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Review Article

Recent Advances in Sorghum Improvement Research at ICRISAT

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ABSTRACT

Sorghum (*Sorghum bicolor* (L.) Moench) is one of the most important cereal crops widely grown for food, feed, fodder, forage and fuel in the semi-arid tropics of Asia, Africa, the Americas and Australia. In spite of rapid decreases in the area of sorghum in Asia, the production level has been maintained owing to the adoption of high yielding hybrids. Though impressive progress has been made in improving the sorghum cultivars for resistance to biotic and abiotic challenges, grain mold, shoot fly and terminal drought haunt sorghum growers across Asia. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and national programs in India, China and Thailand are working on genetic enhancement of sorghum for high yield, grain mold and shortly resistance. In addition, the trait focus at ICRISAT includes post rainy season adaptation encompassing terminal drought tolerance, genetic enhancement for high Fe and Zn contents in grain and sweet stalk traits for ethanol and animal feed production. Genetic and cytoplasmic diversification of hybrid parents for key traits is critical for sustaining the productivity across different production systems. The grain and stover quality need special attention in sorghum improvement research to enhance the market value of sorghum. A brief description is provided of the progress made at ICRISAT in partnership with national programs in recent years in these areas of sorghum genetic enhancement.

Keywords: sorghum, genetic enhancement, hybrid

INTRODUCTION

Sorghum is the fifth most important cereal crop and is the dietary staple of more than 500 million people in more than 30 countries. It is grown on 42 million ha in 98 countries in Africa, Asia, Oceania and the Americas. Nigeria, India, USA, Mexico, Sudan, China and Argentina are the major sorghum producers in the world (Available from: http://faostat.fao.org/site/567/default.aspx#ancor [cited 2009 February 3]). Grain is mostly used for food (55%), consumed in the form of flat breads and porridges (thick or thin) and is an important feed grain (33%), especially in the Americas. Stover is an important source of dry fodder for dry season maintenance rations for livestock, especially in Asia.

The sorghum area in Asia decreased from 23 million ha to 11 million ha between the early 1970s and 2007 (Figure 1). However, production increased from 19 million t in the early 1970s to 21 million t in the late 1970s, but decreased

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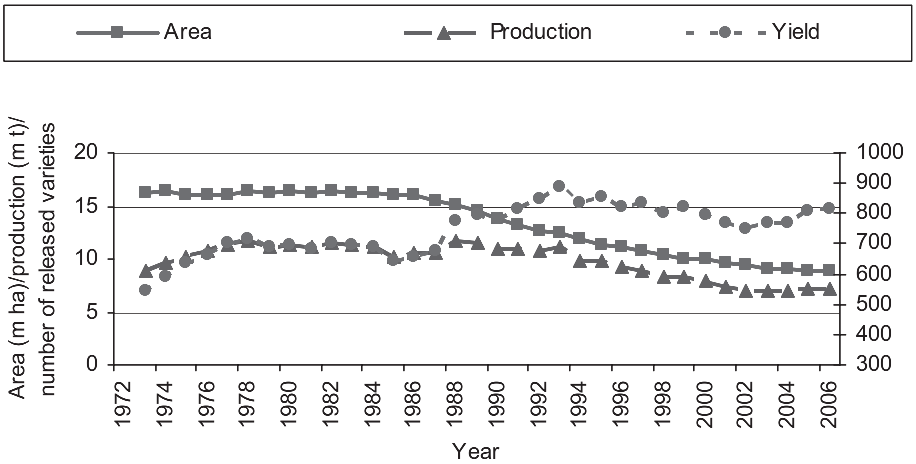

Figure 1 Three-year moving average for sorghum area, production and yield based on ICRISAT-bred material in Asia.

thereafter to 11 million t in 2006. Yield has increased from 800 kg ha^{-1} in the early 1970s to 1,000 kg ha^{-1} in 2006.

In India, sorghum production increased from 9 million t in the early 1970s to 12 million t in the early 1980s and was maintained at this level for over a decade, until the early 1990s, when there was a sharp decrease to 7.2 million t. Despite the decrease in sorghum area over the years, the production level during 2006 was almost similar to that in early 1970s, which can be largely attributed to the adoption of improved varieties and hybrids. In 2006–07, India's sorghum was grown on 8.7 million ha (20% of the world's sorghum area), with 3.9 million ha in the rainy season and 4.8 million ha in the post rainy season. In China and Thailand, sorghum is grown on 0.56 and 0.03 million ha, respectively. Productivity in India is 1,345 kg ha^{-1} in the rainy season and 480 kg ha^{-1} in the post rainy season, while in China, it is 4,636 kg ha^{-1} and in Thailand, it is 1,735 kg ha^{-1}.

ICRISAT is a major repository of germplasm, with a total of 36,774 accessions from 90 countries (Reddy *et al.*, 2008). The existing collections represent about 80% of the variability present in the crop (Eberhart *et al.,* 1997). Since the establishment of ICRISAT in 1972, germplasm sources have been screened and utilized in the development of high yielding male-sterile lines (CK 60, 172, 2219) and restorers (IS 84, IS 3691, IS 3541). They have been valuable sources for incorporating shoot fly and stem borer resistance (IS 1082, IS 2205, IS 5604, IS 5470, IS 1054, IS 18432, IS 18417, IS 18425), midge resistance (DJ 6514, IS 3443), multiple disease resistance (IS 3547, IS 14387,), *Striga* resistance (IS 18331, IS 2221), drought tolerance (IS 12611, IS 69628), high lysine content (IS 11167, IS 11758), stalk sweetness (IS 20963, IS 15428), forage quantity and quality (IS 1044, IS 1059) and salinity tolerance (IS 164, IS 19604) (Reddy *et al.*, 2008).

Over the years sorghum improvement research at ICRISAT, Patancheru has developed more than 680 A-/B-pairs and more than 880 R-lines with focused selection for different traits [high yield, large grain, biotic stress resistance (shoot fly, midge and grain mold) and abiotic stress tolerance (drought and salinity), grain micronutrient (Fe and Zn) density and sweet stalk traits] for use as parents in hybrid development. In some cases, the resistance sources *per se* were directly converted into male-sterile lines. Of late, cytoplasmic and racial diversification have provided a major thrust in sorghum improvement.

Considerable progress has been made in developing techniques to screen for resistance to four insect pests, five diseases and drought. Apart from identification of resistant germplasm sources (particularly shoot fly and midge, and grain mold), considerable information has also been generated on the mechanisms and inheritance of resistance to insects such as shoot fly (*Atherigona soccata*), stem borer (*Chilo partellus*), shoot bug (*Perigrinus maidis*), aphid (*Melanaphis sacchari*), midge (*Stenodiplosis sorghicola*) and head bug (*Calocoris angustatus*) (Sharma *et al.,* 2008). A glossy trait at the seedling stage to select for resistance to shoot fly, short and tight glumes to select for midge resistance and long glumes to select for head bug resistance have been identified as marker traits. Similarly, grain hardiness, flavan-4-ols in the grain and loose panicles help in reducing damage by grain molds (Thakur *et al.,* 2006). At ICRISAT, sorghum research on the development of hybrid parents is summarized in Gowda *et al.* (2006). Some of the more recent advances in sorghum improvement research at ICRISAT, Patancheru, India are summarized below.

Hybrid parents improvement for rainy season adaptation

Sorghum grain produced in the rainy season in India and other Asian countries is not always preferred for human consumption, if the grain gets moldy, especially when grain development is matched with high rainfall. Most of the mold-affected grain is used as poultry feed or for industrial purposes. However, rainy season stover is very important as animal feed. The research target for India is to develop hybrid parents that yield grain 15 to 20% higher than the commercial hybrid CSH 18 (4.5 t ha^{-1}) and produce fodder amounts that are about 20% higher compared to CSH 18 (13 t ha^{-1}).

Grain and fodder yields, height and maturity

In addition to dual-purpose types, the major focus has been on hybrid parents to develop dwarf hybrids for mechanized harvesting and fodder-purpose hybrids with high recovery ability (for multi-cut forage purpose) over a range of maturation periods (70 to 75 d to 50% flowering). The focus is on fodder varieties amenable to both single- and multi-cutting.

Considering that the *Caudatum* race has been exploited extensively for diversification of hybrid parents in India and elsewhere, since 2000, at ICRISAT, Patancheru, greater emphasis has been given to the use of other races (*durra, guinea, and feterita*) for the development of hybrid parents. According to Schertz and Pring (1982) and Schertz *et al.* (1989), three CMS groups (Indian, Kansas and Texas) are predominant in sorghum. In addition to the 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 (Nagur, 1971; Rao *et al.,* 1984; Worstell *et al.,* 1984; Xu *et al.,* 1995; Schertz *et al.,* 1997). Considering restoration frequency, the development of high yielding male-sterile lines using A_1 restorers, and hybrid performance, comparable A_1 and A_2 CMS effects for grain yield and resistance to shoot fly and grain mold, it is advantageous to use the A_2 CMS system among the alternate cytoplasms available. As a result of concerted efforts, a total of 85 new race-specific A-/B-lines (39 A_1 and 46 A_2 CMS-systems based) have been developed (Table 1).

The grain yield potential of some of the best *durra* bold grain B-lines (A_1) are significantly better than the control 296B, with a comparable grain size (Table 2).

Grain mold tolerance. Grain mold is one of the most important biotic challenges to address in growing rainy season sorghum. Both greenhouse and field screening techniques have been standardized by ICRISAT and partners for

Table 1 Race-specific A-/B-lines developed at ICRISAT, Patancheru since 2000.

Race	Number of A-/B-lines	
	A_1	A_2
Durra bold grain	23	28
Caudatum	6	4
Guinea	10	5
Feterita	—	9
Total	39	46

Table 2 Grain yield potential of best *durra* bold grain B-lines (A_1) during rainy season 2003 at ICRISAT, Patancheru, India.

B-line	Time to 50% flowering	Plant height (m)	Grain yield (t ha^{-1})	100-seed mass (g)
SP 58441	67	1.9	3.3	2.2
SP 58427	67	1.6	2.7	2.1
SP 58415	74	1.9	2.3	2.7
SP 58435	70	1.7	2.2	2.2
SP 58429	68	1.6	2.2	2.2
SP 58437	67	2.0	2.2	2.3
Control 296B	73	1.3	1.0	2.1
Trial mean	72	1.6	1.4	2.0
SE±	0.97	0.04	0.14	0.13
CD (0.05)	2.75	0.12	0.39	0.38

effective screening for grain mold resistance (Thakur *et al.,* 2006) and new sources of resistance have been identified for use in breeding programs. Bandyopadhyay *et al*. (1988) identified 156 grain mold tolerant/resistant lines from screening 13,000 photoperiod-insensitive sorghum germplasm lines. Resistance has been found mostly in colored-grain sorghums with and without tannins and also in very few white-grain sorghums (Bandyopadhyay *et al.,* 1988, 1998; Thakur *et al.,* 2006). Using the grain mold resistant white-grained germplasm sources, a couple of hybrid parents and varieties have been developed (Bandyopadhyay *et al.,* 1988). PVK 801 is one such example developed by Marathwada Agricultural University, India in partnership with ICRISAT, which is quite popular in the rainy season in India. Recent research has indicated that it is possible to breed for grain mold tolerant hybrids with grain yield comparable to popular high grain yielding hybrids.

Shoot fly resistance. Shoot fly is a major problem in late-sown crops in regions or years with erratic rainfall. At ICRISAT, the interlard-fishmeal technique (Nwanze, 1997) has been used to develop shoot fly resistant seed parents. While breeding for shoot fly resistance, resistant sources with a desirable agronomic background (ICSV 702, ICSH 705, ICSV 708, PS 21318, PS 30715-1 and PS 35805), as well as other sources (IS 18551) were used. Following a trait-based pedigree breeding approach, a large number of shoot fly resistant seed parents for both the rainy season (ICSA//B-409 to ICSA-/B-436) and post rainy season (ICSA-/B-437 to ICSA-/B-463) were developed (Reddy *et al.*, 2005). All these B-lines have been designated and their characteristics are available from the ICRISAT website at: http// www.icrisat.org/ text/research/grep/homepage/ sorghum/breeding/main.htm, [cited 2009 February 3]. More recently, new sources of resistance (IS 923, IS 1057, IS 1071, IS 1082, IS 1096, IS 2394, IS 4663, IS 5072, IS 18369, IS 4664, IS 5470 and IS 5636) have been used in the development of shoot fly resistant hybrid parents.

Hybrid parents with post rainy season adaptation

Post rainy sorghum is crucial for food and fodder security in drought-prone areas of the Maharashtra, Karnataka and Andhra Pradesh states of India (Anonymous, 2001), as there is no alternative cereal grown during this season, which receives only 8% of the annual rainfall. Due to excellent grain quality, post rainy sorghum crops are used mostly for food. The grain productivity of post rainy sorghum in India is very low, as much of the cultivated area is under landraces that are poor in grain yield. Drought stress is a major production constraint in the post rainy season, as sorghum is grown under receding soil moisture after the cessation of the rainy season. Low levels of heterosis for grain yield were observed in hybrids in the post rainy season. Therefore, most farmers use either landraces or open pollinated varieties (OPVs) for post rainy season sowing. Although some hybrids have been released by the Indian national program, they are not popular with farmers, as these hybrids lack the terminal drought tolerance, shoot fly resistance and grain quality traits (pearly white, lustrous globular grain) of M 35-1, the popular post rainy season adapted variety. Considering that low temperature tolerance early in the season, terminal drought tolerance, and grain quality traits are critical for the post rainy season crop, ICRISAT scientists are engaged in developing hybrid parents involving several landraces adapted to the post rainy season (M 35-1, Giddi Maldandi, DSH 128, E 36-1, Barsizoot, Dagadi Sholapur, Dagadi local, Amaravathi local, M 35-1 selection bulks) and elite varieties and B-lines with good grain quality traits. Several elite selections were made, including nine BC_4s (with A_1 cytoplasm) for high yield and large grain during the 2007 post rainy season, based on grain size and luster and agronomic desirability. Those selections with desirable agronomic and grain quality traits that matched with M 35-1 are under conversion into A-lines (A_1). In addition, Giddi Maldandi, which is a restorer on A_1, is being converted into A_2, A_3 and A_4-based A-lines.

Grain micronutrient density

Biofortification (increasing the grain Fe and Zn status through genetic means) complements the on-going efforts to address hidden malnutrition in sub-Saharan Africa and South Asia. Biofortification is one of the cheapest and most sustainable options to combat malnutrition in predominantly sorghum-eating populations. Based on sorghum grain consumption levels, nutrient availability and nutrient retention, ICRISAT targeted 70 ppm for Fe and 40 ppm for Zn contents in grain for the populations that predominantly depend on cereals for their nutrient requirements. ICRISAT undertook screening of core germplasm accessions to identify lines with high Fe and Zn. A total of 2,267 core germplasm accessions were screened and promising donors identified under the HarvestPlus Challenge Programme (Table 3). ICRISAT is developing the hybrid parents for high grain Fe and Zn contents, in order to enhance the dissemination of hybrids with high micronutrient density. Twenty B-lines with Fe content over 45 ppm and 13 B-lines with Zn content over 32 ppm have been identified. Assessing the grain Fe and Zn contents of commercial sorghum hybrids is underway.

Sweet sorghum for ethanol and animal feed

Sweet sorghum is a SMART biofuel crop that yields food, fodder and fuel. ICRISAT, under its BioPower strategy, is working on sweet sorghum improvement for bioethanol production without unduly compromising the food or fodder use of the crop. Ethanol feedstock CSH 22 SS, the first sweet sorghum hybrid released in India, was based on the ICRISAT-bred female parent ICSA 38. Strategic research under the Indian national program by ICRISAT indicated that ethanol production in India using sweet sorghum is cost-effective and its cultivation gives 23% additional income to farmers compared to the grain sorghum. There are minimal food-fuel tradeoffs in sweet sorghum but season-specificity exists. Hybrids are cultivar options, as hybrids are high-yielding, flower early and are less photoperiod-sensitive compared to the varieties. ICRISAT, along with its partners, is working on the development of the sweet sorghum ethanol value chain to increase the period of feedstock availability and supply chain management for commercial ethanol production. Sweet sorghum, when fed directly as forage, was found to have high daily intake and higher digestibility in large ruminants (cows and buffaloes). No significant differences were observed in the intake or body weight of animals when bagasse and stripped leaves feed blocks were used to feed the ruminants, indicating that sweet sorghum bagasse (after juice extraction) can be used as animal feed without chemical or physical upgrading (Table 4) (Blummel *et al.,* 2009).

Table 3 Germplasm lines with grain Fe content over 90 ppm and/or grain Zn content over 50 ppm evaluated in sorghum core germplasm set 2 collection, 2006-07 post rainy season, ICRISAT-Patancheru, India.

IS No.	Fe (ppm)	Zn (ppm)	Origin	Race
3106	192.3	60.3	USA	*Bicolor*
32	184.5	44.1	USA	*Bicolor*
12805	124.2	46.8	Turkey	*Bicolor*
12	106.8	41.7	USA	*Bicolor*
12600	103.2	52.6	Zambia	*Bicolor*
32163	95.6	36.6	Yemen, Republic of Yemen	*Durra-caudatum*
12759	54.2	55.2	India	*Durra-bicolor*
3875	76.0	52.6	Mali	*Guinea*
PVK 801 (Control)	41.2	16.2	High yielding variety rich in grain Fe and Zn content	

Table 4 Nitrogen, neutral detergent fiber (NDF), *in vitro* digestibility (all in % of dry matter), mega joule (MJ) of metabolizable energy content, voluntary feed intake and changes in live weight in bulls fed: 1) marketed commercial sorghum stover-based feed block (CFB); 2) experimental sweet sorghum bagasse/stripped leaves-based feed block (SLB); and 3) sorghum stover of the type used in the CFB.

Diets	Nitrogen (%)	NDF (%)	Iv Dig. (%)	ME (MJ/kg)	Intake (kg/d)	Intake (g/d/kg LW)	Weight changes (kg/d)
CFB	1.81^{a}	56.1^{a}	57.5^{a}	8.21^{a}	7.31^{a}	35^{a}	0.82^{a}
SLB	1.65^{b}	56.2^{a}	54.6^{b}	7.77^{b}	7.52^{a}	37^{a}	0.73^{a}
Sorghum stover	0.45^{c}	70.2^{b}	50.5^{b}	7.30^{b}	2.31^{b}	13^{b}	-0.38^{b}

Note: Different superscripts in columns denote significant differences ($P < 0.05$).

Future plans

In addition to the biotic and abiotic challenges, climate change is expected to influence the sorghum area and its importance globally. With the current level of greenhouse gas emissions and the associated temperature rise, the areas suitable for sorghum are likely to increase by 9% globally, but many areas currently suitable for sorghum will be lost. Increased temperature makes sorghum crops mature early. Considering all these points, crop improvement research in sorghum needs to be oriented towards genetic and cytoplasmic diversification for high yield and large grain, shoot fly and grain mold resistance, drought and salinity tolerance, post rainy season adaptation, sweet stalk traits and grain micronutrient density. Grain and stover quality needs special attention to enhance the market value.

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