or 20 mhos/cm).

Biochemical basis of resistance to salinity: The concentration of biochemical components such as proline and hydrocyanic acid (HCN) increase with an increase in salinity levels in resistant genotypes, but not in the susceptible genotypes of sorghum at the seedling stage (Richards and Dennett, 1980; de al Rosa Ibarra and Maiti, 1994). The detailed study of resistance mechanism of these lines would aid in incorporation of resistance in elite agronomic background.

Attempts to breed sorghum for salinity tolerance is rather limited. This is because the major problem when breeding sorghum for abiotic stresses such as salinity is the choice of optimal selection environment/s due to the high levels of both spatial and temporal variation in salinity-affected fields (Richards and Dennett, 1980; Richards *et al.*, 1987; Igartua, 1995). Spatial variation occurs horizontally and vertically on very small scales, and, therefore, most salinity-affected lands are actually comprised of many micro-environments, ranging from low to high salinity in the same field (Igartua, 1995).

Testing genotypes across a broad range of salinity levels shows that genotype×salinity level interactions are commonly large and significant in sorghum, forcing the plant breeder to decide whether to work over the whole target environment (breeding for wide adaptation), or subdivide it into more homogeneous sub-environments (breeding for specific adaptation) (Azhar and Mc Neilly, 1987; Igartua, 1995). This decision depends mainly on the relative sizes of the genotype×year and genotype×location interaction (Austin, 1993). Unfortunately, when working in areas with saline soils, this choice does not exist as the highly variable conditions occur concurrently in the same field. Thus, breeding for saline areas can be compared to wide adaptation.

The target environments, both for breeding for saline soils or for wide adaptation, are actually a population of many possible environments, for which there exists a significant component of genotype×environment interaction (Igartua, 1995). Three environment selection strategies have been proposed: (i) make selection in a stressful environment; (ii) select under optimum growing conditions and (iii) use a combination of both the approaches, that is, select materials that perform well under both stress- and non-stress conditions (Calhoun *et al.*, 1994). The third option appears to be the best as separate selection for distinct environments is not possible, and greater accuracy of selections is achieved over more environments used (Igartua, 1995). However, as testing resources are limited, a sensible compromise seems likely to be combination of a non-stress location, and at least one stress environment (within the range of target environment) between which there is G×E interaction (of cross over type). Selection of breeding populations for salinity tolerance over three salinity levels: low, high and average of the two extreme levels, instead of the whole range of salinity levels, has demonstrated the usefulness of option 3 to select for improved yield in grain sorghum under saline soil conditions (Maas and Hoffman, 1977; Igartua, 1995).

Salinity causes more serious damage to sorghum cultivars in the seedling-emergence stage than in any other stage as revealed through both field and laboratory experiments in China (Jiqing Peng *et al.*, 1994). Therefore, enhancing the salinity tolerance of grain sorghum at the germination-emergence stage should be one of the breeding objectives sought for areas affected by soil salinity (Hassanein and Azab, 1990). The effectiveness of divergent selection for tolerance to salinity at germination-emergence stage in grain sorghum has been demonstrated where subsets of the progenies showing best and least tolerance to salinity were selected and recombined to constitute the next cycle. Evaluation of the original and four subpopulations under saline conditions evaluated in the laboratory and the field for germination-emergence ability revealed the effectiveness of selection in separating the subpopulations (Igartua and Gracia, 1998).

Thus, it appears that while attempts to enhance salinity tolerance of sorghum in saline areas are limited, much progress has been achieved in breeding sorghum for soil acidity tolerance with and without Al^{3+} toxicity. Future breeding programmes should aim at specific adaptations in view of significant genotype×Al^{3+} toxicity interaction variation, and variation in Al^{3+} saturation from location to location. Further, the possibility of different resistance mechanisms due to varying levels of Al^{3+} saturation necessitates the study of resistance mechanisms and their genetics in selected sorghum lines. Wide adaptation for salinity tolerance is also warranted due to the considerable variability in soil salinity levels both spatially and temporally within field plots.

1.7.1.3 Breeding for Biotic Stress Resistance

Breeding schemes involving simultaneous selection for resistance and grain yield and converting the maintainer selections into male-sterile lines has been used effectively to develop male-sterile lines for resistance to pests and diseases in the shortest possible period of 4 years (Reddy, Prakasha Rao *et al.*, 2004). Breeding for insect resistance targets multiple traits. For stem borer resistance, the independence of antibiosis and the difference in patterns of inheritance of resistance to flower and peduncle damage and dead heart formation must be considered. The traits foliar and stem damage, and the percentage of dead hearts were targeted with stem-borer-resistant genotypes identified (Singh and Rana, 1994). For shoot fly, the most important factor is to select for resistant germplasm in the season for which the material is intended (Jayanthi, 1997). In selecting for resistance and increased yield, a multiple selection approach is employed with resistance selected on a family basis, and then selecting individuals within the resistant family for yield (ICRISAT, 1995). In combining resistance characters that are simply inherited with grain yield, multiple crosses (three- or four-way) are as effective as single crosses. However, the selection for resistance of quantitatively inherited traits, such as resistance to stem borer or shoot fly, is not effective in four-way crosses (Reddy, 1993).

Extensive use of the zera zera group of converted sorghums has made major contribution to disease resistance, yield potential and grain quality of the US hybrid sorghum (Rosenow and Dalhberg, 2000). On a global scale, breeding for grain mould in sorghum has been accorded the highest priority. However, the success rate has been disappointing, because grain mould is caused by a complex of parasitic fungi (species of *Fusarium*, *Curvularia*, *Phoma* and *Colletotrichum*) that damage endosperm and saprophytic fungi (species of *Aspergillus* and *Cladosporium*) that affect the pericarp. Mould-resistance sources are mostly red or brown grain types, which are associated with high tannins and (or) phenolic compounds such as flavan-4-ols. A few good resistance sources with red grain types have been found in tannin-free backgrounds (Bandyopadhyay *et al.*, 1988). In white grain sorghums, moderate levels of resistance are available only in hard endosperm backgrounds. Associations such as these have deterred the incorporation of mould resistance into early-maturing and large-seeded white grain sorghums with high grain yield. Other biotic constraints have received relatively low priority in the semi-arid tropical regions of Asia and Africa. These can be grouped into two categories. The first category includes anthracnose (*Collitotrichum graminicola* (Ces.) Wils.), leaf blight (*Exserohilum turcicum* Leo and Sug.) and leaf spot (*Cercospora sorghi* Ellis and Everhert), diseases of sorghum; midge (*Stenodiplosis sorghicola* Coquillett)) and head bugs (*Calocoris* and *Eurystylus* species) insect pests of sorghum; and the root parasite *Striga hermonthica* (Del.) Benth. of sorghum. For these, good resistance sources and effective screening techniques have been developed (Sharma *et al.*, 1991; 1993; Thakur *et al.*, 1992; 1993; Ejeta *et al.*, 1997). However, these have been shown not to have as large an impact on yield, on as large a geographical scale, as grain mould. Crop losses due to *S. hermonthica* can be considerably reduced in both crops through the use of trap and catch crops, and through various cultural practices (Lagoke *et al.*, 1991). The second category includes stem borers (species of *Busseola*, *Eldana*, *Sesamia* and *Chilo*) shoot fly (*Atherigona soccata* Rodani) and ergot (*Claviceps africana*, Frederickson, Mantle and de Milliano) of sorghum for which confirmed sources of good resistance are not available and (or) the trait inheritance is too complex to permit its effective utilisation in breeding. This category has received little attention in breeding programmes in Asia and Africa.

1.7.1.3.1 Resistance to Foliar, Stem and Head Feeding Insects

The lack of elite insect-resistant varieties and hybrids is due to low resistance levels when transferred into agronomically improved sorghum. When resistance is high, progenies are agronomically undesirable (Nwanze *et al.*, 1995). In addition, resistance to some insects is quantitatively inherited and difficult to incorporate into elite, high-yielding varieties or hybrids (Pederson *et al.*, 1997).

Population, pedigree and/or backcross breeding methods are adopted to develop insect-resistant sorghum genotypes. If resistance is evaluated using the techniques developed by entomologists in collaboration with plant breeders such as in the greenhouse (as for green bug), only resistant genotypes are taken to the field for further selection or crossing (Pederson *et al.*, 1997). On the other hand, if resistance evaluation is done in the field, resistant genotypes should be identified before pollination to expedite development of improved plant populations. The appropriate method to use will be specific to a particular research programme, the genetics of resistance, research objectives and the needs of collaborators (Pederson *et al.*, 1997).

Development of improved germplasm and/or varieties resistant to shoot fly, stem borer and midge are the examples for the success of conventional breeding programmes in Africa and India (Sharma, 1993). Low levels of resistance to shoot fly have been incorporated into a few promising cultivars, and although several improved shoot fly-resistant male-sterile lines have been developed by involving these improved varieties and restorers in back-cross programme, hybrid parents with improved agronomic characters such as greater seed size coupled with shoot fly-resistance are needed to produce post-rainy-season hybrids in India. Until now, pedigree and backcross breeding have been used (supported by artificial screening) at ICRISAT–Patancheru to breed hybrid parents resistant to shoot fly and adapted to the rainy-season-production systems from a broad range of germplasm accessions and several breeding lines. Use of wild sorghums, *S. versicolor* and *S. arundinacium* to obtain qualitatively different sources of resistance is the future objective. Absolute resistance to shoot fly was noticed in wild relatives *S. dimidiatum and S. australiense*, with efforts currently underway to exploit and introgress these using molecular markers.

Several midge-resistant varieties and hybrid parents have been developed at ICRISAT–Patancheru using pedigree selection and backcross techniques; however, these are mostly based on single source of resistance that loses its resistance at the high altitudes and low temperatures of Eastern Africa. An immediate objective would be to incorporate midge resistance expressed at low temperatures into agronomically improved cultivars. In Western and Central Africa, advanced midge-resistant lines bred at Patancheru are crossed to locally adapted elite materials to obtain improved midge-resistant cultivars.

Breeding efforts for resistance to stem borer by ICRISAT in India and western and central Africa are focused on *C. partellus* and *B. fusca*, with several stem-borer-resistant male-sterile lines, pollinators, and varieties developed. In Western and Central Africa, a random mating population with sources of resistance to *B. fusca* and adapted high-yielding lines are being developed and pursued through recurrent selection procedures. To make necessary genetic improvement in insect resistance, breeders and other scientists will need to incorporate molecular biological tools into their programmes to a greater extent (Peterson *et al.*, 1997).

1.6.1.3.2 Breeding for Disease Resistance

Disease management through genetic manipulation has been the most effective means of reducing losses in many crop species. However, managing all diseases by genetic means is neither feasible nor possible (Thakur *et al.*, 1997).

Breeding for host-plant resistance is one of several methods of protecting the crop. Therefore, before a resistance breeding programme begins, it must be clearly determined that: (i) the disease is of sufficient economic importance, (ii) sufficient information is available on the nature of host-pathogen system and on screening techniques, (iii) well-defined sources of resistance are available and (iv) the expected economic output will occur within a given time.

Breeding for disease resistance in sorghum began about three decades ago (Mukuru, 1992; Rosenow, 1992). Crop improvement employed diverse exotic germplasm to improve both grain yield and the agronomic characters of local cultivars. Choice of parents is the first crucial step in any hybridisation and selection programme. Usually an agronomically good, high-yielding cultivar is crossed to other parents with disease resistance, good grain quality, local adaptation, etc. Appropriate weight should be given to the maturity period, height, grain quality and status of resistance to various stress factors of the parents involved in the cross. The genetic basis of resistance should suggest the selection procedure (Thakur *et al.*, 1997). Disease control through host genetic manipulation is difficult and has been slower for charcoal rot and grain mould, in which gene effects are small, compared to downy mildew, anthracnose and leaf blight, in which gene effects are large (Thakur *et al.*, 1997).

Pedigree breeding with selection for resistance based on families and agronomic desirability within the selected families of single crosses, and frequently in three-way crosses has resulted in disease-resistant, high-yielding hybrid parents. It has been found that a third parent in the cross can supplement useful traits/recessive genes and increase their frequency in the segregating populations without seriously affecting agronomic eliteness. Specific improvement for resistance to a simple disease (e.g. rust) can be obtained by back-cross breeding. Pedigree-breeding selection procedures to accumulate favourable alleles for multiple resistance factors for diseases such as grain mould, downy mildew, charcoal rot, etc. were used at ICRISAT–Patancheru, and considerable progress has been made in transferring resistance to individual diseases into several high-yielding sorghum lines for grain mould, downy mildew, rust, leaf blight and anthracnose.

Current breeding methods at ICRISAT–Patancheru, India, include both pedigree and population improvement for grain mould resistance breeding. Pedigree selection using artificial screening for grain mould resistance has resulted in improved high-yielding lines and hybrid parents with white grain types. A random mating population with white grains and *guinea* type panicle and glume traits is under improvement at ICRISAT–Patancheru. Male-sterile lines with white, red and brown grain colours and with resistance to grain mould have also been developed. The possible roles of antifungal proteins that inhibit the growth of grain mould fungi are being investigated at ICRISAT–Patancheru and Texas A&M University in the United States. Several male-sterile lines resistant to anthracnose (*Colletotrichum graminicola*) have been developed at ICRISAT–Patancheru, India, following pedigree selection and back-cross methods.

With the advent of modern molecular techniques, however, significant advances have occurred in molecular characterisation of resistance genes and identification of markers for tagging. Present-day breeding for disease resistance is a collaborative effort of pathologists, molecular biologists and breeders working across locations and regions (Thakur *et al.*, 1997).

1.7.1.3.3 Breeding for Striga Resistance

Witchweed (*Striga* spp.) is endemic to subtropical regions and comprise about 36 species, of which around 31 occur in Africa (Raynal-Roques, 1987). Five species of *Striga* attack cultivated cereals: *Striga hermonthica* (Del.) Benth, *S. aspera* (Willd) Benth, *S. forbesii* Benth, *S. asiatica* (L) Kuntze and *S. densiflora* Benth (Doggett, 1984). Only three species are of widespread economic importance in Africa: *S. asiatica* and *S. hermonthica*, which attack cereals, and *S. gesnerioides* that parasitise legumes, principally cowpea (*Vigna unguiculata*) (Doggett, 1988).

Striga asiatica occurs mainly in Southern and Central Africa while *S. hermonthica* predominates in the semi-arid zones of tropical Eastern, Central and Western Africa where it attacks food crops such as sorghum, pearl millet (*Pennisetum glaucum*), maize (*Zea mays*), upland rice (*Oryza sativa*), sugarcane (*Saccharum officinarum*), as well as several wild grasses (Tarr, 1962; Doggett, 1988). *Striga hermonthica* and *S. asiatica* are obligate parasitic weeds of sorghum with significant economic importance. The yield losses from damage are often significant with estimates varying from 10 to 70% depending on crop cultivator and degree of infestation (Doggett, 1988). Crop losses due to *Striga* infestation are often higher in Africa than in India. The *Striga* parasite produces large numbers of tiny seeds that remain viable in the soil for many years, germinating only when a host root grows in close proximity, and once established in the fields, it is virtually impossible to eradicate, making this parasite extremely difficult to control (Doggett, 1988).

Host plant resistance is the most practical and economically feasible means for reducing crop losses due to *Striga* and is central to an integrated control approach. *Striga* resistance is defined as the capacity of a host plant to support fewer emerged *Striga* plants and to yield more grain than a susceptible crop plant grown under similar infestation (Ejeta *et al.*, 1997). Characterisation of source germplasm, development of simple and efficient screening techniques and a well-planned selection strategy for yield and other traits of importance in subsistence agriculture are the bare essentials for embarking on breeding for *Striga* resistance. Given the widespread *Striga* problem, and the opportunities for natural and deliberate selection in environments where the host and parasite have co-evolved, there has been surprisingly low genetic variability for *Striga* resistance in sorghum germplasm (Ejeta *et al.*, 1997).

Pedigree breeding selections for agronomic and grain quality traits in early-generation breeding progenies, with selection for *Striga* resistance defered until homozygous progenies are derived after several generations of selfing. This is necessary because, selecting for field-*Striga* resistance in unreplicated segregating progenies on per plant basis is uninformative. Seed parents (with genes for *Striga* resistance) were developed following pedigree breeding and used to develop resistant hybrids at ICRISAT–Patancheru and Purdue University.

Recurrent selection schemes involve a population-improvement approach using a cyclical selection scheme in a carefully synthesised random-mating population to pyramid genes for *Striga* resistance from several sources into one common background. A random-mating sorghum population has been developed at Purdue University (Ejeta and Bulter, 1993b).

1.7.1.4 Breeding for Grain Quality

The starch content of whole sorghum is about 70%, and its protein content is about 11% (flour weight basis), which is higher than in maize (Klopfenstein and Hoseney, 1995). The digestibility of sorghum protein is relatively poor, because cross-linked prolamine levels are relatively higher in sorghum which are known to be extremely low in the essential amino acid lysine, rich in leucine and with low protein digestibility (i.e. lowered when the grain is cooked) (Deosthale *et al.*, 1972; Maclean *et al.*, 1983; Rao, Mehta *et al.*, 1984; Magnavaca *et al.*, 1993). The digestibility problem is further complicated by the presence of polyphenols as condensed tannins in some brown grain sorghums (those with a testa). Sorghum is usually rich in glutamic acid, leucine, alanine, proline and aspartic acid, with the level of amino acid highly positively correlated with protein content (Waggle and Deyoe, 1966). Similar protein content of immature and mature grain coupled with higher content of lysine, aspartic acids and glycine and much lower glutamic acid, proline and leucine makes immature grain more nutritionally balanced than mature grain in terms of amino acid composition (Deyoe *et al.*, 1970). The proteins albumin and globulin, glutein and prolamins are best, intermediate and poorest proteins in terms of nutrition (Virupaksha and Sastry, 1969; Wall and Blessin, 1970).

Considerable variability has been reported for protein content as well as essential amino acid levels such as: lysine, methionine, tryptophan, histidine, arginine, aspartic acid, threonine, serine, glutamic acid, proline, glycine, alanine, cystine, valine, methionine, isoleucine, tyrosine and phenylalanine (Virupaksha and Sastry, 1968; 1969; Deosthale *et al.*, 1970; Reich and Atkins, 1971; Mali and Gupta, 1974; Nanda and Rao, 1975a; 1975b).

While the protein content of sorghum grain is governed by additive gene action, essential amino acids such as lysine and methonine are controlled by both additive and non-additive gene action. Another essential amino acid, tryptophan appears to be governed by non-additive gene action (Nanda and Rao, 1975a; 1975b; Rana and Murty, 1975; Singhania *et al.*, 1979; Nayeem and Bapat, 1984; Chinna and Phul, 1986; Mallick *et al.*, 1988). While the high-lysine natural mutant gene (hl) is a monogenic recessive (Singh and Axtell, 1973), lysine content is inherited as a single gene with partial dominance in p-721 Q, a chemically induced high-lysine mutant of sorghum (Mohan, 1975; Axtell *et al.*, 1979). Similarly, protein digestibility in a sorghum line, p-851171 derived from p-721 Q is inherited as a simple Mendelian trait (Oria *et al.*, 2000; Axtell, 2001).

The identification of naturally high-lysine Ethiopian sorghum mutants from the world sorghum collection, a chemically induced high-lysine mutant, and the recent identification of a sorghum line with high protein digestibility levels surpassing that of maize, facilitated the prospects for combining high nutritional quality and grain yield (Singh and Axtell, 1973; Mohan, 1975; Oria *et al.*, 2000). The two high-lysine Ethiopian lines, IS 11758 and IS 11167, have exceptionally high-lysine contents, are photoperiod-sensitive, tall, late and have shrivelled or dented seeds. Their acceptance is limited due to many problems associated with their opaque kernel characteristics, reduced grain yield, slow drying in the field, increased susceptibility to moulds and insects and the tendency of the seed to crack when mechanically harvested (Rao, Mehta *et al.*, 1984; Ejeta and Axtell, 1990). Similarly, the chemically induced high-lysine strain p-721 Q has soft kernel and floury endosperm with reduced yielding ability (Rao, Rana *et al.*, 1984; Asante, 1995; Axtell, 2001).

Earlier attempts to select agronomically desirable recombinants with dwarf- to medium plant height, early maturing and relatively photoperiod-insensitive with superior protein quality, from various cross combinations of the very tall, late, photoperiod-sensitive Ethiopian high-lysine parents were not fruitful (Rao *et al.*, 1983b). Although it was possible to select plump, corneous grain types with the high-lysine trait, as breeding continued and generations advanced, there was a reduction in the frequency of plants with high levels of lysine. Selection during 1994 from a high-lysine population developed at Purdue University had 0.30–0.49% lysine (flour basis), compared to normal sorghum cultivars that contain about 0.24% lysine with grain yield in this group ranging from 3 to 4 t/ha (Hamaker and Axtell, 1997). Establishment of a negative correlation between protein and lysine content in several segregating generations of Ethiopian high lysine × agronomically superior varieties forced the breeders to improve lysine at moderate protein levels (Rao *et al.*, 1983a; Rao, Rana *et al.*, 1984).

Ejeta and Axtell (1990) were able to select modified endosperm of p-721 opaque (high lysine mutant) with vitreous kernels similar to normal types. But, vitreous phenotypes have been detected in advanced generation (F_6) of breeding. However, crosses between p-721 Q (high protein digestibility) and other elite lines resulted in improved yields (Axtell *et al.*, 1979). The recent identification of sorghum line, p-851171, (a derivative of p-721 Q) with protein digestibility levels surpassing that of maize raises the hopes of improving protein digestibility in sorghum (Oria *et al.*, 2000). However, to date, no studies have examined the association between protein digestibility and lysine concentration in crosses involving p-85117 (Axtell, 2001).

Recent development of a rapid protein digestibility assay for identifying highly digestible sorghum lines will help in screening large number of breeding lines for protein digestibility (Aboubacar *et al.*, 2002). Sorghum germplasm with high protein digestibility as high as or higher than maize or other staple cereals have been identified through Purdue/INTSORMIL research. In addition, lines having vitreous kernels with good food grain and processing properties have been identified and are available for breeding programmes at Purdue University (Axtell, 2001).

Whole-grain digestibility of sorghum is sometimes a problem; however, local processing techniques convert sorghums into digestible foods. Development of highly digestible sorghum is desirable, but in many environments, the highly digestible sorghums are predigested by moulds and insects in the field and have quite low yields. Therefore, highly digestible types may be limited to production in extremely dry environments where the grain is not subjected to humidity after maturity. It is difficult to improve digestibility without enhancing the susceptibility of the grain to deterioration, thus, efforts to enhance digestibility of sorghum must be done with care. Waxy sorghums have improved digestibility for ruminants and possibly swine, but that improvement is accompanied by poor seedling emergence and viability. Current waxy sorghum hybrids have lower grain yields, however hetero-waxy hybrids, where one parent is waxy and one non-waxy, provide high-yielding hybrids with improved digestibility (Rooney *et al.*, 2003).

Contrary to the belief of many scientists and nutritionists that all sorghums contain tannins, sorghums without a pigmented testa do not contain tannins (Bulter, 1990a).

The tannin (brown) sorghums have a very definite pigmented testa (caused by combination of dominant B_1-B_2-S-genes) with levels of condensed tannins which may offer resistance to birds and grain mould (Tipton *et al.*, 1970; Mc Millian *et al.*, 1972; Bulter, 1990b; Rooney *et al.*, 2003). The rate of pre-harvest germination is significantly lower for most high-tannin sorghums (Harris and Burns, 1970; Chavan *et al.*, 1980; Asante, 1995). The level of tannins in high-tannin sorghums is enough to cause significant anti-nutritional effects, especially if the diet is inadequate in protein (Bulter, 1990b). Adding extra protein to the ration overcomes the effects of the tannins. The tannin sorghums decrease feed efficiency by about 10% when fed to livestock. The tannin sorghums have high anti-oxidant activities and may be a very important source of nutraceuticles. Thus, we might someday use the sorghums with a pigmented testa and dominant spreader gene as potent, more efficient sources of anti-oxidants than fruits or berries (Rooney *et al.*, 2003). Thus, it appears that tannins have more beneficial than harmful effects, and hence the problem of tannins can be addressed by identification and development of sorghums in which beneficial effects are retained, while anti-nutritional effects are eliminated.

Two micronutrients, iron (Fe) and zinc (Zn) and pro-vitamin A (β-carotene) are recognised by the World Health Organization (WHO) as limiting. Deficiency for Fe, Zn and β-carotene is highest in South Asia, Southeast Asia and sub-Saharan Africa. These are also the regions where sorghum is cultivated and consumed as food by large number of people.

Considering the prospects of large genetic variability and presumably simpler genetic inheritance for Zn and Fe, as evidenced from other cereals like rice, wheat and maize, levels of these mineral nutrients can be further improved through concerted breeding efforts (Banziger and Long, 2000; Gregorio *et al.*, 2000). A fairly good variability coupled with additive genetic inheritance and moderate heritability of β-carotene levels brightens the prospects of improving this trait in sorghum (Nanda and Rao, 1974; 1975a; 1975b). Further, positive association of β-carotene with grain yield offers opportunities for combining high yield with enriched β-carotene in sorghum (Nanda and Rao, 1975a, 1975b). ICRISAT–Patancheru has initiated sorghum improvement for improved Zn, Fe and β-carotene levels.

1.7.2 Forage Sorghum

Single-cut forage sorghums grow upto 3 m tall and have large stem diameter. These sorghums produce silage of a lower quality than corn. However, incorporation of brown midrib (BMR) trait can improve the digestibility. Sudangrass has finer stems, produces numerous tillers and is leafier than single-cut forage sorghums. They produce very few seed, and regrowth rate is high. Furthermore, sudangrass accumulates less of the poisonous compound prussic acid (HCN) than forage sorghums.

Sorghum × sudangrass hybrids: Hybrids of forage sorghum and sudangrass have the highest yield potential if adequate rainfall is received or irrigation is provided. The forage should reach 24 inches before grazing. At this stage, sorghum×sudangrass hybrids will generally have total digestible nutrients (TDN) values in excess of 53–60% and crude protein (CP) concentrations of 9–15%. Varieties with the BMR trait are usually preferred for grazing. Research in Texas has indicated that BMR varieties may improve animal gains by as much as 5–8% relative to non-BMR varieties. In the southeastern United States, sorghum×sudangrass hybrids are commonly used as a forage crop for stocker cattle and brood cows following a winter or spring crop. Sorghum×sudangrass forage crops are designed for multiple harvests and can be used as hay, silage, pasture or green chop. Unfortunately, these hybrids dry very slowly, even if an impeller (flail) or roller-crimper conditioner is used during crop harvest. Consequently, hay production from these species is at greater risk of rain damage or being allowed to get too mature before hay harvesting is possible.

Forage is defined as 'food for animals especially when taken by browsing or grazing' (Webster, 1986). Sorghum grown for forage in the tropics is often tall (2–3 m) but can be the very same dwarf hybrid grown for grain production and may or may not include grain fraction of the plant (Pedersen and Fritz, 2000). However, from a definition point of view, the forage sorghum includes cultivars ranging from silage sorghum hybrids, to varieties, to *S. sudanense* ($2n = 10$) and sorgo-sudangrass hybrids to sudangrass varieties ($2n = 10$) and hybrids (Kalton, 1988). The uses of forage sorghum varies; in India it is commonly used as green fodder in northern states, and as stover after the grain harvest in southern states (House *et al*., 2000); whereas in the United States they are primarily used as silage, and to a limited extent, as pasture and hay for livestock (Kalton, 1988).

Forage sorghums make efficient use of soil moisture by resorting to a semi-dormant state during stress, with a rapid response to moisture and a wide range of adaptability (Hanna and Cordona, 2001). They also make efficient use of soil fertility by producing higher number of tillers and biomass and thus take advantage of growing conditions (Ahlrichs *et al*., 1991). Owen and Moline (1970) proposed a general classification of the forage sorghums based upon their use: (i) pasture using Columbus grass (*S. almum*); (ii) pasture and green chop or hay using Johnson grass (*S. halepense*, $2n = 40$), sudangrass (*S. sudanense*, $2n = 10$) or sudangrass hybrids; (iii) green chop or hay using sorghum–sudangrass hybrids; (iv) silage using sorgos and canes and (v) dual-purpose (i.e. for production of grain and stover) using grain sorghums or single- or two-gene dwarf sorghums.

Genetic improvement of forage sorghums has often been a secondary objective of grain sorghum breeding programmes. Until 1988, the primary objective of most forage breeding programmes was forage yield (Kalton, 1988). However, after 1988, efforts were directed towards improving quality traits. Although most forage quality traits like *in vitro* dry matter digestibility (IVDMD), crude protein (CP), neutral detergent fiber (NDF) and acid detergent fiber (ADF) appear to be quantitatively inherited, several simply inherited qualitative traits such as plant height, maturity, juiciness, sweetness, plant colour, stay-green trait, etc., have significant impact on forage quality (Bramel-Cox *et al*., 1995; Pederson, 1997). Improvements in forage quality hold the greatest opportunities in improving forage sorghum (Hanna and Cordona, 2001).

Owen and Moline (1970) concluded that the stage of maturity was the most important factor influencing the quantity and quality of forage produced. From heading to the ripe-seed stage, forage sorghums generally declined in protein content, crude fiber and ash. An increase in lignin content followed by variable sugar content was observed with stage of maturity in grain sorghum. The sudangrass and sorghum–sudangrass hybrids were the most affected by maturity, with reduced protein content.

Four basic height genes are related to the dwarfing of the sorghum plant (Quinby and Karper, 1954). It has been shown that dwarf sorghums containing one, two or three of these dwarfing genes have no difference in leaf percentage; however, the percentage stalk versus head was significantly affected. The one-dwarf type had 75% stalks and 7% heads, the two-dwarf type had 56% stalks, 23% heads, and the three-dwarf type had 36% stalks and 43% heads (Gourley and Lusk, 1978).

The usefulness of forage incorporated into diets of ruminants and forage used as biomass for biological conversion to liquid fuels, is limited by the quantity of lignin present (Cherney *et al.*, 1991). Hence, there is worldwide interest in improving the quality of forage through breeding to reduce or alter lignin content by incorporating BMR trait in plants (Cherney, 1990). Brown-midrib, a single gene trait, has greatest forage quality, and Kalton (1988) recognised that great improvement was possible with increased incorporation of BMR trait into all types of forage sorghum. Brown-midrib mutants were discovered in maize in 1924 by Jorgenson (1931), and the trait was later induced in sorghum (Porter *et al.*, 1978). Lignin concentrations in BMR mutants are consistently lower than their normal counterparts in sorghum. While *in vitro* digestibility of BMR genotypes has been consistently higher than normal, their *in vitro* rate of digestion does not appear to be consistently affected. Brown mid-rib mutants, differing in quantity and quality of lignin from normal genotypes, offer an opportunity to increase the overall digestion of plant fibre which is a major constituent of forage crops, comprising 30–80% of their dry matter (Cherney *et al.*, 1991). Several sorghum lines with high biomass were selected for the BMR trait at ICRISAT, with several white-grained B-lines, a red-grained B-line and two red-grained varieities identified.

Stay-green is another simply inherited trait that is known to improve forage quality. Whether sorghum is grown for dual-purposes (grain and stover) or forage, incorporation of the ‘stay-green’ trait is a boon for improving the quality of fodder. Stay-green, governed by a recessive allele, not only slows down senescence, but also arrests the decline in protein content of the ageing leaves (Humphreys, 1994). It is also known to contribute to terminal drought and charcoal rot resistance (Rosenow and Clark, 1995). Several stay-green hybrid parental lines have been developed at ICRISAT–Patancheru with their information available from the webpage: http:/www.icrisat.org/text/research/grep/homepage/sorghum/breeding/main.htm

Kalton (1988) proposed that an ideal silage sorghum would include traits such as red seed, yellow endosperm, absence of testa layer, BMR, tan plant colour, juicy stalk, moderate- to low hydro cyanic acid (HCN), high IVDMD, good protein content and good leafiness and green leaf retention. However, incorporating all of these, along with high yield and agronomic acceptability into hybrids would be an ambitious effort by forage sorghum breeders.

ICRISAT has developed a strong forage sorghum improvement programme that has developed a diversified set of hybrid parents, grain and dual-purpose varieties, and a population improvement programme to improve sudangrass sorghums. Breeding has focussed on high biomass, grain yield and stem-sugar content, BMR lines, grain types that tiller under stress conditions such as drought and stem borer resistance (Reddy *et al.*, 1994). This programme has resulted in the production of several lines with high tiller numbers, and the identification of sweet-stalk lines, useful for developing ratoon and multicut sweet sorghum, dual-purpose and forage varieties and hybrids.

1.7.3 Sweet Sorghum

Sweet sorghums have a great potential for ethanol production by virtue of their high stem-sugar concentrations, with a brix value up to 24% (Reddy, Ramesh *et al.*, 2004). Ethanol extracted from sweet sorghum has superior quality, less sulphur content, high octane rating and automobile friendly (up to 25% blending). Bagasse obtained after juice extraction has higher biological value and rich in micronutrients and is used as feed or for power cogeneration. At ICRISAT, it was found that the representative internode for Brix estimation is third in B-lines, fifth in varieties and fourth in hybrids. Sweet-stalk sorghum hybrids in rainy season out yield the non-sweet stalk hybrids both for stalk sugar and grain yield. There is no decrease in sugar yield if sweet sorghum is harvested at maturity instead of at flowering time. As there is season specificity in sweet sorghum, cultivars should be specific to season of cultivation. Sweet sorghum cultivars grown in vertisols (black soils) give maximum sugar and grain yields per hectare than those grown in alfisols. The feed stock supply can be extended by using cultivars with different maturity durations, extension of planting time and seasons, planting in wider areas, establishment of decentralised crushing units and widening the harvest window. Harvest window can be increased by more than 4 days if the panicle is harvested at physiological maturity and water is given to the standing stalks. It will also give increased sugar yield per hectare. The overall sugar yield will go down with the delay in crushing of harvested stalks.

The BMR mutant sorghum, pearl millet and maize lines have significantly lower levels of lignin content (51% less in stems and 25% less in leaves). Research at Purdue University showed 50% higher yield of the fermentable sugars from stover of certain sorghum BMR lines after enzymatic hydrolysis. Therefore, the use of BMR cultivars would reduce the cost of biomass-based ethanol production. ICRISAT is developing BMR sorghum hybrid parents (involving the genes *bmr* 1, *bmr* 3 and *bmr* 7) useful for developing high-biomass BMR hybrids.

1.8 Sorghum Improvement Across Diverse Parts of the World

1.8.1 Sorghums of India

In India, sorghum is grown during both *kharif* (rainy) and *rabi* (post-rainy/winter) seasons for multiple uses as a food, feed, fodder and a fuel crop. The cultivar requirements for these two seasons are quite diverse due to different agro-climatic conditions (Rana *et al*., 1997). During rainy season, sorghum at the maturity stage is often caught in rains and the grain quality is affected due to grain moulds. Hence, the grain is mainly utilised as feed. However, *rabi* (post-rainy) sorghum is primarily used as food owing to its good grain quality and also serves as a main source of fodder especially during dry seasons when fodder from other sources are not available. Rabi sorghum is grown under receding soil moisture conditions during winter season and without irrigation after the cessation of rains.

1.8.1.1 Rainy / kharif Sorghum

Before the advent of hybrid technology, the varieties were tall, late in flowering, photoperiod sensitive, low in harvest index and locally preferred. Modifications of excessive height and maturity period have been possible through the introduction of early maturity and dwarfing genes from the temperate germplasm of US origin. The optimum genotype was characterised by a height of 175–180 cm and flowering at 68–70 days with reduced leaf numbers. These intermediate types between temperate and tropical parents, as a bridge population, offered further opportunities for rapid recombination. These types with optimal dry matter production per unit time and distribution and growth rhythms used water efficiently and formed the basis of improving rainy-season sorghum in India for yield and stability. However, reduction in duration of maturity coinciding with occasional rains resulted in grain deterioration following grain mould attack rendering the grain less preferred for human consumption and marketing. Rana *et al.* (1978) utilised hard grain, low water absorption and tan plant background as a selection criterion to breed for grain mould resistance. Tan plant pigment has also been useful in furnishing resistance to more prevalent leaf diseases (Rana *et al.*, 1976).

In the early 1960s, the Indian Council of Agricultural Research, with Rockefeller Foundation assistance, initiated research on hybrid sorghum. ICAR then initiated the All India Coordinated Sorghum Improvement Project (AICSIP) in 1969. This programme organised the research of National Agricultural Research Systems (NARS) and conducted multi-location testing for improved characteristics of hybrids and varieties, working with state agricultural universities, research institutes, ICRISAT and experiment stations. The first sorghum hybrid, CSH 1 (Coordinated Sorghum Hybrid), was bred in India and officially released for commercial cultivation in 1964. The first set of sorghum hybrids was released in the mid-1960s. These were followed by the release of more popular hybrids, like CSH 5 and CSH 6 in the mid-1970s and CSH 9 in the early 1980s, augmenting the spread of sorghum high yielding varieties (HYVs) and open-pollinated varieties and boosting productivity. The gains in productivity, however, were countered by the decline of planted area. Sorghum production levels increased slowly from 6 million tons during the 1950s to a maximum of 11 million tons in the early 1980s. It started declining thereafter, and currently stands around 9.2 million tons. The hybrids played a major role in pushing up productivity and production, particularly in the case of *kharif* sorghum (NRCS, 2007). In view of seed production problems and stagnating yield levels, the need for diversification of hybrid parents was felt. As a result, a high-yielding hybrid, CSH16, was developed from new MS line 27A and the R-line C43. This hybrid showed improvement in grain mould-tolerance as the grain-mould-resistant genes from Ethiopian germplasm line IS 23549 were introduced to its male parent (Audilakshmi *et al.*, 2003). CSH 1, CSH 5, CSH 6, CSH 9, CSH 14 and CSH 16 show dramatic increases in productivity. From CSH 5 and CSH 6, with a yield potential of 3.4 t/ha, yield potential was raised to 4 t/ha in CSH 9 and to more than 4.1 t/ha in CSH 16 and CSH 23 (NRCS, 2007).

Varietal improvement was achieved by introducing temperate and tropical germplasm. The first variety, CSV 1 is a direct introduction of line IS 3924 from the United States. By crossing temperate and tropical germplasm, the varieties CSV 2 and CSV 3 were developed. CSV 5 was another variety derived from a cross between Indian local and US line IS 3687. It showed resistance for *Striga*. The variety, CSV 10, which became popular for higher fodder value was developed from a cross between Texas elite variety SC 108 and the Indian elite variety CS 3541. CSV 13, yet another high-yielding variety with medium height was developed from multiple cross having exotic and local parentage. Another variety, CSV 15 was developed from the segregating population derived from the cross between SPV 462 and CSV 13. It is a dual-purpose variety having grain yield comparable to that of hybrid CSH 5 and fodder yield comparable to CSH 10.

1.8.1.2 Post-rainy / winter Sorghum

Unlike in the case of *kharif* sorghum, where 90% of the area is dominated with hybrids, *rabi* sorghum varieties have better preference over hybrids for reasons of adaptability and grain quality. Most of the *rabi* sorghum varieties are only of *durra* type where as *kharif* sorghum cultivars belonged to *Caudatum* and *Kafir* races (Reddy *et al.*, 2003). Natural selection and domestication over thousands of years have resulted in the development of numerous varieties highly local in their adaptation. The variety M 35-1 has been ruling most of the *rabi* tracts since 7½ decades. Most of the present-day improved varieties are the result of pure-line selection practised among the local/ popular varieties. The popular varieties have lustrous, bold and globular grain distinct, the traits highly preferred by farmers. Some of the popular landraces emerged in various regions include Giddi Maldandi, Yennigar jola, Bilichigan, Fulgar white, Fulgar yellow, Kanki Nandyal, Hagari and Dagadi types from Karnataka, Barshi joot, Saoner, Ramkhe, Aispuri, Maldandis (M 35-1, M 47-3 and M 31-2) and Dagadi types of Maharashtra (Deshpande *et al.*, 2003). Notable among the varieties developed from NARS during the early period and which are still under cultivation are the co-series in Tamil Nadu; the Nandyal, Guntur and Ankapalle series of Andhra Pradesh; and the PJ *rabi* series of Maharashtra. Focussed breeding on *rabi* sorghum was initiated in the early 1970s which over the years led to the release of several state and central release varieties. At the national level, the variety CSV 7R was released in 1974, CSV 8R in 1979, Swati in 1984, CSV 14R in 1992, Sel 3 in 1995, Phule Yashoda in 2000, CSV 18 in 2005, CSV 22 in 2007 and CSV 26 in 2012 and CSV 29 in 2013. Several varieties were released at the state level, which included Mukti, Parbhani Moti/ SPV 1411 from Parbhani centre, NTJ 2 and NTJ 3 from the Nandyala station of Andhra Pradesh state (Lakshmaiah *et al.*, 2004). Sorghum programme of Karnataka state released varieties DSV 4 and DSV 5. The Maharashtra state sorghum improvement programme released varieties like Swati, Selection 3, CSV 216/ Phule Yashoda/ SPV 1359, RSLG 262/ Phule Maulee, Phule Anuradha, Phule Revati, Phule Vasudha, Phule Chitra and Phule Suchitra. The released post-rainy sorghum varieties, CSV 8R, CSV 14R, CSV 18 and Swathi, were better received than the post-rainy hybrids such as CSH 7R and CSH 8R.

Among the yield component traits, long panicles, number of grains per panicle, 100-seed weight contributed for grain yield, and most of these traits have high heritability enabling the plant breeder to improve these traits through simple selection (Patil *et al.*, 2014). The gap between flag leaf sheath and panicle base should be minimum to have good grain filling and the glume coverage on grains is to be less for higher threshability (Reddy *et al.*, 2009). The high-yielding crosses should have at least one good general combiner and the average general combining ability (gca) effect of both the parents showed significant positive relationship with yield (Rani and Rao, 2008). Several varieties such as CSV 7R, CSV 8R and CSV 14R were developed using selections from segregating populations derived from the crosses among Indian locals, M 35-1 and IS 2644 with American germplasm lines. Productivity of *rabi* sorghum depends not only on the moisture availability but also on the soil types under which it is grown and the genotypes (Jirali *et al.*, 2007). Much of the post-rainy-season sorghum is grown on residual and receding soil moisture on shallow and medium–deep soils. Under shallow soils, the genotypes were shorter, flowered and matured early while in medium–deep soils, mean leaf area, grain number and 1000 grain mass, grain and fodder yields were higher (Rafiq *et al.*, 2003). Breeding varieties suitable for varying soil depths was emphasised at Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India. The variety RSLG 262/Phule Maulee was released for shallow to medium soils of Maharashtra in 1999; Phule Chitra (SPV 655×RSLG 112) was released for medium soils in 2006; Phule Vasudha (RSLG

206×SPV 1247) was released for deep soils in 2007; and Phule Anuradha (RSLG 539×RSLG 1175) was released for shallow soils in 2008. The reduction in grain yield under shallow soils was found to be due to reduction in LAI, TDM, grain number per panicle and 1000-grain weight.

The released *rabi* hybrids could not progress well as compared to the varieties. However, studies indicated appreciable levels of heterosis for grain yield and other agronomic traits by Rana *et al.* (1997). Large heterotic response for grain yield and harvest index was accompanied by susceptibility to stalk rot and shoot fly susceptibility (Rao, 1982). Increase in number of seeds per panicle branch in short compact-headed varieties (tropical) and increase in the panicle branches in the long-panicle type (temperate) by introgression of genes from African germplasm result in yield heterosis (Rana and Murty, 1978). The combining ability of compact-headed Indian landraces was found to be relatively poorer than very long panicle types of exotic origin as poor combining of genes responsible for primary axis length and those contributing to girth resulted in lack of marked heterosis for ultimate grain yield (Rao, 1970). Pollinators and female lines from exotic germplasm contributed to poor grain quality. The derivatives *durra–caudatum* (*zera zera*) crosses as pollinators developed for post-rainy-season, and CMS lines developed for *kharif* season from *kafir–caudatum* (*zera zera*) crosses did not attract the attention of farmers as they lacked grain lustre, size and shape and fodder yield comparable to M 35-1, despite their superiority under late sowings in post-rainy-season with yield heterosis of 45–64%.

With the view of introgressing many of the desirable attributes of landraces, landrace pollinator-based hybrids were developed. Though they exhibited moderate levels of shoot fly resistance and desirable grain-quality traits, they lacked lodging resistance and had moderate yielding ability (Reddy *et al.*, 1983). Most of the landraces, including M 35-1, showed segregation for fertility restoration/sterility maintenance ability indicating the need to select for restoration ability within the landraces. This also explains the partial restoration observed when bulk pollen of M 35-1 was used by many workers. Upto 100% better-parent heterosis using landraces as pollinators over the A-lines 104A and M 31-2A were obtained (Sajjanar *et al.*, 2011). Fertility restoration by landraces was poorer on *durra*-derived A_1 CMS lines than on *caudatum*-derived A_2 CMS lines. When both A_1 and A_2 CMS lines were based on *caudatum*, fertility restoration was higher on A_1 than A_2. This finding has a bearing on developing CMS lines involving *caudatum*-based germplasm lines adapted to post-rainy-season and testing for fertility restoration in hybrids. The hybrids involving *caudatum*-based female parents and *durra*-based landraces showed high heterosis for grain yield but grain quality was poor. *Milo* hybrids exhibited superiority over *maldandi* hybrids for most of the characters in desired direction (Pattanashetti *et al.*, 2005). There is season specificity in breeding for shoot fly resistance and the studies by Jayanthi (1997) have shown that shoot fly resistance in both the parents or at least in seed parents in order to realise higher frequency of shoot-fly-resistant hybrids in post-rainy-season. As rabi sorghum is cultivated in winter season, the anthesis period is exposed to low night temperatures. When minimum temperatures go below 10°C during flowering, hybrids that are otherwise male fertile show male sterility as evidenced by partial to complete absence of seed set under bagging. Therefore, greater attention is required to ascertain the differences among the landraces for their ability to restore fertility in hybrids, especially under low temperatures, normally observed in post-rainy-season. By eliminating temperature sensitivity (in relation to development) in both male and female parents, greater success could be achieved in breeding hybrids for post-rainy-season. However, male sterile lines bred from landraces adapted to post-rainy-season, showed temperature-induced restorer inefficiency. Also, the hybrids developed from landraces crossed to female lines derived from M 35-1 did not show high heterosis. While the use of the *durra* race directly introduces high sensitivity to low temperatures, the direct use of *guineas* in developing hybrid parents, produce hybrids with clasped glumes, an undesirable trait. Hence, *durra* (bold grain lines) and *guinea* (grain-mould-resistant restorers) materials have to be introgressed into high-yielding *caudatum* background to enhance the yield potential of elite sorghum B-lines. Reddy *et al*. (2014) observed significant and positive correlation between low temperature during flowering and germinability and viability of pollen. Among the hybrid parents, R-lines exhibited stability for many characters across the dates of sowing, while B-lines were less stable, indicating the need for the development of stable B-lines for *rabi* season. Leaf sugary melady (Chikta) occurs when morning humidity is between 54 and 74% and minimum temperatures below 18°C. The disease was characterised by an extensive leaf chlorosis followed by oozing of sugars. It was first observed at the flag leaf stage (2%) and it increased until harvest (72%). A steep increase in disease incidence was observed from full bloom (7%) to the hard dough phase (51%). Due to oozing of sugars, the last few leaves (11th, 12th and 13th [flag leaf]) stuck to each other, not allowing the inflorescence to emerge from the boot. The affected plants attracted a variety of insects and supported an extensive bacterial and fungal colonisation. SPV-504 demonstrated least incidence of the disorder sugary disease (*chikta*).

Charcoal rot caused by the pathogen *Macrophomina phaseolina* is a major disease of sorghum grown in arid regions. Sorghum is vulnerable to charcoal rot when it undergoes stress from flowering to grain-filling period. Warm, moist followed by hot, dry growing conditions are favourable for disease development. Resistance to charcoal rot was found to be polygenic, moderate to lowly heritable and partially dominant (Rana *et al*., 1982). Tenkouano *et al*. (1993) reported that charcoal rot resistance is controlled by two dominant genes that are modified by a third locus. Non-senescence is a delayed leaf and plant death-resistance mechanism in sorghum that circumvents the detrimental effects of reduced soil moisture combined with high temperatures during post-anthesis growth. They also noted that charcoal rot and non-senescent phenotypes were controlled by independent loci even though these traits are often associated. They also concluded that non-senescence alone cannot account for, and should not be used as the sole breeding criterion for, resistance to charcoal rot in sorghum.

1.8.1.3 International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)

ICRISAT was established in 1972 at Patancheru, Andhra Pradesh, India, with sorghum as one of its five mandate crops. Improvement for yield potential and resistance to drought, *Striga*, grain mould, downy mildew, charcoal rot, shoot fly, stem borer, midge and head bug and wide adaptability received major attention up to 1980. Genetic male-sterility facilitated populations and pure-line varieties were the target cultivars during the initial years. In resistance breeding programmes, emphasis was given to developing and standardising screening techniques and identification and breeding of improved resistance sources. The initial emphasis on red grain types up to 1975 was gradually shifted to white grain types by the end of the 1970s. During the 1980s, major emphasis was given to regional adaptation and breeding for resistance to biotic stresses (grain moulds and insect pests only) in white grain background. Breeding for resistance to drought, downy mildew, charcoal rot and *Striga* was discontinued, while development and improvement of male-sterile lines for grain yield and food-quality traits were initiated. Initially, several open-pollinated populations were introduced from the US, West African and East African programmes and were reconstituted with selection. Several of the hybrid seed parents derived from some of these populations are being extensively used for the development of high-yielding hybrids in China. Later on, several high-yielding good grain inbred-lines and *zera zera* landraces (*caudatum*) were extensively involved in breeding at ICRISAT Asia Center (IAC), and *guinea* local landraces along with *caudatum* derived lines at ICRISAT West African Center (Reddy and Stenhouse, 1994). During 1985–1989, major thrust was given for specific adaptation and trait-based breeding for resistance traits. A total of 92 high-yielding A-/B-lines, including 17 early-maturity lines and 75 medium maturity lines, were developed during this period. By late 1980s, many national agricultural research systems (NARS) had enhanced crop improvement programmes aimed at specific adaptation. Thus, the global sorghum improvement programme reoriented itself to develop materials suited for 12 productive systems (PS) in Asia, six in Western Africa, six in Eastern and Southern Africa and five in Latin America. As a result of this reorientation, at ICRISAT's Asia Center (IAC), strategic research on the development of screening techniques, breeding concepts and methods and intermediate products for utilisation in partnership with NARS programmes was given emphasis during 1990–1994. A total of 567 trait-based A-/B-lines (487 A1, 51 A2, 17 A3 and 12 A4 CMS systems-based) were developed during 1989–1998. Besides these, 57 high-yielding A-/B-lines were also developed. In addition, an extensive programme of breeding new *Milo* cytoplasm male-sterile lines for earliness, introgression with *durra* and *guinea* races, incorporating bold and lustrous grain characters and resistance to *Striga*, shoot fly, stem borer, midge, head bug, grain mould, downy mildew, anthracnose, leaf blight and rust was carried out (ICRISAT, 1993). With a major objective of trait-specific breeding, novel populations or trait-specific genepools for bold grain and highly productive tillering were developed. Test crosses involving post-rainy-season 'landraces' as pollinators were examined for their fertility restoration ability under cool nights and for productivity in post-rainy-season. Variability for restoration was quite significant indicating the possibility of selection within hybrids (Reddy and Stenhouse, 1994). Lines with high Fe and Zn content in the grains were identified and the variation for these micronutrients did not appear to be significantly influenced by the environment.

Sweet sorghum research has been given major emphasis at ICRISAT. The sweet-sorghum-based ethanol technology has become a reality with the establishment of Rusni Distilleries near Hyderabad, India, in collaboration with ICRISAT's Agri Business Incubator (ABI). It has become a model for such distilleries all over the world. In collaboration with International Centre for Biosaline Agriculture (ICBA), Dubai and Agriculture Research Station (ARS), Gangavathi, Karnataka, India, ICRISAT has identified promising lines under saline conditions. Similarly, improved lines have been developed for fodder quality and quantity and Al^{3+} tolerance. From 1995 onwards, a partnership mode of conducting research to develop improved intermediate products at ICRISAT, Patancheru, India, and finished products (varieties and hybrids) at other ICRISAT locations in Africa were being emphasised. ICRISAT, working in partnership with NARS, partners helped in release of 200 cultivars in several countries in Asia (53), Africa (112) and Latin America (35).

1.8.2 Sub-Saharan Africa

A high proportion of the population (25%) of sub-Saharan Africa lives in semiarid regions (Sanders *et al.*, 1996). The major emphasis of technological change in the semi-arid region over the last three decades has been new cultivars (Ahmed *et al.*, 2000). Regional sorghum breeding approach began at different periods in three regions – East and Central Africa (ECA), South African Development Community (SADC) and West and Central Africa (WCA) with the objective of tackling different production constraints specific to different regions. ICRISAT has been improving sorghum through its programme in Western and Southern Africa over two decades. In the last 35 years, the area harvested to sorghum in Africa has nearly doubled, but yields averaging 800 kg/ha have not increased. Sorghum research in sub-Saharan Africa has been successful in diffusing a large number of new cultivars onto farmers' fields. The last two decades of research have resulted in the release of over 40 sorghum cultivars (Ahmed *et al.*, 2000).

1.8.3 Western and Central Africa (WCA)

The first West Africa breeding research on sorghum started in 1931 using an experiment station created in 1921 at Bambey, Senegal (Atokple, 2010). ICRISAT's involvement in sorghum breeding in WCA began in 1979, and the centre has made extensive sorghum improvement efforts in WCA targeting the unique requirements of the diverse array of production systems in the SAT (Obilana, 2004). The local landraces are mostly two types – guinea race and durra-caudatum – in WCA. Initial efforts were targeted to improve the local landrace germplasm by selection within the landraces or in the segregating progenies derived from crosses among themselves and release them as varieties to farmers. Later on, new germplasm, namely zera zeras (caudatum race) were introduced, and several lines were developed by selection in the segregating progenies involving introduced caudatums and local guineas. In the more recent years, therefore, efforts are being made to develop guinea-based hybrid parents to develop guinea hybrids. As guineas have good food quality attributes and adaptation to local drought conditions, the guinea-based hybrids are expected to have good acceptability and good adaptation to moisture stress environments prevalent in the region (Camara *et al.*, 2006). While guinea landrace-based A-lines are tall, photoperiod sensitive, and possess typical guinea grain and panicle architecture, the inter-races cross derivatives-based A-lines are dwarf, basically photoperiod insensitive and possess relatively small grain. The development of new A-lines (on A1 CMS system) continues with sterilisation of guinea-core collection accessions from Burkina Faso, Senegal, Gambia, Sudan, Uganda and Malawi by the ICRISAT programme and inter-racial lines by IER (Olembo *et al.*, 2010).

1.8.4 Eastern and Southern Africa (ESA)

In the beginning, most of the breeding programmes placed emphasis on introductions, evaluating them and then selecting adapted lines. Later, programmes embarked on hybridisation followed by evaluation and selection in segregating populations. The main focus was on earliness, increasing grain yield and disease and pest resistance. Varieties such as Framida and Red Swazi were released with wide appeal. Governments in Southern Africa pooled their resources together and established Sorghum and Millet Improvement Programme (SMIP) in the early 1980s. The programme was managed by

ICRISAT. In early 1983, significant efforts were made through the regional programme SMIP to acquire new and enhanced germplasm from all possible sources. About 10200 exotic germplasms of sorghum were acquired and evaluated at the regional centre at Matopos. As a result of concerted efforts of SMIP, International Sorghum/Millet Collaborative Research Support Program (INTSORMIL), United States, and ICRISAT–Patancheru, India, several hybrid parental lines were developed. Sorghum yields averaged 1.8 t/ha in South Africa since 1980 despite the six drought years after 1980 and the 1991–1992 drought. This contrasts with the 0.8 t/ha in the rest of sub-Saharan Africa. The success of the intensive production pattern of sorghum in Sudan and South Africa is similar to the success of cotton in Francophone Africa and maize technologies in the Sudano-Guinean zone of the Sahel. In these higher-rainfall regions, new cultivar introductions were combined with crop-management improvements, including increases in fertilisation, density and pest control (Ahmed *et al.*, 2000).

1.8.5 Latin America

In Latin America, sorghum is produced on intermediate to large farms except in some inland valleys and eroded mountain slopes of Central America utilising hybrids imported from the United States and cultivars developed in the regions. In Guatemala, El Salvador, Honduras, Nicaragua and Haiti, a large part of the production is on small subsistence holdings often less than one hectare in size where farmers use photoperiod-sensitive landraces intercropped with maize and beans using traditional production practices. The damages due to downy mildew, anthracnose, grain mould, stem borer and midge among the biotic stresses and soil acidity and alkalinity, drought and cold temperature among the abiotic stresses are the major yield constraints apart from the lack of early-maturing, tropically adapted cultivars with high yield potential and tolerance to major stresses in the region. ICRISAT initiated the Latin America and Caribbean Program in 1976 by stationing its staff at International Wheat and Maize Improvement Center (CIMMYT), Mexico. The programme was aimed at developing early, dwarf and bold grain varieties for fertile soils in both the highlands and lowlands of Central America. The programme was later transformed as Latin American Sorghum Improvement Program (LASIP) in 1990. LASIP had a comparative advantage in the development of tropically adapted improved germplasm that was resistant/tolerant to major production constraints for foodgrade cultivars in Latin America. Several varieties were released and adopted based on ICRISAT-bred improved germplasm. Due to funding constraints, LASIP was discontinued in 1993. However, considering the interest shown by Latin American NARS, a programme for improving sorghum for acid soil tolerance was initiated in 1996 with funding support from Inter American Development Bank (IADB). The INTSORMIL programme identified 20 acid soil tolerant lines in the 1980s (Gourley, 1991), but they were susceptible to leaf diseases. At its centres in India and Africa, ICRISAT has developed diverse sets of high-yielding sorghum breeding lines useful as base materials for testing in acid soils of Latin America. Since 1996, ICRISAT, International Center for Tropical Agricultural (CIAT) and the national programmes of Brazil, Colombia, Honduras and Venezuela have jointly implemented an IADB-funded project on 'A research and network strategy for sustainable sorghum production systems for Latin America'. The major objectives of this project include: (i) to assemble, multiply and evaluate grain and forage sorghum breeding lines for tolerance to acid soils and resistance to foliar diseases, (ii) to develop a research network of scientists working on this crop in the region and train them in sorghum research and (iii) to test the most promising genotypes in the target production systems.

1.8.6 China

Modern sorghum breeding in China began in the 1920s, and heterosis breeding has been the main method of breeding since 1965 in China. The major objectives of sorghum improvement research in China include: grain yield, multiple resistance to abiotic (low temperature and drought) and biotic (aphids and head smut) stresses, grain quality, grain feed and forages for livestock. The increase in yield due to utilisation of hybrids is estimated at 30–40%, with the remaining improvement being due to better cultivation conditions (Zhen Yang, 1997). Low temperature is an important stress factor, especially for northeastern China in both the seedling and grain filling stages. Some cold-tolerant local varieties have been identified using low temperature seedling treatment (Zheng Yang, 1997). New male-sterile lines and restorers with resistance to drought are being developed by selecting for rapid seedling-emergence rates in water-limited areas (Zheng Yang, 1997). Most Chinese sorghum varieties lack genetic resistance to aphids. Several new male-sterile lines with high degree of resistance have been developed by the Sorghum Research Institute (SRI), Liaoning Academy of Agricultural Sciences (LAAS) (Zheng Yang, 1997). Sorghum head smut caused by the fungus, *Sphacelotheca reliana* is a serious disease. There are three different physiological races of the pathogen in China. Resistance to head smut is controlled by both major genes of two or three pairs and some minor genes (Yang Zhen and Yang Xiaoguang, 1993). Among 10083 germplasm accessions screened, 39 showed immunity to race 2, while 3 accessions have shown resistance to race 3. Chinese Kaolings are an excellent source of good grain quality types such as Xiang Yanai and Zhen Zhubai. However, they are not used directly in heterosis breeding due to low combining ability and poor restoration. Nutritive composition of hybrid sorghum grain is poor and the traditional fragrance of original local varieties needs to be recovered in high-yielding background (Zheng Yang, 1997). Since sorghum is the main raw material of compound feeds for livestock and poultry, breeding for feed quality has been one of the major objectives of sorghum breeding in China (Shi Yuxue *et al.*, 1992). Most forage sorghums can be classified as dual purpose in China, with the grain for human consumption and stover for other purposes. At present, the focus is on breeding for high biomass coupled with good nutritional value and low HCN content (Zhen Yang, 1997). In China, sweet sorghum is primarily used for silage preparation. With the introduction of improved sweet sorghum varieties such as Rio, Roma, Ramada and Wray from several countries, a systematic sweet sorghum breeding programme was initiated in LAAS in 1985. As a result, two sweet sorghum hybrids, Liaosiza No.1 and Liaosiza No.2 were developed and released during 1989 and 1995, respectively.

1.9 Future Prospects

As sorghum is grown under marginal and harsh environments, the options to shift to other lucrative crops are limited. Investments should flow towards breeding varieties incorporating the quality attributes preferred by end users. Breeding efforts for value-added characteristics like tolerance to drought, grain mould, charcoal rot, shoot fly, stem borer and striga should continue as their yield loss due to these factors is to the tune of 30–50%. The second priority is to breed varieties to increase the shelf life of grain and reduce the undesirable attributes in the grain like reducing fat content and phenol compounds, followed by improving/keeping quality of the flour and exploring the health benefits and nutraceutical value. Industrial demand for grain-based alcohol is also expected to propel a double-digit growth rate. Investment in research should be directed towards increasing productivity of *rabi* sorghum which would help in bringing down the prices and make it affordable for lower-income consumers. In order to improve productivity of *rabi* sorghum, besides targeting improved varieties, targeting on the key recommended technologies, management practices like drilling of fertiliser along with seed, seed treatment, deep sowing, wide row spacing, optimum plant population, integrated pest management (IPM) and integrated nutrient management (INM) is crucial. In addition, the biotic and abiotic problems such as resistance to shoot fly, aphid, charcoal rot, drought and cold are important for adaptation in *rabi* season. Consumer acceptability is towards bold, round and lustrous grain and higher flour recovery. Thus, research efforts on *rabi* sorghum should address the above problems on priority in order to augment productivity rendering sorghum as a profitable crop benefiting the small and marginal farmers in SAT areas. Exploring non-conventional uses and extrusion products is another important area for future investment in these crops. Incentives should be provided to food industry to use *rabi* sorghum for novel processed food products (snacks, bread, biscuits, flakes, papad, rava, etc.) and also traditional processed products. Enriching nutritional value in zinc and iron content should be continued.

Much of the millets in the rural areas are processed at household level by following a tedious method involving considerable drudgery. So, there is vast scope to transfer information regarding modern technologies and benefits of value addition to the farmers. Providing backward and forward linkages for value chain using innovative value addition in domestic and international markets is required. Capacity building for social capital formation among farmers and consumers regarding their cooperation for millet cultivation and consumption considering their nutraceutical properties is quintessential. Field level findings suggests that there is scope to arrest the declining demand for sorghum in urban centres by promoting value added and ready to eat products as they are in much demand in hotels and restaurants. Though consumers are aware of the health benefits of sorghum in their dietary requirement, unavailability of processed products as in the case of wheat have contributed to decline in consumption of sorghum. Hence, keeping in view the potential benefits of sorghum, research efforts should be focused on releasing varieties to cater to needs of processing sector for better value-added products and to meet the demands of the growing urban population.

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