Sorghum improvement (1980–2010): Status and way forward

Belum VS Reddy[1]*, A Ashok Kumar[1], HC Sharma[1], P Srinivasa Rao[1], Michael Blümmel[2], Ch Ravinder Reddy[1], Rajan Sharma[1], Santosh Deshpande[1], DattaMazumdar Saikat[1] and **Elango Dinakaran[1]**

1. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India
2. International Livestock Research Institute (ILRI) (Asia Center), Patancheru 502 324, Andhra Pradesh, India

*Corresponding author: b.reddy@cgiar.org

Citation: Reddy BVS, Ashok Kumar A, Sharma HC, Srinivasa Rao P, Blümmel M, Ravinder Reddy Ch, Sharma R, Deshpande S, DattaMazumdar S and Dinakaran E. 2012. Sorghum improvement (1980–2010): Status and way forward. Journal of SAT Agricultural Research 10.

Introduction

Sorghum (*Sorghum bicolor*) is the fifth most important cereal crop globally and is the dietary staple of more than 500 million people in over 90 countries, primarily in the developing world (Reddy et al. 2010). With its C_4 photosynthetic pathway, it is adapted to a wide range of environmental conditions. It has multiple uses as a food, feed, fodder, fuel and fiber crop (Paterson et al. 2009). More than 35 percent of world sorghum production is going for food consumption (Awika and Rooney 2004) by the poorest of the poor in the largely low-income deficit countries. Worldwide, it is grown on about 40 million ha, of which about 9 million ha are cultivated in Asia; of this the largest area is in India (7.53 milion ha) which has a production of 7.25 million t (FAOSTAT 2011).

Sorghums are classified based on relative height and grain/stover productivity and with or without sugars in the stem. These are: grain sorghum, dual purpose (grain and fodder) sorghum, fodder sorghum, forage sorghum, and sweet stalk sorghum. Unlike other countries, there are two distinct sorghum growing seasons in India, *kharif* (rainy season – June to October) and *rabi* (postrainy season – October to February). The adaptation, trait focus and constraints are different in different kinds of sorghums and hence the breeding approaches differ accordingly while some of them are cross-cutting.

This review summarizes the research on sorghum improvement over the past two decades, in relation to various key constraints that affect sorghum productivity. These include: diseases, insect pests, drought, high temperatures, edaphic problems, salinity and aluminum toxicity, phenology, weeds and yield potential. In addition, research focus on the traits associated with nutritional value and alternative uses were also mentioned. Finally the way forward for global sorghum improvement research is briefly discussed.

Key traits or areas

Photoperiod and temperature sensitivity

Photoperiod sensitivity basically allows for the length of the vegetative phase to vary with planting date, such that flowering occurs around the same time each season (Vaksmann et al. 1996). In West Africa and also in postrainy season in India this mechanism works particularly well as the end of the season is far more predictable (and less variable) than the start (Craufurd et al. 2011). In studies at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India involving diverse genotypes in postrainy season it was established that M 35-1, the postrainy season ruling variety has a distinct feature of photoperiod sensitivity and thermo-insensitivity that offers the ability to finish flowering in more or less same time even in delayed sowings (Reddy et al. 1987). Further breeding work involving M 35-1 as parent, several improved progenies were developed for postrainy season adaptation (Reddy et al. 2009b). In future, identification of markers linked to photoperiod sensitivity QTLs (quantitative trait loci) and cloning and transformation of other maturity genes may help in transferring photoperiod sensitivity to elite cultivars for better adaptation to tropical and subtropical environments.

In addition to photoperiod sensitivity, tolerance to early and mid-season cold temperature is needed for increasing the production in temperate and tropical sorghum production areas around the world where the plants experience cold stress during emergence and/or at anthesis. Tolerant genotypes show increase in seedling vigor, resulting in greater biomass and grain yield in cold and dry environments. Sorghum cultivars produced more leaves, had delayed floral initiation (Caddel and Weibel 1971), and were found to be male sterile (Downes and Marshall 1971, Singh 1977) when low temperatures occur at anthesis. At ICRISAT, Patancheru, simple and cost-effective screening methodologies were developed to screen genotypes for cold tolerance in the same field trials that are intended for grain yield selections. The response in seed set and grain filling to cold tolerance provides good levels of genotypic discrimination. Panicle harvest index (PHI) and 100-seed weight are the two traits that will indicate cold tolerance in field trials. PHI explains the reproductive success of the genotypes at single plant level for reproductive stage cold tolerance.

Yield potential

Sorghum has a high yield potential, comparable to those of rice (*Oryza sativa*), wheat (*Triticum aestivum*) and maize (*Zea mays*). On a field basis, yields have exceeded 11,000 kg ha^{-1}, with above average yields ranging from 7,000 to 9,000 kg ha^{-1} where moisture is not a limiting factor. In those areas where sorghum is commonly grown, yields of 3,000 to 4,000 kg ha^{-1} are obtained under better conditions, dropping to 300 to 1000 kg ha^{-1} as moisture becomes limiting (House 1985). Grain yield is the most important trait in sorghum breeding as in other crops; however, stover yield is equally important in sorghum particularly in countries like India. Breeding for grain yield improvement is carried out by selecting genotypes directly for grain yield and for component traits. For higher yield, genotypes with a plant height of around 1.5 m are desirable which are amenable for mechanical harvesting with medium maturity duration (100–120 days). Longer duration types give higher yields but the length of growing period in most sorghum growing areas does not allow for breeding long-duration types, with the exception of West Africa. If the crop duration is reduced, it is likely that the yield will also decline. Moreover, yield is governed by polygenes and the effects are cumulative in nature.

Heterosis for grain and stover yield is high in sorghum and therefore hybrids development should be targeted in dual purpose background. A heterosis of 30–40% for grain yield is reported in hybrids compared to the best varieties (Ashok Kumar et al. 2011b). Hybrids are the cultivar options and hybrid parents' development is critical for exploiting heterosis. In addition to dual purpose types, the major focus should be on hybrid parents to develop dwarf hybrids for mechanized harvesting and fodder hybrids with high recovery ability (for multi-cut forage purpose) and maturity of 70 to 85 days to 50% flowering. Additionally, forage varieties amenable for both single- and multi-cuts to meet the needs of farmers and dairy industry forms another focus of the program. Genetic and cytoplasmic diversification of hybrid parents through pedigree breeding is a major breeding objective in developing improved male and female parents. Population improvement is also being followed for improving the grain and stover yields in both maintainer and restorer backgrounds separately both for grain (dual purpose) and fodder/forage sorghums.

Considering that *caudatum* race has been exploited extensively for diversification of hybrid parents at ICRISAT, and elsewhere, greater emphasis was given for the use of other races (*durra* and *guinea*) for hybrid parents' development since 2000 at ICRISAT, Patancheru (Reddy et al. 2010). Availability of cytoplasmic-nuclear male sterility (CMS) system, higher heterosis for grain yield in the improved hybrids, and strong private sector presence facilitated the development of improved hybrids in large part of the globe. In addition to the widely used *milo*-cytoplasm (A_1), cytoplasmic male-sterile lines are also available in A_2, A_3, A_4, A_{4M}, A_{4VZM}, A_{4G1}, A_5, A_6, 9E and KS cytoplasms (Ashok Kumar et al. 2011b). Considering the restoration frequency, hybrid performance and comparable A_1 and A_2 CMS effects for grain yield and resistance to shoot fly and grain mold, it is advantageous to use A_2 CMS system for developing hybrid parents, among the alternate cytoplasms available. This not only increases the cytoplasmic diversity but reduces the possibility of epidemics occurrence when a single source of cytoplasm is used.

Genetic and CMS systems

Inflorescence in sorghum is a panicle or raceme with spikelets/florets which are either sessile or pedicellate. The floret is bisexual and the caryopsis or seed is the product of self-fertilization in sessile florets. However, there is a 5–15% of outcrossing depending on the wind direction, nature of genotype and humidity (House 1985). The genetic male-sterile genes ms_1 to ms_7 and *al* (described by Rooney 2000) discovered during 1936 to 1971 has greatly helped in diversification and the improvement of sorghum through recurrent selection. At ICRISAT, using ms_3 and ms_7 genes, several trait specific gene pools (19) are developed and they were described by Reddy et al. (2005b). Presently, ICRISAT is developing populations for the following traits: (i) Tillering (as it relates to fodder value); (ii) Grain mold resistance; and (iii) Postrainy season adaptation – maintainer and restorer backgrounds.

Another system, CMS has been used extensively to exploit heterosis in sorghum through hybrids development on a large scale for commercial cultivation since 1960. In 1954, Stephens and Holland discovered A_1 or *milo* system, which has been commercially exploited for developing the female hybrid parents and restorers and several hybrids were released all over the world. Since then several CMS systems were identified and among these the most important are A_1, A_2, A_3, A_4, 9E, A_5 and A_6 (Schertz 1994). At ICRISAT, the emphasis since 1980 has been to develop high-yielding trait and race specific male-sterile lines and restorers. So far more than 800 A_1 CMS lines and more than 1000 A_1 restorer lines were developed and documented at ICRISAT, Patancheru (Reddy et al. 2006, 2007, Ashok Kumar et al. 2011b). Also cytoplasm base of hybrid seed parents is diversified and high-yielding A_2, A_3 and A_4 based male-sterile lines were developed and documented. Recently, ICRISAT, Bamako started working on *guinea*-based improved male-sterile lines and restorers and some high-yielding hybrids were tested and found to be superior over varieties under harsh conditions prevailing in Western and Central Africa (WCA).

Diversity assessment and molecular characterization of cytoplasms and factors influencing CMS systems (stability of CMS systems, effect of CMS systems on economic traits, restorer gene frequency and cytoplasm effect on heterosis) were studied. Diversification of CMS systems that includes germplasm base and traits and effect of genetic backgrounds were also studied (Reddy et al. 2005b). Although diverse male-sterile cytoplasm lines are available, these alternative sources are not used in hybrid development primarily because the frequency of restorer genes in such systems is low, and male-sterile anthers cannot be readily distinguished from male-fertiles. Therefore, there is a need to search for a more useful form of male sterility, yet different from *milo* (A_1). *Milo* restorers have been developed predominantly on *caudatum*-based germplasm. Therefore, they need to be diversified with *guinea* race as this showed higher heterosis compared to other races. Restorer frequency is low in alternate cytoplasms, hence efforts should be made to identify and breed for high-yielding non-*milo* cytoplasm restorers. Limited work has been carried out on fertility restoration and there is a need to identify molecular markers linked to restorer genes. The use of isonuclear lines will provide a better means to identify new restorer genes. Although *milo* male-sterile lines were diversified for resistance to biotic and abiotic stresses at ICRISAT, further breeding for grain yield potential, bold lustrous grain and superior agronomic performance is needed.

Water use efficiency

Sorghum is a C_4 plant with an extensive and fibrous root system enabling it to draw moisture from deep layers of soil. It requires less moisture for growth compared to other major cereal crops; for example, in some studies sorghum required 332 kg of water per kg of accumulated dry matter whereas maize required 368 kg of water, barley (*Hordeum vulgare*) required 434 kg and wheat required 514 kg (House 1985). Maman et al. (2003) showed clearly that yields of pearl millet (*Pennisetum glaucum*) were 1.9 and 3.9 t ha^{-1} in 2000 and 2001 compared to 4.1 and 5.0 t ha^{-1} of sorghum in 2000 and 2001 respectively under similar water use conditions (336 and 370 mm in pearl millet; and 330 and 374 mm in sorghum in 2000 and 2001 respectively). In another study involving sorghum, maize and soybean (*Glycine max*), sorghum was found to be the most consistent water use-efficient crop between the two years of varying environmental conditions with rainfall received from crop emergence to physiological maturity of 10.1 inches in 2009 and 16.4 inches in 2010 in Nebraska, USA (Rees et al. 2006). Similarly sweet sorghum gives higher biomass per unit of water used compared to maize or sugarcane (*Saccharum officinarum*) (Reddy et al. 2008).

Nitrogen use efficiency

Sorghum is grown in a range of soils where nutrient deficiency in particular nitrogen is common. There are number of studies establishing variability in nitrogen use efficiency (NUE) in sorghum. For example, Gardner et al. (1994) demonstrated that among the sorghum cultivars studied, M 35-1 was consistently high in NUE. They also found plants with fewer, larger and thicker leaves and that lower dark respiration rates are related to NUE and can be used as a selection criterion in breeding. Interestingly, sorghum possesses biological nitrification inhibition that reduces nitrogen losses from soil.

Insect pests

Nearly 150 insect species have been reported as pests on sorghum, of which sorghum shoot fly (*Atherigona soccata*), stem borers (*Chilo partellus* and *Busseola fusca*), sugarcane aphid (*Melanaphis sacchari*), sorghum midge (*Stenodiplosis sorghicola*) and head bugs (*Calocoris angustatus* and *Eurystylus oldi*) are the major pests worldwide.

Infester row, artificial infestation and no-choice cage screening techniques have been standardized to evaluate sorghum germplasm, breeding material and mapping populations for resistance to insect pests (Sharma et al. 1992). Large-scale screening of the sorghum germplasm at ICRISAT has resulted in identification of several lines with reasonable levels of resistance to shoot fly, stem borer, midge and head bugs (Sharma et al. 2003). Sources of resistance to insects in sorghum have been used in the breeding program, and many varieties with resistance to insect pests have been developed (Sharma et al. 2005). Cultivars with resistance to midge have been released in India and Myanmar, but are cultivated on a limited area due to non-availability of seed. However, these lines have been used by the seed industry to develop midge-resistant hybrids in Australia and USA. Resistance to midge and shoot fly has been transferred into maintainer lines, which have been supplied to, and used by the NARS partners and the industry in developing improved varieties in different regions (Ashok Kumar et al. 2011b).

Wild relatives of sorghum belonging to *Parasorghum* and *Stiposorghum* have shown high levels of resistance to shoot fly, stem borer and sorghum midge (Sharma and Franzmann 2001, Kamala et al. 2008), and have diverse mechanisms of resistance to insects. These can be used to transfer resistance genes into the cultigen. The presence of trichomes has been found to contribute to oviposition non-preference and the trichomes controlled by a single recessive gene (House 1985). Polymorphic simple sequence repeat (SSR) loci associated with resistance to shoot fly and the traits associated with resistance to this insect have been identified (Folkertsma et al. 2003), and are now being transferred into the locally adapted hybrid parental lines via SSR based marker-assisted seletion (MAS). The QTLs associated with antibiosis and antixenosis mechanisms of resistance to sorghum midge (Tao et al. 2003), and tolerance to green bug (Nagaraj et al. 2005) have also been identified. MAS will allow for rapid introgression of the resistance genes, and ultimately gene pyramiding, into the high-yielding varieties and hybrids. Sorghum plants having *cry1Ac* gene have been developed. Combining transgenic resistance to insects with the conventional plant resistance will make plant resistance an effective component for insect pest management in sorghum.

While host plant resistance is an effective tool to manage midge in sorghum, there is need to develop other tools of integrated pest management (IPM) for managing white grubs, shoot fly and stem borer and sprays for head bugs in sorghum (Sharma 2006). Seed treatment with systemic insecticides can be very effective in combination with host plant resistance for shoot fly control, and can contribute as much as 20 to 40% increase in grain yield gain. Intercropping and proper storage of the grain are other interventions that help reduce losses in dryland cereals. While effective tools have been developed to identify sources of resistance to major insect pests in sorghum, there is a need to refine the screening technique for aphids in sorghum. Also gene pyramiding and development of cultivars with multiple resistance to insect pests and diseases, transfer of insect resistance genes into CMS-maintainer and restorer lines, exploitation of alternate CMS systems that are less susceptible to insect pests, identification of toxin genes for shoot fly, stem borer and head bugs for developing transgenic plants with resistance to insect pests, and identification and application of molecular markers associated with resistance to insects for use in crop improvement should be the focus for future research in dryland cereals.

Diseases

In most semi-arid tropical environments, economically important diseases of sorghum are grain mold, anthracnose, leaf blight, downy mildew, charcoal rot, rust, ergot and smuts. These diseases, either alone or in combinations, cause substantial damage to crops resulting in heavy economic losses every year (Thakur et al. 2007). Grain mold is a major disease of improved white-grained, short- to medium-duration sorghum cultivars that mature during rainy season. The disease affects both grain production and quality and can cause 30–100% losses depending on cultivar, time of flowering and weather conditions during flowering to harvest (Singh and Bandyopadhyay 2000). Several toxigenic *Fusarium* spp associated with grain mold complex that produce mycotoxins, such as fumonisins and trichothecenes have been characterized (Sharma et al. 2011). Anthracnose, leaf blight and rust are the important foliar diseases and under favorable conditions up to 50% losses have been reported (Thakur et al. 2007). Downy mildew is another destructive disease due to its systemic nature of infection resulting in the death of plants or lack of panicle initiation. Charcoal rot is the most important disease of postrainy (*rabi*) season sorghum that is generally grown on residual soil moisture in India. The disease is more severe and destructive on high-yielding sorghum cultivars when grain filling coincides with low soil moisture in hot dry weather. Management strategy for these diseases has been mainly through host plant resistance, which is economical, environment friendly and technically feasible at farmers' level. Disease management through host plant resistance involves development of a simple and effective screening technique to identify genetic resistance that could be appropriately utilized in breeding programs to develop disease resistant cultivars. Over the years, screening techniques have been developed and refined for major sorghum diseases, such as grain mold, anthracnose, leaf blight, downy mildew, ergot, rust and charcoal rot. Although high level of mold resistance is not available in white-grained sorghum, several tolerant lines have been identified and utilized in the breeding program. Efforts are also being made to map QTLs for grain mold resistance for their introgression into elite backgrounds. In addition, efforts are also required to identify resistance against toxigenic Fusaria associated with grain mold complex. Several sorghum germplasm and/or breeding lines with moderate to high levels of resistance to anthracnose, downy mildew, rust and leaf blight have been identified and used in trait-specific breeding program at ICRISAT (Thakur et al. 2007). Recently grain mold resistance hybrids in white grain backgrounds were developed at ICRISAT (Ashok Kumar et al. 2008, 2011a). Ergot being more a localized problem particularly in seed production plots, not much effort has been made to develop resistant hybrid parental lines. High level of charcoal rot resistance is not available; moreover, abiotic factors such as soil moisture stress and high temperature predispose plants to charcoal rot infection and disease development. Therefore, there is a need to explore other methods of disease control in addition to host plant resistance for the management of charcoal rot.

Weeds

Striga was first recognized as a serious parasitic weed nearly 100 years ago. Over the past 60 to 70 years considerable research efforts have been directed at understanding and managing it. *Striga* is a genus of obligate, root-parasitic flowering plant, with most of the species occurring in Africa. These include *Striga hermonthica, S. asiatica, S. aspera* and *S. forbesii.* Of these, *S. asiatica* used to be a major constraint limiting yield in sorghum in Asia.

During 1972 to 1985, ICRISAT, Patancheru concentrated its major efforts in developing a three-stage screening technique for identifying resistant sources and improving them for high yield under adaption to rainy season conditions in India. SAR 1 to SAR 36 refers to improved restorer lines and varieties developed at ICRISAT, Patancheru. Work was also directed at identification of resistant mechanisms (mechanical, strigol negative and antibiosis). Also several improved *Striga* resistant male-sterile lines were developed at ICRISAT, Patancheru during 1985 to 2003 (Reddy et al. 2004). These include ICSB 567, ICSB 568, ICSB 569, ICSB 571, ICSB 572, ICSB 584, ICSB 594, ICSB 598 and ICSB 599 (Reddy et al. 2007).

In Africa, much of the research work on *Striga* control was carried out initially in the national programs of Nigeria, Sudan, Uganda and Kenya before 1970. In 1987, ICRISAT *Striga* research efforts were moved to Bamako, Mali. Efforts were carried out to develop resistant varieties (Obilana and Reddy 1996), and also various other control measures such as cultural management (Hess and Dembele 1996), chemical control (Hess and Grard 1996) and biological control (Abbasher et al. 1996). Obilana (2004) indicated that the future research includes adopting new breeding strategies adopting marker technology, identifying the physiological basis of *Striga* pathogen variability, adopting non-conventional approach to *Striga* control including transposon-based mutation and integrated *Striga* control technology exchange and up-scaling.

The networking efforts of ICRISAT in use and adoption of biotechnology tools – developing RIL populations of 296 B × Framida (SRN 4841) (stimulant negative) and N 13 (mechanical resistant) × E 36-1 at ICRISAT, Patancheru, phenotyping in pot and field conditions in WCA and Eastern and Southern Africa (ESA) through networking with national programs, genotyping and identification of markers and QTLs in Germany and at ICRISAT, Patancheru (Haussmann et al. 2000) and adoption of marker-assisted backcross breeding – paid rich dividends in developing and release of four *Striga* resistant varieties in Sudan in the genetic backgrounds of popular, but *Striga* susceptible improved sorghum varieties, Tabat, Wad Ahmed and AG 8. These four released varieties are Asareca.T1, Asareca.W2, Asareca.AG3 and Asareca.AG4.

Therefore, the emphasis now is to follow conventional and marker-assisted breeding and integrated control of *Striga* and up-scale these through networking and partnership at ICRISAT African centers.

High temperature

Sorghum grows well in a temperature range of 15–40°C but temperatures below and above this may have a bearing on crop germination, establishment, flowering and seed setting. Sorghum flowers and sets seed under high temperatures (up to 43°C) provided soil moisture is available (House 1985). In many regions of the world, sorghum production encounters heat and drought stress concurrently but heat tolerance and drought tolerance are unique and independent traits (Jordan and Sullivan 1982). Despite the level of adaptation of sorghum in the semi-arid tropics, seedling establishment is still a major problem. Failure of seedling establishment due to heat stress is one of the key factors that limits yields and affects stability of production. Thomas and Miller (1979) reported that sorghum seedlings respond differently when exposed to varying temperatures, and genetic variation for thermal tolerance in sorghum has been shown to exist in certain lines that are capable of emerging at soil temperature of about 55°C. Peacock et al. (1993) and Howarth (1989) have discussed the need for greater diversity in sorghum seedling tolerance to heat in superior genotypes, as this will improve the crop establishment in the semi-arid tropics. Genetic variability for heat tolerance among the genotypes at seedling stage was demonstrated by Wilson et al. (1982). Using screening techniques such as leaf disc method (Jordan and Sullivan 1982) and leaf firing ratings by ICRISAT breeders, genetic variability past the seedling stage was demonstrated and positive correlation found between grain yield and heat tolerance thus making breeding for heat tolerance a viable option. Genetic variability for heat tolerance in sorghum was also reported by other researchers (Jordan and Sullivan 1982).

Khizzah et al. (1993) studied four sorghum parental lines RTx430, BTx3197, RTx7000 and B 35 and their F_1 and reciprocals, and F_2 progenies during their reproductive phase to assess the genetic basis of heat tolerance in sorghum. They reported that inbreds were more heat tolerant compared to their F_1 progenies. Also, cultivars which had good late season, field drought tolerance appeared to be heat tolerant, suggesting a possible relationship between drought and heat responses. They also reported cytoplasmic effects for heat tolerance. Using the F_2 frequency distribution of the crosses with B 35, Khizzah et al. (1993) made the following assumptions: (i) two loci were responsible for expression of heat tolerance, and (ii) complete dominance at both gene pairs, but one gene when dominant is epistatic to the other. Low to high heritability of heat tolerance reported in sorghum suggests the feasibility of genetic enhancement. B 35 and BTx3197 could be used as sources for heat tolerance in sorghum improvement programs (Khizzah et al. 1993). The importance of additive gene effects over dominance effects for heat tolerance index was reported by Setimela et al. (2007). However, selection for heat tolerance has limited success as: (i) laboratory techniques to screen for heat tolerance have not been effective in improving heat tolerance in field studies; and (ii) field screening for heat tolerance is difficult to manage and is often confounded with drought tolerance (Rooney 2004). Due to the confounding effects, though the heat and drought tolerance are independent traits, the selection for drought tolerance traditionally has been assumed to improve heat tolerance.

Drought

Sorghum has the capacity to survive some dry periods and resume growth upon receipt of rain. Sorghum also withstands wet extremes better than many other cereal crops especially maize. Sorghum continues to grow, though not well, in flooded conditions; maize by contrast will die.

At ICRISAT, four specific droughts were recognized. These are: (1) Seedling emergence under deep planting and high temperature; (2) Early seedling drought; (3) Mid-season drought or pre-flowering drought; and (4) Post-flowering/terminal drought. Among these, the two distinct drought-stress responses, a pre-flowering drought tolerance that occurs prior to anthesis and a post-flowering drought-stress that is observed when water-limitation occurs during grain-filling stage as in postrainy season adaptation have been considered as the most important in sorghum (Rosenow et al. 1983).

At ICRISAT, growth stage-specific breeding for drought tolerance, which involves alternate seasons of screening in specific drought and well-watered environments, has been used to breed sorghum that can yield well in both high yield potential environments as well as in drought-prone environments (Reddy et al. 2009a). Since hybrids have exhibited relatively better performance than open-pollinated cultivars for grain yield under water-limited environments, hybrid cultivar development (including their parents) should be given strategic importance for enhancing sorghum production in water-scarce environments (Reddy et al. 2009a).

Some of the drought tolerant sources identified in sorghum in early work at ICRISAT include Ajabsido, B 35, BTx623, BTx642, BTx3197, El Mota, E36Xr16 8/1, Gadambalia, IS 12568, IS 22380, IS 12543C, IS 2403C, IS 3462C, CSM-63, IS 11549C, IS 12553C, IS 12555C, IS 12558C, IS 17459C, IS 3071C, IS 6705C, IS 8263C, ICSV 272, KoroKollo, KS19, P898012, P954035, QL10, QL27, QL36, QL41, SC414-12E, Segaolane, TAM422, Tx430, Tx432, Tx2536, Tx2737, Tx2908, Tx7000 and Tx7078. ICRISAT has identified lines that are tolerant to drought at various growth stages. Drought tolerance of M 35-1, a highly popular postrainy season adapted landrace in India, has been amply demonstrated.

In another study, the results for the measured variables [carbon exchange rate (CER), transpiration, transpiration ratio (CER/transpiration), leaf diffusive resistance, leaf water potential and osmotic adjustment] showed a general trend for greater drought resistance in sorghum than in millet, indicating that the commonly observed adaptation of the millets to dry environments may be due to other factors, such as drought escape or heat tolerance (Blum and Sullivan 1985).

Among several drought tolerant traits, stay-green trait in sorghum (the capacity of certain genotypes to maintain their leaves green during the grain-filling period) is the well characterized and exploited as a post-flowering drought tolerant trait (Reddy et al. 2009a, Haryarimana et al. 2010). It is well documented to be polygenic and heritable, and is used extensively in breeding programs for developing drought tolerant cultivars (Jordan et al. 2012). This phenotype is also reported to be associated with reduced stalk lodging, reduced susceptibility to charcoal rot and maintenance of seed size (Borrell et al. 1999, 2000). Several studies have identified genomic regions/QTLs underlying stay-green expression (Haryarimana et al. 2010). Physiological mechanisms such as improved capacity and water use efficiency for water extraction, response to vapor pressure deficit, transpiration efficiency, leaf conductance and kinetics, specific leaf area and canopy development have been associated with stay-green QTLs (Vadez et al. 2011). These QTLs have been used for developing drought tolerant cultivars through marker-assisted backcrossing (Kassahun et al. 2010, Jordan et al. 2012) and effects of each QTL on stay-green expression, grain and fodder yield have been reported. This needs to be further validated across several genetic backgrounds and different target regions. Similarly modeling efforts to characterize soil and agroclimatic parameters for production areas where postrainy season sorghum is grown have been reported (Hammer et al. 2010). Further studies are required to integrate individual QTL effects in postrainy season sorghum models and successful models can further be utilized to develop breeding strategies for similar agroclimatic regions in Africa.

Salinity

Salinity toxicity in crops is caused by the presence of high levels of soluble salts in the soil solution, namely the Na^+ cation and probably to a lesser extent Cl^-. Salinity affects approximately 830 million ha worldwide and is becoming an increasing problem in regions where saline water is used for irrigation. There are many areas with varying degree of salinity in India, Africa and countries in West Asia. Salinity retards seed germination and root emergence causes ion toxicity, osmotic stress and mineral deficiencies which adversely affect photosynthetic, physiological and biochemical processes limiting crop yield (Krishnamurthy et al. 2007, Gates et al. 2009). The genetic differences can be exploited to search varieties/cultivars for salt tolerance by rapid screening methods using different growth parameters such as relative shoot growth, leaf blades, sheaths, leaf water potential, osmotic potential, nitrate reductase activity and relative water contents. Krishnamurthy et al. (2007) reported that germination and emergence stages in sorghum might be useful criteria to evaluate the effect of salinity. Using Na accumulation and other measures of salt tolerance, major and minor QTLs have been mapped (Flowers and Flowers 2005, Jenks et al. 2007). Significant variability was observed for high biomass and grain yield under saline conditions among hybrids and varieties; hybrids were superior to varieties under field conditions (10–12 dS) in India (Krishnamurthy 2010). In a study at International Center for Biosaline Agriculture (ICBA), UAE using saline water (2 dS, 8 dS and 13 dS) showed that hybrids were superior to varieties for biomass production and two sorghum hybrids ICSA 474 × NTJ 2 and ICSA 702 × ICSV 93046 were promising for biomass. The results of multilocational trials of sweet sorghum improved breeding materials helped to identify salinity tolerant sweet sorghum varieties (ICSV 93046, ICSV 25274, ICSR 93034 and ICSV 25275) and hybrids (ICSSH 28, ICSSH 58 and ICSSH 64) that are productive in normal and saline conditions.

Aluminum toxicity

Aluminum (Al) toxicity is a major abiotic constraint on sorghum production and productivity worldwide (Magalhaes et al. 2004). Moreover, over 40% of the arable lands are acidic. Aluminum toxicity is widely prevalent in many countries of East Africa (Tanzania, Kenya) and Latin America (Colombia, Venezuela, Brazil, Bolivia, Peru, etc). Aluminum in acidic soil inhibits water and mineral uptake and consequently, reduces plant vigor and yield. Hanning et al. (1992) described the mechanisms of tolerance to acid soils and indicated that it is generally controlled by polygenic genes in crop plants. In sorghum, the AltSB locus, located on chromosome 3, was first identified as a major determinant for Al tolerance in the sorghum line SC283, explaining 80% of the phenotypic variation. Root organic acid release into the rhizosphere resulting in the formation of stable, non-toxic complexes with Al has long been hypothesized as a major physiological mechanism of tolerance via root Al exclusion in plants (Ma et al. 2001). More recently, genes encoding root citrate transporters belonging to the MATE (multidrug and toxic compound extrusion) family, ie, SbMATE has been cloned in sorghum (Magalhaes et al. 2007). Aluminum tolerance was found to be rather rare and present primarily in *guinea* and to lesser extent in *caudatum* sub-populations. AltSB was found to play a role in Al tolerance in most of the Al tolerant accessions. ICRISAT work in Llanos in Colombia and Cerrados in Brazil (where Al toxicity related acidity in the soil is predominant) established significant variability for biomass and grain yield in field testing. This work helped to release two high biomass forage sorghums in Colombia (Reddy et al. 1999). Also, ICRISAT work demonstrated that there are significant G×E interactions in sorghum under acid soil conditions for biomass and grain yield (Reddy and Rangel Andres 1999).

Nutritional value

Sorghum being one of the major food crops in the world has predominant role in meeting the dietary energy and micronutrient requirements particularly in the low income group populations; thus improving sorghum nutrition quality is of paramount importance. High genetic variability for protein content has been reported. The best method for phenotyping for protein content is through using Microkjeldahl method or Techniconautoanalyser (TAA) method. A study on limited number of germplasm lines and hybrid parents in sorghum did not show appreciable variability for β-carotene content in sorghum (Reddy et al. 2005a).

Similar is the case with yellow endosperm lines wherein the β-carotene did not exceed 1.1 ppm. For phenotyping for this trait, spectrophotometry can be followed but estimation using High-Performance Liquid Chromatography (HPLC) gives more accurate information.

Enhancement of grain iron (Fe) and zinc (Zn) contents is one of the major breeding objectives at ICRISAT and elsewhere. Large-scale screening of sorghum core germplasm accessions, hybrid parents and commercial hybrids showed high genetic variability for grain Fe and Zn contents and most of this variation is heritable (Reddy et al. 2005a, Ashok Kumar et al. 2012). Significant positive association exists between grain Fe and Zn contents (r^2=0.6–0.8) and it is possible to simultaneously improve both the traits (Ashok Kumar et al. 2009, Reddy et al. 2011). Additive gene action plays significant role in conditioning the grain Zn content while non-additive gene action is predominant for grain Fe content (Ashok Kumar et al. 2012).

High energy sorghum

Sorghum has distinct advantage as energy sorghum because of its high biomass production and adaptation across semi-arid tropical environments. Hence, this crop is widely believed as a model biofuel feedstock owing to its adaptation and ease of handling segregating generations. Sorghum biomass yields vary between 15 and 25 t ha^{-1}, but have been reported to be as high as 40 t ha^{-1} (Rooney et al. 2007). Sorghum is a very robust plant that not only produces high biomass but also accumulates large quantities of sugars in the stalks that can be used for biofuel production without scarifying the grains. Sweet sorghum or high energy sorghum can also thrive under moderate water stress conditions (Reddy et al. 2004, 2008), on marginal lands and with little external inputs (Rao et al. 2009). It also can be grown successfully in degraded and marginal lands contaminated with heavy metals (Zhuang et al. 2007). Thus, energy sorghum (both biomass and sweet sorghum) is well suited for land of low productivity or at higher risk for drought or waterlogging stress and is unlikely to replace food crops from higher-quality land (Rao et al. 2010). Specific traits of interest are stalk sugars accumulation, biomass yield, post-flowering drought adaptation, water use efficiency, non-lodging and cell wall composition. Post-flowering drought adaptation in sorghum is associated with the stay-green phenotype and four major QTLs associated with this trait were identified. In India, stay-green, tall stature and a medium to long growth cycle have been proven useful in selection criteria for improving dry matter yield under terminal moisture stress. With the availability of the sorghum genome sequence (Paterson et al. 2009), and the recent release of a sorghum consensus genetic linkage map that includes major effect genes make it feasible to associate individual genes or clusters of genes with specific QTLs (Mace and Jordan 2010), which greatly enhances breeding efforts. Elucidating the genetic basis of stem sugar and stem juice accumulation, modifying cell wall composition through *bmr* alleles introgression so that sorghum biomass can be processed more efficiently, maximizing biomass yield for a given geographic area and production system, and understanding the different mechanisms underlying drought tolerance are the main focus areas among sorghum researchers that target bioenergy traits. As mapping populations and collections of mutants increase, it will become easier to identify genes of interest, and it will ultimately become possible to identify all the genes involved in a particular process or pathway, and know how they interact. Plant breeding will continue to play an important role in combining this information to generate germplasm that will enable sustainable bioenergy production.

Fodder quality

Extensive market survey of fodder trading in India has shown that the ratio of stover to grain price is narrowing and is now about 0.5 (Sharma et al. 2010). Additionally price premiums are paid for higher quality stover and a difference of about 1 percentage unit in stover digestibility was associated with a price premium of about 5% (Blümmel and Rao 2006).

Phenotyping for stover fodder quality of pipelined and release tested hybrids and open-pollinated varieties has shown that about 5 units difference in stover digestibility exists that can be exploited without detriment to grain and stover yield (Blümmel et al. 2010b). Price premium for such stover is 25 to 30%. Near Infrared Spectroscopy (NIRS) platforms were developed and validated to phenotype for stover quality in multidimensional crop improvement programs (Sharma et al. 2010). The dry stalks are controlled by a simple dominant gene, D; juiciness is recessive (House 1985).

Stay-green QTL introgression can improve stover digestibility by 3 to 5 percentage units without detriment to grain and stover yields, in addition to improving drought resistance of sorghum cultivars and their water use efficiency. Brown mid-rib introgressions improved stover quality similarly, but had a depressing effect on grain and stover yields.

Fortification and densification work has shown that sorghum stover based feed blocks, feed mash and feed pellets have the potential to increase average milk yields (currently <4 kg day^{-1}) by 3- to 4-fold (12 to 16 kg day^{-1}) (Anandan et al. 2010). The effect of such intensification on natural resource usage and greenhouse gas emission is dramatic. For example an increase in average daily milk yield from 4 to 6 kg would reduce methane emission from Indian dairy by more than 1 million tons per year (Blümmel et al. 2010a).

Alternative uses

Sorghum is an important food and fodder crop in semi-arid tropics. At present, most of the sorghum produced in India is consumed as human food in the form of *roti*, *bhakri* or *chapathi* in India and *ugali*, *kisra*, *injera*, *to*, etc in Africa. Main traditional uses of sorghum encompass utilization of grain for food and stalks as fodder. The possible promising alternative food products from sorghum are bakery products, maltodextrins as fat replacers in cookies, liquids or powder glucose, high fructose syrup and sorbitol. Malted sorghum can be a good alternative for baby weaning foods. Popped sorghum and sorghum noodles, also as breakfast or snack foods form good alternative uses.

The industrial products made from sorghum grain include alcohol (potable grade) and lager beer. Other technologies such as production of glucose, maltodextrins, high fructose syrup and cakes from sorghum are yet to be scaled up. The juice from sweet sorghum stalks is fermented to produce ethanol (biofuel) and other sweet sorghum products like syrup and *jaggery* have received good attention in production of food products like sweets and ready to serve foods.

Recently the NutriPlus Knowledge (NPK) program of the Agribusiness and Innovation Platform (AIP) at ICRISAT has demonstrated that sweet sorghum juice and syrup can be used as sugar alternative for meeting certain requirements of the beverage industry (DattaMazumdar et al. 2012). Value addition, through conversion of the juice to syrup and beverages, offers farmers an excellent opportunity to improve farm income and productivity in semi-arid regions. In this study a new method to produce clarified sweet sorghum juice was demonstrated. Further, flavored nutritious beverage formulations, with acceptable sensory properties were successfully developed using the clarified juice and syrup.

The expert meeting held at ICRISAT discussed the scope for various alternative uses in sorghum (CFC and ICRISAT 2004). The solid bagasse which remains after pressing sweet sorghum has several potential uses. One potential use is as an animal feed source, directly after chopping or after ensiling (Linden et al. 1987). It has also been used as a source of pulp for the paper industry (Belayachi and Delmas 1997). Another potential use of the bagasse is as a fuel source for the processing plant. With the addition of a solid fuel boiler, the bagasse can be used to provide process heat to run the plant. With its heating value it is likely to require only 20–30% of the available biomass to fuel the plant (Bennett and Annex 2009). In addition, processes for conversion of lignocellulosic material to ethanol are becoming more economically viable, making sweet sorghum bagasse a possible source of biomass for such a process. Studies have demonstrated that a large portion of the insoluble carbohydrate (cellulose and hemicellulose) from sorghum can be readily converted to ethanol (Sipos et al. 2009).

Malting and processing quality

Understanding the malting properties of sorghum varieties and identifying varieties that yield malts with highest levels of enzyme (α-Amylase and β-Amylase) activity is key to adoption of sorghum in the malting industry. Sorghum has been malted for centuries and is used for the production of baby food and traditional alcoholic and nonalcoholic beverages. Both α-Amylase and β-Amylase are needed to hydrolyze starch and produce fermentable sugars in these processes. However, improvements and standardization of malting procedures and of malt evaluation techniques need to be made. Malting properties were investigated for 16 sorghum varieties using a germinator method (which mimics the pneumatic malting process) and for six sorghum varieties using a jar method (which mimics the floor malting process). Density of caryopses decreased for all sorghums after malting. Dry matter losses ranged from 8 to 19%. α-Amylase activity determined by colorimetric assay ranged from 25 to 183 U/g, with two cultivars having activity levels similar to that of commercial barley malt. Reduction in pasting viscosity was significantly correlated with α-Amylase activity. Sorghum diastatic (SDU) power was positively correlated to α-Amylase activity in cultivars with SDU values >30. β-Amylase activity was low, ranging from 11 to 41 U/g. The jar malting method yielded malts with lower dry matter losses and low levels of α-Amylase and β-Amylase activity, except for one cultivar (Beta et al. 1995) Thus, to obtain the highest levels of enzyme activity with the lowest dry matter losses, malting conditions need to be controlled and optimized.

Summary

Sorghum improvement research has come a long way from using simple methods like mass selection to advanced level of selection using molecular markers for trait improvement. Efforts are underway to use new genomic tools for sorghum improvement facilitated by the availability of aligned genome sequence. In addition to the yield and quality, biotic and abiotic constraints and the presumed climate change effects profoundly influence the sorghum area and its importance globally. The climate change effects modify the length of growing period across the sorghum regions, but this can be mitigated to some extent by re-targeting and re-deployment of existing germplasm. Predicted temperature increases, through their effect on increasing rate of crop development, will have greater negative impact on crop production than the relatively small (+/– 10%) changes in rainfall that are predicted to occur. Yield gap analyses at ICRISAT and elsewhere showed that the negative impacts of climate change can be largely mitigated through greater adoption of improved crop, soil and water management innovations by farmers and better targeted crop improvement approaches by researchers, more explicitly focused on adaptation to climate change. Keeping all these points in view, crop improvement research in sorghum need to be oriented towards greater genetic and cytoplasmic diversification for high yield and large grain, *Striga*, shoot fly and grain mold resistance, drought, acid soil and salinity tolerance, postrainy season adaptation, sweet stalk traits and grain micronutrient density. The grain and stover quality attributes need special attention in sorghum improvement programs to enhance the market value.

Combining classical breeding techniques with new science tools helps in efficient and quick development of improved products. While the genotyping tools are increasingly available and more affordable now, phenotyping is not receiving equal attention in sorghum like in other crops. One should keep in mind that without good quality phenotyping data, the genotyping data is of no use, no matter how it was generated. Therefore the progress in sorghum improvement in the years to come depends upon the quality of the phenotyping data that we generate for traits of interest and most appropriate use of genomic tools available. Further enhanced collaboration is required between IARCs (international agricultural research centers) and NARS (national agricultural research system) partners across the globe to make use of new tools and information in development of improved products.

References

Abbasher AA, Hess DE, Sauerborn J and **Kroschel J.** 1996. Biological control of *Striga*. Presented at ICRISAT Sector Review for *Striga* Control in Sorghum and Millet, ICRISAT-Bamako, 27–28 May 1996.

Anandan S, Khan AA, Ravi D, Jeethander Reddy and **Blümmel M.** 2010. A comparison of sorghum stover based complete feed blocks with a conventional feeding practice in a peri urban dairy. Animal Nutrition and Feed Technology 105:23–28.

Ashok Kumar A, Reddy BVS, Ramaiah B, Sahrawat KL and **Pfeiffer WH.** 2012. Genetic variability and character association for grain iron and zinc contents in sorghum germplasm accessions and commercial cultivars. European Journal of Plant Science and Biotechnology 6 (Special Issue 1):66–70.

Ashok Kumar A, Reddy BVS, Ramaiah B, Sanjana Reddy P, Sahrawat KL and **Upadhyaya HD.** 2009. Genetic variability and plant character association of grain Fe and Zn in selected core collections of sorghum germplasm and breeding lines. Journal of SAT Agricultural Research 7:1–4. (ejournal.icrisat.org)

Ashok Kumar A, Reddy BVS, Ramaiah B and **Sharma R.** 2011a. Heterosis in white-grained grain mold resistant sorghum hybrids. Journal of SAT Agricultural Research 9:1–6. (ejournal.icrisat.org)

Ashok Kumar A, Reddy BVS, Sharma HC, Hash CT, Srinivasa Rao P, Ramaiah B and **Sanjana Reddy P.** 2011b. Recent advances in sorghum genetic enhancement research at ICRISAT. American Journal of Plant Sciences 2:589–600.

Ashok Kumar A, Reddy BVS, Thakur RP and **Ramaiah B.** 2008. Improved sorghum hybrids with grain mold resistance. Journal of SAT Agricultural Research 6:1–4. (ejournal.icrisat.org)

Awika JM and **Rooney LW.** 2004. Sorghum phytochemicals and their potential impact on human health. Phytochemistry 65:1199–1221.

Belayachi L and **Delmas M.** 1997. Sweet sorghum bagasse: a raw material for the production of chemical paper pulp. Effect of depithing. Industrial Crops and Products 6:229–232.

Bennett AS and **Annex RP.** 2009. Production, transport and milling costs of sweet sorghum as a feedstock for centralized bioethanol production in the upper Midwest. Bio-resource Technology 100:1595–1607.

Beta T, Rooney LW and **Waniska RD.** 1995. Malting characteristics of sorghum cultivars. Cereal Chemistry 72(6):533–538.

Blum A and **Sullivan CY.** 1985. The comparative drought resistance of landraces of sorghum and millet from dry and humid regions. Annals of Botany 57(6):835–846.

Blümmel M and **Rao OPP.** 2006. Economic value of sorghum stover traded as fodder for urban and peri-urban dairy production in Hyderabad, India. International Sorghum and Millets Newsletter 47:97–101.

Blümmel M, Seetharama N, Bidinger FR, Hash CT, Choudhary S and **Reddy BVS.** 2010a. Sustainability of livestock production and considerations for sorghum and millet improvement. Pages 19–26 *in* Research and developments in millets: present status and future strategies (Patil JV, Dayakar Rao B, Umakanth AV, Tonapi VA, Rskshit S, Rao SS and Ganapathy KN, eds.). Rajendranagar, Hyderabad, Andhra Pradesh, India: Directorate of Sorghum Research.

Blümmel M, Vishala A, Ravi D, Prasad KVSV, Ramakrishna Reddy Ch and **Seetharama N.** 2010b. Multi-environmental investigations of food-feed trait relationships in kharif and rabi sorghum (*Sorghum bicolor* (L) Moench) over several years of cultivars testing in India. Animal Nutrition and Feed Technology 10S:11–21.

Borrell AK, Bidinger FR and **Sunitha K.** 1999. Stay-green associated with yield in recombinant inbred sorghum lines varying in rate of leaf senescence. International Sorghum and Millets Newsletter 40:31–34.

Borrell AK, Hammer GL and **Henzell RG.** 2000. Does maintaining green leaf area in sorghum improve yield under drought? 2. Dry matter production and yield. Crop Science 40:1037–1048.

Caddel JL and **Weibel DE.** 1971. Effect of photoperiod and temperature on the development of sorghum. Crop Science 63:799–803.

CFC and **ICRISAT.** 2004. Alternate uses of sorghum and pearl millet in Asia: proceedings of expert meeting, ICRISAT, Patancheru, Andhra Pradesh, India, 1–4 July 2003. CFC Technical Paper No. 34. Amsterdam, The Netherlands: Common Fund for Commodities; and Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 365 pp.

Craufurd P, Cooper P, Rao KPC, Stern R, Vadez V, Cairns J and **Rao VNN.** 2011. Traits for ideotypes to adapt African crops to climate change. Pages 30–34 *in* Book of Abstracts, International Conference on Crop Improvement, Ideotyping, and Modelling for African Cropping Systems under Climate Change – CIMAC, 7–9 February 2011, University of Hohenheim, Germany.

DattaMazumdar S, Poshadri A, Srinivasa Rao P, Ravinder Reddy Ch and **Reddy BVS.** 2012. Innovative use of sweet sorghum juice in the beverage industry. International Food Research Journal 19(4):1361–1366.

Downes RW and **Marshall DR.** 1971. Low temperature induced male sterility in *Sorghum bicolor*. Australian Journal of Experimental Agriculture and Animal Husbandry 11:352–356.

FAOSTAT. 2011. http://faostat.fao.org/faostat/ (Last accessed 27 October 2011.)

Flowers TJ and **Flowers SA.** 2005. Why does salinity pose such a difficult problem for plant breeders? Agricultural Water Management 78:15–24.

Folkertsma RT, Sajjanar GM, Reddy BVS, Sharma HC and **Hash CT.** 2003. Genetic mapping of QTL associated with sorghum shoot fly (*Atherigona soccata*) resistance in sorghum (*Sorghum bicolor*). Page 42 *in* Final Abstracts Guide, Plant & Animal Genome XI, Jan 11–15, 2003, San Diego, CA, USA. (http://www.intl-pag.org/11/abstracts/P5d_P462_XI.html)

Gardner JC, Maranville JW and **Paparozzi ET.** 1994. Nitrogen use efficiency among diverse sorghum cultivars. Crop Science 34:728–733.

Gates CT, Haydock KP, Claringbold PJ and **Robins FM.** 2009. Growth of varieties of three sorghum species at different levels of salinity. Australian Journal of Experimental Agriculture and Animal Husbandry 6:161–169.

Hammer GL, van Oosterom E, McLean G, Chapman SC, Broad I, Harland P and **Muchow RC.** 2010. Adapting APSIM to model the physiology and genetics of complex adaptive traits in field crops. Journal of Experimental Botany 61:2185–2202.

Hanning GF, Timm DA and **Nabot MW.** 1992. Acid soil tolerance in tissue-culture derived sorghum lines. Crop Science 32:324–327.

Haryarimana E, Lorenzoni C and **Busconi M.** 2010. Search for new stay-green sources in *Sorghum bicolor* (L.) Moench. Maydica 55:187–194.

Haussmann BIG, Hess DE, Reddy BVS, Mukuru SZ, Seetharama N, Kayentao M, Welz HG and **Geiger HH.** 2000. QTL for Striga resistance in sorghum populations derived from IS 9830 and N 13. Pages 29–37 *in* Breeding for Striga resistance in cereals. Proceedings of a Workshop, IITA, Ibadan, Nigeria, 18–20 August 1999 (Haussmann BIG, Koyama ML, Grivet L, Rattunde HF and Hess DE, eds.). Weikersheim, Germany: Margraf.

Hess DE and **Dembele B.** 1996. Cultural management of *Striga* on cereals. Presented at ICRISAT Sector Review for *Striga* Control in Sorghum and Millet, ICRISAT-Bamako, 27–28 May 1996.

Hess DE and **Grard P.** 1996. Chemical control of *Striga*. Presented at ICRISAT Sector Review for *Striga* Control in Sorghum and Millet, ICRISAT-Bamako, 27–28 May 1996.

House LR. 1985. A guide to sorghum breeding. 2nd edition. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 165 pp.

Howarth CI. 1989. Heat shock proteins in *Sorghum bicolor* and *Pennisetum americanum.* I. Genotypical and developmental variation during seed germination. Plant Cell and Environment 12:471–477.

Jenks MA, Hasegawa PM and **Mohan Jain S.** 2007. Advances in molecular breeding toward drought and salt tolerant crops. Dordrecht, The Netherlands: Springer.

Jordan DR, Hunt CH, Cruickshank AW, Borrell AK and **Henzell RG.** 2012. The relationship between the stay-green trait and grain yield in elite sorghum hybrids grown in range of environments. Crop Science 52:1153–1161.

Jordan WR and **Sullivan CY.** 1982. Reaction and resistance of grain sorghum to heat and drought. Pages 131–412 *in* Sorghum in the eighties: proceedings of the International Symposium on Sorghum, 2–7 November 1981, ICRISAT, Patancheru, India. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Kamala V, Sharma HC, Manohar Rao D, Varaprasad KS and **Bramel PJ.** 2008. Wild relatives of sorghum as sources of resistance to sorghum shoot fly, *Atherigona soccata.* Plant Breeding 128:137–142.

Kassahun B, Bidinger FR, Hash CT and **Kuruvinashetti MS.** 2010. Stay-green expression in early generation sorghum [*Sorghum bicolor* (L.) Moench] QTL introgression lines. Euphytica 172(3):351–362. (doi: 10.1007/s10681-009-0108-0)

Khizzah BW, Miller FR and **Newton RJ.** 1993. Inheritance and heritability of heat tolerance in several sorghum cultivars during the reproductive phase. African Crop Science Journal 1:81–85.

Krishnamurthy L. 2010. Cultivar options for salinity tolerance in sorghum. Journal of SAT Agricultural Research 8. (ejournal.icrisat.org)

Krishnamurthy L, Serraj R, Hash CT, Dakheel AJ and **Reddy BVS.** 2007. Screening sorghum genotypes for salinity tolerant biomass production. Euphytica 156:15–24.

Linden J, Henk L and **Murphy V.** 1987. Preservation of potential fermentables in sweet sorghum by ensiling. Biotechnology and Bioengineering 30:860–867.

Ma JF, Ryan PR and **Delhaize E.** 2001. Aluminum tolerance in plants and the complexing role of organic acids. Trends in Plant Science 6:273–278.

Mace E and **Jordan D.** 2010. Location of major effect genes in sorghum (*Sorghum bicolor* (L.) Moench). Theoretical and Applied Genetics 121:1339-1356.

Magalhaes JV, Garvin DF, Wang Y, Sorrells ME and **Klein PE.** 2004. Comparative mapping of a major aluminum tolerance gene in sorghum and other species in the Poaceae. Genetics 167:1905–1914.

Magalhaes JV, Liu J, Guimaraes CT, Lana UGP and **Alves VMC.** 2007. A gene in the multidrug and toxic compound extrusion (MATE) family confers aluminum tolerance in sorghum. Nature Genetics 39:1156–1161.

Maman N, Lyon DJ, Mason SC, Galusha TD and **Higgins R.** 2003. Pearl millet and sorghum yield response to water supply in Nebraska. Agronomy Journal 95:1618–1624.

Nagaraj N, Reese JC, Tunistra MR, Smith CM, Amand PT, Kirkham MB, Kofoid KD, Campbell LR and **Gerald EW.** 2005. Molecular mapping of sorghum genes expressing tolerance to damage by green bug (Homoptera: Aphidae). Journal of Economic Entomology 98(2):595–602.

Obilana AB. 2004. Sorghum breeding research in Africa. *In* Sorghum genetic enhancement: research process, dissemination and impacts (Bantilan MCS, Deb UK, Gowda CLL, Reddy BVS, Obilana AB and Evenson RE, eds.). Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Obilana AB and **Reddy BVS.** 1996. Host-plant resistance to *Striga* in sorghum and pearl millet. Presented at ICRISAT Sector Review for *Striga* Control in Sorghum and Millet, ICRISAT-Bamako, 27–28 May 1996.

Paterson AH, Bowers JE, Bruggmann R, Dubchak I, Grimwood J, Gundlach H, Haberer G, Hellsten U, Mitros T, Poliakov A, Schmutz J, Spannagl M, Tang H, Wang X, Wicker T, Bharti AK, Chapman J, Alex Feltus F, Gowik U, Grigoriev IV, Lyons E, Maher CA, Martis M, Narechania A, Otillar RP, Penning BW, Salamov AA, Wang Y, Zhang L, Carpita NC, Freeling M, Gingle AR, Hash CT, Keller B, Klein P, Kresovich S, McCann MC, Ming R, Peterson DG, Mehboob-ur-Rahman, Ware D, Westhoff P, Mayer KFX, Messing J and **Rokhsar DS.** 2009. The *Sorghum bicolor* genome and the diversification of grasses. Nature 457:551–556.

Peacock JM, Soman P and **Jayachandran R.** 1993. Effects of high soil surface temperature on seedling survival in pearl millet. Experimental Agriculture 29:215–225.

Rao PS, Prakasham RS, Umakanth AV, Deshpande S, Ravikumar S and **Reddy BVS.** 2010. Pages 1–7 *in* Brown midrib sorghum – current status and potential as novel ligno-cellulosic feedstock of bioenergy (Srinivasa Rao, Prakasham RS and Deshpande S, eds.). Germany: Lap Lambert Academic Publishing Gmbh and Co KG.

Rao PS, Rao SS, Seetharama N, Umakanth AV, Sanjana Reddy P, Reddy BVS and **Gowda CLL.** 2009. Sweet sorghum for biofuel and strategies for its improvement. Information Bulletin No. 77. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 80 pp.

Reddy BVS, Ashok Kumar A, Ramesh S and **Sanjana Reddy P.** 2011. Breeding sorghum for coping with climate change. Pages 326–339 *in* Crop adaptation to climate change (Yadav SS, Redden B, Hatfield JL and Herman Lotze-Campen, eds.). Iowa, USA: John Wiley & Sons Inc.

Reddy BVS, Ashok Kumar A and **Sanjana Reddy P.** 2010. Recent advances in sorghum improvement research at ICRISAT. Kasetsart Journal (Natural Science) 44:499–506.

Reddy BVS, Ramesh S, Ashok Kumar A, Wani SP, Ortiz R, Ceballos H and **Sreedevi TK.** 2008. Bio-fuel crops research for energy security and rural development in developing countries. Bioenergy Research 1:248–258.

Reddy BVS, Ramesh S and **Longvah T.** 2005a. Prospects of breeding for micronutrients and carotene-dense sorghums. International Sorghum and Millets Newsletter 46:10–14.

Reddy BVS, Ramesh S and **Ortiz R.** 2005b. Genetic and cytoplasmic nuclear male sterility in sorghum. Plant Breeding Reviews 25:139–172.

Reddy BVS, Ramesh S and **Sanjana Reddy P.** 2009a. Genetic enhancement for drought tolerance in sorghum. Plant Breeding Reviews 31:189–222.

Reddy BVS and **Rangel Andres F.** 1999. Genotypes (G) and G×Environment (E) interaction in sorghum in acid soils of the oriental Llanos of Colombia. Pages 46–53 *in* Proceedings of the Workshop on A Research and Network Strategy for Sustainable Sorghum and Pearl Millet Production Systems for Latin America, 24–26 Nov 1998, Experimental Centre ‘LaLibertad’, Villavicencio, Meta, Colombia (Reddy BVS, CeballosHernan and Ortiz R, eds.). Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics; and Cali, Colombia: Centro Internacional de Agricultural Tropical.

Reddy BVS, Rangel Andres F, Iglesias Carlos A and **Bernal Jaime H.** 1999. Evaluation of sorghum and pearl millet for acid-soil tolerance in the oriental Llanos of Colombia. Pages 37–45 *in* Proceedings of the Workshop on A Research and Network Strategy for Sustainable Sorghum and Pearl Millet Production Systems for Latin America, 24–26 Nov 1998, Experimental Centre ‘LaLibertad’, Villavicencio, Meta, Colombia (Reddy BVS, CeballosHernan and Ortiz R, eds.). Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics; and Cali, Colombia: Centro Internacional de Agricultura Tropical.

Reddy BVS, Rao P, Deb UK, Stenhouse JW, Ramaiah B and **Ortiz R.** 2004. Global sorghum genetic enhancement processes at ICRISAT. *In* Sorghum genetic enhancement: research process dissemination and impacts (Bantilan MCS, Deb UK, Gowda CLL, Reddy BVS, Obilana AB and Evenson RE, eds.). Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 320 pp.

Reddy BVS, Seetharama N and **House LR.** 1987. Sorghums in the postrainy season. 1. Effect of irrigation and date of sowing on the grain and stover yields of diverse cultivars. Experimental Agriculture 24:31–36.

Reddy BVS, Sharma HC, Thakur RP and **Ramesh S.** 2006. Characterization of ICRISAT bred sorghum hybrid parents (Set I). International Sorghum and Millets Newsletter 47:1–21.

Reddy BVS, Sharma HC, Thakur RP, Ramesh S and **Ashok Kumar A.** 2007. Characterization of ICRISAT bred sorghum hybrid parents (Set II). International Sorghum and Millets Newsletter 48:1–123.

Reddy PS, Reddy BVS and **Ashok Kumar A.** 2009b. M 35-1 derived sorghum varieties for cultivation during the postrainy season. Journal of SAT Agricultural Research 7. (ejournal.icrisat.org)

Rees JM, Andersen D and **Irmak S.** 2006. Comparison of water use and crop water use efficiency of maize, sorghum, and soybean in Nebraska. Agricultural Water Management 83(1–2):135–143.

Rooney WL. 2000. Genetics and cytogenetics. Pages 261–307 *in* Sorghum: origin, history, technology and production (Smith CW and Frederiksen RA, eds.). New York, USA: Wiley.

Rooney WL. 2004. Sorghum improvement – Integrating traditional and new technology to produce improved genotypes. Advances in Agronomy 83:38–110.

Rooney WL, Blumenthal J, Bean B and **Mullet JE.** 2007. Designing sorghum as a dedicated bioenergy feedstock. Biofuels, Bioproducts & Biorefining 1:147–157.

Rosenow DT, Quisenberry JE, Wendt CW and **Clark LE.** 1983. Drought tolerant sorghum and cotton germplasm. Agricultural Water Management 7:207–222.

Schertz KF. 1994. Male sterility in sorghum: Its characteristics and importance. Pages 35–37 *in* Use of molecular markers in sorghum and pearl millet breeding for developing countries. Proceedings of the International Conference on Genetic Improvement, ODA Plant Science Research Conference, 29 March to 1 April 1993, Norwich, UK (Witcombe JR and Duncan RR, eds.). UK: Overseas Development Administration.

Setimela PS, Andrews DJ and **Eskridge KM.** 2007. Genetic evaluation of seedling heat tolerance in sorghum. African Crop Science Journal 15(1):33–42.

Sharma HC. 2006. Integrated pest management research at ICRISAT: Present status and future priorities. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 43 pp.

Sharma HC and **Franzmann BA.** 2001. Host plant preference and oviposition responses of the sorghum midge, *Stenodiplosis sorghicola* (Coquillett) (Dipt., *Cecidomyiidae*) towards wild relatives of sorghum. Journal of Applied Entomology 125:109–114.

Sharma HC, Reddy BVS, Dhillon MK, Venkateswaran K, Singh BU, Pampapathy G, Folkerstma R, Hash CT and **Sharma KK.** 2005. Host plant resistance to insects in sorghum: Present status and need for future research. International Sorghum and Millets Newsletter 46:36–43.

Sharma HC, Taneja SL, Kameswara Rao N and **Prasada Rao KE.** 2003. Evaluation of sorghum germplasm for resistance to insect pests. Information Bulletin no. 63. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 184 pp.

Sharma HC, Taneja SL, Leuschner K and **Nwanze KF.** 1992. Techniques to screen sorghums for resistance to insects. Information Bulletin no. 32. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 48 pp.

Sharma K, Pattanaik AK, Anadan S and **Blümmel M.** 2010. Food-feed crop research: A synthesis. Animal Nutrition and Feed Technology 10S:1–10.

Sharma R, Thakur RP, Senthilvel S, Nayak S, Reddy SV, Rao VP and **Varshney RK.** 2011. Identification and characterization of toxigenic Fusaria associated with sorghum grain mold complex in India. Mycopathologia 171:223–230.

Singh SD and **Bandyopadhyay R.** 2000. Grain mold. Pages 38–40 *in* Compendium of sorghum diseases (Frederiksen RA and Odvody GN, eds.). Second edition. St. Paul, MN, USA: The American Phytopathological Society.

Singh SP. 1977. Breeding grain sorghum for cold tolerance. Presented at the International Sorghum Workshop held at ICRISAT during 6–12 March 1977, Hyderabad, India.

Sipos B, Reczey J, Somorai Z, Kadar Z, Dienes D and **Reczey K.** 2009. Sweet sorghum as feedstock for ethanol production: enzymatic hydrolysis of steam-pretreated bagasse. Applied Biochemistry and Biotechnology 153:151–162.

Stephens JC and **Holland PF.** 1954. Cytoplasmic male sterility for hybrid sorghum seed production. Agronomy Journal 46:20–23.

Tao YZ, Hardy A, Drenth J, Henzell RG, Franzmann BA, Jordan DR, Butler DG and **McIntyre CL.** 2003. Identifications of two different mechanisms for sorghum midge resistance through QTL mapping. Theoretical and Applied Genetics 107:116–122.

Thakur RP, Reddy BVS and **Mathur K.** 2007. Screening techniques for sorghum diseases. Information Bulletin No. 76. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 92 pp.

Thomas GL and **Miller FR.** 1979. Base temperature for germination of temperate and tropically adapted sorghum. Page 24 *in* Proceedings of Biennial Grain Sorghum Research and Utilization, Feb 28–Mar 2, 1979. Lubbock, Texas, USA: Grain Sorghum Producers Association.

Vadez V, Deshpande SP, Kholova J, Hammer GL, Borrell AK, Talwar HS and **Hash CT.** 2011. Staygreen QTL effects on water extraction and transpiration efficiency in a lysimetric system: Influence of genetic background. Functional Plant Biology 38:553–566.

Vaksmann M, Traore SB and **Niangado O.** 1996. Le photopériodisme des sorghosafricains. Agricultural Development 9:13–18.

Wilson GL, Raju PS and **Peacock JM.** 1982. Effect of soil temperature on seedling emergence in sorghum. Indian Journal of Agricultural Science 52:848–851.

Zhuang P, Yang QW, Wang HB and **Shu WS.** 2007. Phytoextraction of heavy metals by eight plant species in the field. Water, Air and Soil Pollution 184:235–242.