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Scientific Research

Recent Advances in Sorghum Genetic Enhancement Research at ICRISAT

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ABSTRACT

Sorghum 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. The global sorghum areas remained static as the increased area in Africa compensated the area loss in Asia. Inspite of rapid decline in sorghum area in Asia due to competition from other remunerative crops, sorghum grain production levels have not declined at the same rate owing to adoption of high yielding hybrids. Though impressive gains have been made in improving productivity levels, biotic and abiotic challenges such as shoot fly, stem borer, grain molds, and terminal drought stress continue to haunt the sorghum growers across the world. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the respective national programs are working on genetic enhancement of sorghum for high yield; shoot fly, and grain mold resistance, and sweet stalk traits. In addition, research focus at ICRISAT also includes adaptation to postrainy season, terminal drought tolerance, and increasing micronutrient contents (Fe and Zn) in grain. Genetic and cytoplasmic diversification of hybrid parents and varieties for key traitsis critical for sustaining the productivity gains. The grain and stover quality requirements of different market segments needs special attention in sorghum improvement research to enhance its market value. This paper analyses the progress made in sorghum improvement research at ICRISAT in partnership with national programs in recent years and the way forward.

***Keywords**: ICRISAT, Sorghum, Genetic Enhancement, Grain Yield, Shoot Fly, Grain Mold, Drought, Biofortification*

1. Introduction

Sorghum is fifth most important cereal crop globally and is the dietary staple of more than 500 million people in 30 countries. It is grown on 40 m ha in 105 countries of Africa, Asia, Oceania and the Americas. Africa and India account for the largest share (> 70%) of global sorghum area whileUSA, India, Mexico, Nigeria, Sudan and Ethiopia are the major sorghum producers (http://faostat.fao.org/site/567/default.aspx#ancor verified on July 4, 2011). It is the third most important grain crop in U.S. Other sorghum producing countries include Australia, Brasil, Argentina, China, Burkina Faso, Mali, Egypt, Niger, Tanzania, Chad and Cameroon. Sorghum grain is used mostly for food purposes (55%), consumed in the form of flat breads and porridges (thick or thin); stover is an important source of dry season maintenance rations for livestock, especially in drylands; it is also an important feed grain (33%), especially in the Americas [1].

Sorghum area, production and productivity trends indicate that, globally sorghum area increased from 45 m·ha in 1970s to 51 m·ha in 1980s. Later on, there was a fluctuation by 4 to 10 m·ha in area in the next two decades but reached to 40 m·ha by 2009. The productivity increased from 1200 $kg \cdot ha^{-1}$ in 1970s to 1400 $kg \cdot ha^{-1}$ in 2009. Adoption of improved sorghum cultivars and management practices contributed to the productivity gains though large differences exist in different parts of the world for sorghum productivity (**Figure 1**) [2].

Sorghum is a self-pollinating, diploid (2n = 2x = 20) with a genome, about 25% the size of maize orsugarcane. It is a C4 plant with higher photosynthetic efficiency and higher abiotic stress tolerance [3,4]. Its small genome (730 Mb) makes sorghum an attractive model for functional genomics of C4 grasses. Drought tolerance makes sorghum especially important in dry regions such as northeast Africa (its center of diversity), India and the southern plains of the United States [5]. Genetic variation

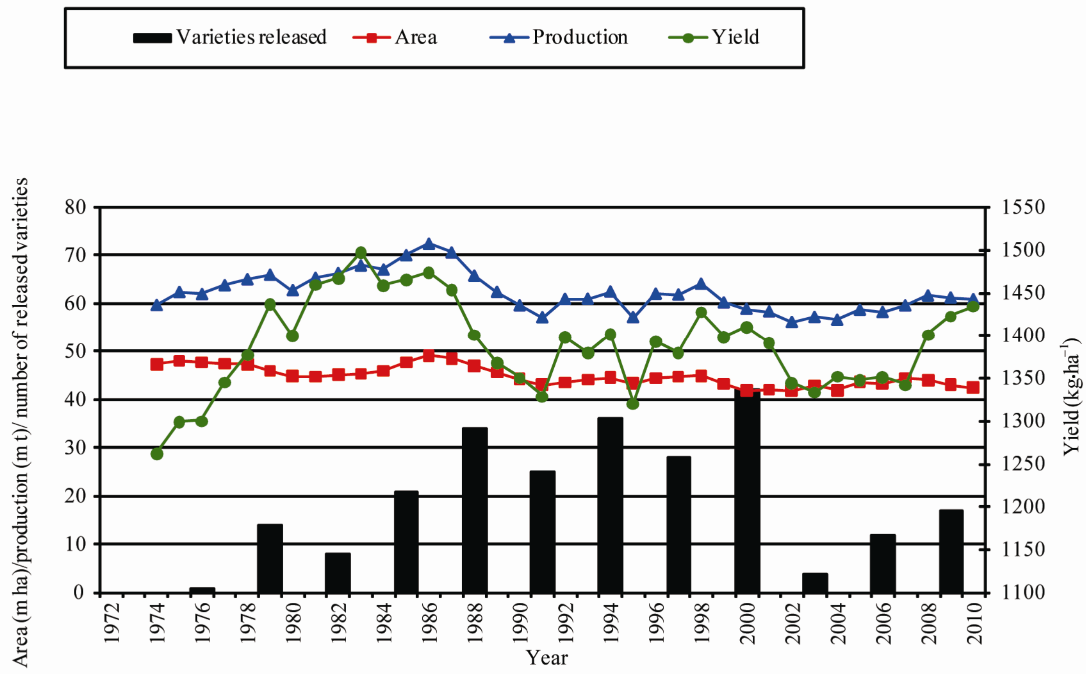

Figure 1. Three-year moving average for sorghum area, production, yield; and number of released varieties (3-years total) based on ICRISAT-bred material globally.

in the partitioning of carbon into sugar stores versus cell wall mass, and in perenniality and associated features such as tillering and stalk reserve retention, make sorghum an attractive system for the study of traits important in perennial cellulosic biomass crops [6]. Its high level of inbreeding makes it an attractive association genetics system. Sorghum is one among the climate resilient crops that can better adapt to climate change conditions [2,7].

ICRISAT has a global mandate for sorghum improvement research and physical mandate of semi-arid tropics (SAT) for enhancing the livelihoods of poor [8]. The total sorghum growing areas can be divided in to eight major research domains [9].

2. Sorghum Research Domains (SRDs)

Of the total 40 m ha global sorghum area, the agro-ecologies, growing conditions and the market requirements are quite different necessitating crop improvement for various adaptations, different uses and market preferences. Sorghum research activities at different locations over the years were conducted under the implicit assumption of eight research domains delineated as homogeneous eco-regions in terms of soil and climatic conditions regardless of national boundaries [9]. **Table 1** summarizes the characteristics of these sorghum research domains (SRDs) across the world. These domains are: wide adaptability (SRD I), dual purpose with specific adaptability (SRD II), dual purpose with fodder emphasis (SRD III), forage sorghum (SRD IV), early-sown postrainy sorghum (SRD V), late-sown postrainy sorghum (SRD VI), irrigated sorghum (SRD VII) and extreme altitude sorghum (SRD VIII).

ICRISAT has one of the largest collections of global sorghum germplasm with > 36,000 accessions in its gene bank. These accessions are maintained under short-term and long-term storage conditions and shared with research organizations globally. ICRISAT and National Agricultural Research Systems (NARS) across the sorghum growing areas are working on sorghum genetic enhancement for traits of global and regional importance. The target materials had been open-pollinated varieties in Africa whereas hybrids and hybrid parents for rest of the world. Hybrid sorghum is gradually picking up in Africa [11]. Exploitation of global germplasm accessions through systematic crop improvement programsto a large extent has contributed to development of large number of sorghum cultivars. The germplasm and improved materials developed at ICRISAT are shared with public sector and private sector partners across the globe. For e.g. during 2010, ICRISAT sent a total of 3275 seed samples of hybrid seed parents/breeding lines to 21 countries. India received 2375 samples, followed by Nigeria and other countries. Of the 2375 samples supplied in India, 888 samples were sent to public sector scientists, 1380 samples to private sector scientists and the remaining 107

Table 1. Characteristics of sorghum research domains.

Domains	Production system characteristics	Major constraints	Locations
SRD I (wide adaptability)	Rainy season, multi-purpose grain, stalk, fodder (fodder emphasis). Wide adaptability (June-August sowing)	Grain mold, shoot fly and head bug	West Africa (southern tier), India (Tamil Nadu, Southern Karnataka, Andhra Pradesh)
SRD II (dual purpose and specific adaptability)	Rainy season, dual purpose (grain and fodder). Specific adaptability (June sowing). Medium- to late-maturing types	Stem borer, grain mild, midge, shoot fly and drought	East and Southern Africa, India (Andhra Pradesh, Northern Karnataka, Maharashtra, Madhya Pradesh, Gujarat), Latin America (some areas)
SRD III (dual purpose, fodder emphasis)	Rainy season, dual purpose (fodder emphasis). Early maturing	Shoot fly and stem borer	West Africa (northern tier), East Africa (Yemen, Somalia), India (Eastern Rajasthan), Latin America (some areas), China, Iran
SRD IV (forage sorghum)	Rainy season, forage type (thin stalk, tillering) and late maturing	Stem borer and leaf diseases	India (Northern Gangetic plains), Pakistan
SRD V (early sown post rainy)	Postrainy (early sown-before October). Bold grain types, dual purpose	Shoot fly, charcoal rot, aphids	India (South Andhra Pradesh, South Karnataka)
SRD VI (later sown postrainy)	Postrainy season (late sown-mid/late October). Bold grain, photoperiod sensitivity required, temperature insensitive	Shoot fly, charcoal rot, drought (shallow soils)	East Africa (Ethiopia, Sudan), India (Gujarat, South Maharashtra, North Karnataka)
SRD VII (irrigated)	Irrigated sorghum		Iran, Egypt, Wad Medani (Sudan)
SRD VIII (extreme altitude)	Others		High altitude: China and low altitude: Indonesia, Brazil, Ecuador, Venezuela

Source: [9-10].

samples to farmers and NGOs. Fourteen sets of sweet stalk trials consisting of 423 entries were sent for evaluation in India, Philippines, Israel, Mexico, Mozambique and Mali. Further seed samples were also sent to Brazil, Mexico, U.S.A, Australia and China. During the period 1976 to 2010, a total of 242 sorghum cultivars were released globally using the ICRISAT-bred sorghum material by private and public sector organizations including National Agricultural Research System (NARS) partners across the world (**Figure 1**). ICRISAT is a major repository of global germplasm collection with a total of 36,774 accessions from 90 countries [12] and the existing collections represent about 80% of the variability present in the crop [13]. Since its establishment in 1972, germplasm sources at ICRISAT 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 incorporateing shoot fly and stem borer resistance (IS 1082, IS 2205, IS 2312, IS 5604, IS 5470, IS 1054, IS 18432, IS 18417, IS 18425), midge resistance (DJ 6514, IS 3443), multiple disease resistance (IS 3547 and IS 14387), *Striga* resistance (IS 18331, IS 2221), drought tolerance (IS 12611 and 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) [12].

Sorghum improvement research program at ICRISAT-Patancheru, India over the years developed more than 680 A-/B-pairs and more than 880 R-lines which were trait specific [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 [14]. In some cases, the resistance sources *per se* were directly converted into male-sterile lines. Of late, cytoplasmic diversification and racial diversification has been given major thrust in sorghum improvement [1].

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 (*Peregrinus maidis*), aphid (*Melanaphis sacchari*), midge

(*Stenodiplosis sorghicola*) and head bug (*Calocoris angustatus*) [15]. Glossy trait at the seedling stage to select for resistance to shoot fly, short and tight glumes for midge resistance and long glumes for head bug resistance have been identified as marker traits. Similarly grain hardness, flavan-4-ols in the grain and loose panicles helps in reducing damage by grain molds [16]. While diversifying sorghum hybrid parents, both geographical and racial diversity were successfully captured. The variation in *caudatum* race being captured for a long time now and more emphasis is given to exploit *guinea* and *durra* races in recent years. Efforts are underway to diversify hybrid parents for shoot fly resistance (SFR) and grain mold resistance (GMR) by introgressing genes from new and diverse sources of resistant germplasm lines, *guinea* race in particular. Postrainy season adapted sweet sorghum parental lines development is in progress. Some of the more recent advances in sorghum improvement research at ICRISAT-Patancheru, India are summarized below:

3. Hybrid Parents Improvement for Rainy Season Adaptation

Sorghum grain produced in rainy season in India and other Asian countries is not always preferred for human consumption if grain gets molded especially when high rain fall occurs during grain development stage. Most of the mold-affected grain goes for poultry feed or for industrial uses. However, rainy season stover is important as animal feed. The research targets are fixed based on the crop utilization and the performance of popular checks in a given ecology. For e.g. 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 $t \cdot ha^{-1}$) and fodder about 20% higher compared to CSH 18 (13 $t \cdot ha^{-1}$).

3.1. Grain and Fodder Yields, Height and Maturity

In addition to dual-purpose types, hybrid parents to develop dwarf hybrids for mechanized harvesting and fodder purpose hybrids with high recovery ability (for multicut forage purpose) in a range of maturity (70 to 85 days to 50% flowering) has been the major focus. Focus is also there on forage varieties amenable for both single- and multi-cuts to meet the needs of farmers and dairy Industry.

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. Availability of cytoplasmic-nuclear male sterility (CMS) system, higher heterosis % 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 [17-23]. 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. This has been a major priority in hybrid seed parents' development at ICRISAT. 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 in last 10 years (**Table 2**).

The grain yield potential of some of the improved B-lines (A_2) was significantly higher than the control 296B (**Table 3**).

3.2. Shoot Fly Resistance

Shoot fly is a major problem in late-sown crop in regions/years with erratic rains. At ICRISAT, interlard-fishmeal technique has been used for screening against shoot fly to develop shoot fly resistant hybrid parents [24]. While breeding for shoot fly resistance, resistant sources in 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 in crossing programs. Following trait-based pedigree breeding approach, a large number of shoot fly resistant seed parents for both rainy season (ICSA-/B-409 to ICSA-/B-436) and post-rainy season adaptation (ICSA-/B-437 to ICSA-/B-463) were developed [25]. All these B-lines have been designated and characterized as per the Distinctness, Uniformity and Stability (DUS) test guidelines and their characteristics are available at ICRISAT website: http//www.icrisat.org/text/research/grep/homepage/sorghum/breeding/main.htm, verified on 5 July 2011 [14]. More recently, new sources of resistance IS 923, IS 1057,

Table 2. The number of race-specific A-/B-lines developed at ICRISAT, Patancheru, India after year 2000.

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

Table 3. Performance of sorghum advanced B-lines (A_2-cytoplasm based) at ICRISAT, Patancheru during 2010 rainy season.

S. No	Origin	Days to 50% flowering	Plant height (m)	Panicle grain mold rating score (1 = no mold, 9 ≥ 90%)	Grain yield ($t \cdot ha^{-1}$)	100-seed weight (g)
1	SP 09 27915	76	2	2.7	2.77	2.7
2	ABT 6	74	1.9	2	2.23	2.6
3	SP 09 27943	79	2	2.3	2.06	2.3
4	SP 09 27917	73	2	3	1.88	2.4
5	SP 09 27911	73	1.9	2.7	1.73	2.6
6	PBTA2 21	73	2.1	2.3	1.66	2.8
7	PBTA2 9	69	1.5	5	1.53	2.1
8	SP 09 27939	79	2	3	1.52	2
9	SP 09 27949	77	1.8	3	1.46	2.7
20	296B	74	1.5	3.3	1.49	2.1
	Grand Mean	76	1.8	3.1	1.52	2.4
	CV	2.7	5.3	19	16.9	13.8
	LSD	3.43	0.16	0.97	0.42	0.55
	PVALUE	0	0	0	0	0.01

IS 1071, IS 1082, IS 1096, IS 2394, IS 4663, IS 5072, IS 18369, IS 4664, IS 5470 and IS 5636 are in use for development of shoot fly resistant hybrid parents. On comparing the A_1 and A_2 systems for shoot fly resistance, no significant differences were observed between A_1 and A_2 cytoplasms [26]. High yielding, shoot fly resistant hybrid parents were developed and heterotic hybrids produced using these parents. The need for having shoot fly resistance in both female and male parents for producing shoot fly resistant high yielding hybrids was demonstrated [27]. In sorghum, quantitative trait loci (QTL) governing various component traits contributing for shoot fly resistance have been identified and mapped in the parent IS 18551 [28] and CT Hash, ICRISAT, Personal communication). The QTL have been transferred to two cultivated backgrounds namely, BTx623 and 296B at ICRISAT (Hash CT, ICRISAT, Personal communication). These lines are currently being used to transfer shoot fly resistance in to elite sorghum hybrid parents. New B-lines with high grain yield and shoot fly resistance were identified during the 2008 rainy season at ICRISAT-Patancheru (**Table 4**).

3.3. Grain Mold Tolerance

Grain mold is one of the important biotic challenges for the rainy season sorghum. Both greenhouse and field screening techniques have been standardized by ICRISAT and partners for effective screening for grain mold resistance [16] and new sources of resistance were identified for use in breeding programs. Grain hardness, red pericarp and pigmented testa contribute to grain mold resistance [16]. In a study at ICRISAT, 156 grain mold tolerant/resistant lines were identified by screening 13,000 photoperiod-insensitive sorghum germplasm lines [29]. Resistance has been found mostly in colored grain sorghums with and without tannins and also in very few white-grain sorghums [29,30]. White grained sorghums are preferred for food use in India whereas colored grains are preferred in other parts of the world. Using the grain mold resistant germplasm sources, acouple of improved hybrid parents and varieties were developed [29]. Recent studies showed that there are no cytoplasmic differences between A_1 and A_2 cytoplasms for grain mold resistance and it is feasible to develop white pericarp grain mold resistant high yielding sorghum hybrids with stable per-

Table 4. Performance of advanced sorghum B-lines for agronomic traits and shoot fly resistance in the 2008 rainy season at ICRISAT-Patancheru, India.

Genotype	Days to 50% flowering	Plant height (m)	Shoot fly deadhearts (%)	Grain yield ($t·ha^{-1}$)
ICSB 29001	70	1.4	38	3.51
ICSB 29002	69	1.5	71	3.63
ICSB 29003	70	1.6	40	3.57
ICSB 29004	69	2.1	45	6.09
ICSB 29005	68	1.5	46	5.33
ICSB 29006	69	1.5	54	4.47
ICSB 29017	68	1.5	33	4.50
ABT 1007	68	1.6	39	4.52
PBT 1004	69	1.8	53	4.29
Controls				
IS 18551	72	3	31	2.57
296B	70	1.5	59	4.11
Swarna	69	1.8	44	4.86
Mean	69	1.73	46.02	4.28
SE (±)	1.18	0.21	14.33	0.35
CV (%)	2.95	21.33	23.93	14.00
CD (5%)	3.47	0.63	4.20	1.00

formance by using improved grain mold resistant hybrid parents, at least one of the parents being resistant to grain mold [31]. For identifying QTL for grain mold resistance, mapping populations (RILs) were developed (296 B × PVK 801; PVK 801 × 296 B) and the phenotyping of these populations for grain mold resistance is in progress. Recently, 14 B-lines with a grain yield of 1.9 to 2.6 $t·ha^{-1}$ and significantly superior to the check, 296 B (1.3 $t·ha^{-1}$) for grain yield were developed and all these B-lines were tolerant to grain mold with panicle grain mold rating ranging from 2.0 to 3.7 compared to the susceptible check, 296B (PGMR: 4.3 on 1 to 9 scale where 1 = no molds and 9 ≥ 90% grain surface area covered with molds) (ICRISAT Archival Report 2009 http://www.icrisat.org/icrisat-archival-reports.htm verified on 5th July 2011).

3.4. Drought Tolerance

Four growth stages in sorghum have been considered as vulnerable to drought: germination and seedling emergence, postemergence or early seedling stage, midseason or pre-flowering, and terminal or postflowering. Terminal drought is the most limiting factor for sorghum production worldwide. In sub-Saharan Africa, drought at both seedling establishment and terminal stages is very common. In India, sorghum is grown during both rainy and postrainy seasons. The variable moisture availability at both pre-flowering and post-flowering stages during the rainy season can have severe impact on grain and biomass yield. Climatic variability and associated genotype × environment interactions do not permit clear definition of target environments. Opportunities to make progress in breeding for drought tolerance occur both in understanding the environmental control of crop growth and in developing simplified approaches to modeling effects of climate change [32].

Drought and/or heat stress at the seedling stage often results in poor emergence, plant death and reduced plant stands. Severe pre-flowering drought stress results in drastic reduction in grain yield. Post-flowering drought stress tolerance is indicated when plants remain green and fill grain normally. A stay-green trait has been associated with post-flowering drought tolerance in sorghum. Genotypes with the stay-green trait are also reported to be resistant to lodging and charcoal rot [33] (**Figure 2**).

Genetic enhancement of sorghum for drought tolerance would stabilize productivity and contribute to sustainability of production systems in drought-prone environments. The extent of grain yield losses due to drought stress depends on the stage of the crop and the timing, duration, and severity of drought stress. Sorghum responses to moisture stress at all four growth stages have been well characterized. Variation in these responses has been observed and found to be heritable [3]. Since the phenotypic responses of genotypes differing in drought tolerance can be masked if drought occurs at more than

Figure 2. Expression of stay-green trait (in sorghum) under receding soil moisture conditions in a vertisol (photo courtesy: C Tom Hash, Santosh Deshpande and Vincent Vadez, ICRISAT).

one stage, screening techniques have been developed to identify drought-tolerant genotypes at each of the growth stages, separately [34-40]. Of the several mechanisms to circumvent drought stress in sorghum, drought escape (related to shorter maturity durations), drought avoidance (maintenance of higher leaf water potential, LWP), and drought tolerance (related to greater osmotic adjustment, OA) are important and have been well characterized [3]. However, LWP and OA did not correlate well enough with grain yield in field conditions to merit selection based on them; in addition, screening techniques developed based on LWP and OA were not cost effective in sorghum breeding. Empirical screening based on imposing drought at various growth stages and measuring plant morphological and yield responses was the most effective approach. Long mesocotyl in seedling establishment and recovery from mid-season stress after release by rains are important traits that can be easily deployed in lines. The stay-green trait has been well exploited to enhance post-flowering drought tolerance in sorghum [3].

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 [3]. Since hybrids have exhibited relatively better performance than open pollinated (OP) 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 [3]. The progress in enhancing drought tolerance in sorghum through conventional approaches is limited by the quantitative inheritance of drought tolerance and yield coupled with the complexity of the timing, severity and duration of drought. Biotechnology appears to offer promising tools, such as marker-assisted selection, for genetic enhancement of drought tolerance in sorghum. Four stable and major QTLs were identified for the stay-green trait and are being introgressed through MAS into elite genetic backgrounds at ICRISAT, QDPI, Purdue University, and Texas A & M University [3].

Integration of the sorghum genetic map developed from QTL information with the physical map will greatly facilitate the map-based cloning and precise dissection of complex traits such as drought tolerance in sorghum. Sorghum has a compact genome size (2n = 20) and can be an excellent model for identifying genes involved in drought tolerance to facilitate their use in other crops. It was reported that with respect to withstanding drought, sorghum has four copies of a regulatory gene that activates a key gene family which is present in a wide variety of plants. Sorghum also has several genes for proteins called expansins, which may be involved in helping sorghum to recover from droughts. In addition, it has 328 cytochrome P450 genes, which may help plants respond to drought stress, whereas rice has only 228 of these genes [5].

Some of the drought tolerant sources identified in sorghum at ICRISAT include Ajabsido, B35, BTx623, BTx642, BTx3197, El Mota, E36Xr16 8/1, Gadambalia, IS12568, IS22380, IS12543C, IS2403C, IS3462C, CSM-63, IS11549C, IS12553C, IS12555C, IS12558C, IS17459C, IS3071C, IS6705C, IS8263C, ICSV 272, Koro Kollo, KS19, P898012, P954035, QL10, QL27, QL36, QL41, SC414-12E, Segaolane, TAM422, Tx430, Tx432, Tx2536, Tx2737, Tx2908, Tx7000 and Tx7078 (www.icrisat.org). ICRISAT has identified lines that are tolerant to drought at various growth stages (**Table 5**). Drought tolerance of M 35-1, a highly popular post-rainy season adapted landrace in India, has been amply demonstrated [41].

4. Hybrid Parents with Postrainy Season Adaptation

Post-rainy sorghums are very crucial for food and fodder security in the drought prone areas of India [43] as there is no alternative cereal grown during this season, which receives only 8% of the total annual rainfall. Due to excellent grain quality, post-rainy sorghums are mostly used as food. The grain productivity of post-rainy sorghum is very low as much of the cultivated area is under landraces that are poor grain yielders. Terminal drought stress is a major production constraint in the post-rainy season as the crop is grown on receding soil moisture after cessation of the rains. Low levels of heterosis for grain yield and low levels of shoot fly resistance were

Table 5. Sorghum germplasm and breeding lines tolerant to drought at specific growth stages, ICRISAT-Patancheru, India.

Growth stage	Drought tolerant sources/improved lines
Seedling emergence	IS 4405, IS 4663, IS 17595 and IS 1037, VZM1-B and 2077 B, IS 2877, IS 1045, D 38061, D 38093, D 38060, ICSV 88050, ICSV 88065 and SPV 354
Early seedling	ICSB 3, ICSB 6, ICSB 11 and ICSB 37, ICSB 54 and ICSB 88001
Mid-season	DKV 1, DKV 3, DKV 7, DJ 1195, ICSV 272, ICSV 273, ICSV 295, ICSV 378, ICSV 572, ICSB 58 and ICSB 196
Terminal drought	E 36-1, DJ 1195, DKV 3, DKV 4, DKV 17, DKV 18, ICSB 17

observed in post-rainy season hybrids. Therefore, most farmers use either landraces or open pollinated varieties (OPVs) for Post-rainy season sowings [44]. Considering that photo- period sensitivity and low temperature tolerance during flowering, terminal drought tolerance, and grain quality traits are critical for post-rainy season crop, ICRISAT is engaged in developing hybrid parents by involving several post-rainy season adapted landraces (M 35-1, *Gidda Maldandi*, DSH 128, E 36-1, *Barsizoot*, *Dagadi Sholapur*, *Dagadi local*, *Amaravathi local*, M 35-1 selection bulks, etc.) and elite varieties and B-lines with good grain quality traits in the crossing program. Promising B-lines with higher yield and good grain quality were developed (**Table 6**).

5. Grain Micronutrient Density

Biofortification (increasing the grain Fe and Zn status through genetic means) complements the on-going efforts to address hidden malnutrition which is rampant in Sub-Saharan Africa and South Asia [45,46]. It is one of the cheapest and sustainable options to combat the malnutrition in predominantly sorghum eating populations [47]. Based on sorghum grain consumption levels, nutriaent retention in grain storage and processing, and nutrient bioavailability ICRISAT targeted 70 ppm Fe and 40 ppm Zn contents in grain for addressing micronutrient malnutrition in populations who depend predominantly on sorghum for their nutrient requirements [47]. ICRISAT un-

Table 6. Performance of post-rainy sorghum advanced B-lines in sorghum (A_1-cytoplasm based) at ICRISAT, Patancheru during 2009 postrainy season.

S. No	Entry	Days to 50% flowering	Plant height (m)	Grain luster score*	Grain yield ($t \cdot ha^{-1}$)	100 grain weight (g)
1	SP 54457-1	74	1.5	2.0	6.3	3.2
2	SP 93037	81	1.3	2.0	5.6	2.3
3	SP 92919	72	1.4	2.0	5.0	2.6
4	SP 92931	73	1.4	2.0	4.7	2.7
5	SP 92929	76	1.1	2.0	4.7	2.5
6	SP 93035	79	1.3	2.0	4.7	2.4
7	SP 92927	72	1.4	2.0	4.6	2.7
8	SP 92925	73	1.3	2.0	4.4	2.6
9	SP 92923	72	1.4	2.0	4.4	2.6
10	SP 92939	76	1.2	2.0	4.4	2.6
11	SP 54425-1	74	1.3	3.0	4.3	3.3
12	SP 92921	72	1.4	2.0	4.2	2.5
13	SP 93019	71	1.2	2.7	3.5	3.3
14	ICSB 52 (Check)	71	1.5	3.0	5.0	4.0
15	296 B (Check)	79	1.1	3.0	3.4	3.0
	Mean	74	1.3	2.2	4.6	2.8
	CV	1.3	4.5	6.6	10.9	5.5
	LSD	2	0.1	0.3	0.8	0.3
	PVALUE	0	0	0	0	0

(*Luster score taken on a scale where 1 = highly lustrous and 5 = dull grain color). Small quantities of all these materials can be obtained from ICRISAT on request.

dertook screening of core germplasm accessions to identify lines with high Fe and Zn contents. A total of 2267 core germplasm accessions were screened and promising donors identified under the HarvestPlus Challenge Programme [48]. Significant positive association between grain Fe and Zn contents and no significant association between grain Fe and Zn contents and agronomic traits were observed [49]. ICRISAT is developing the hybrid parents with high grain Fe and Zn contents in order to develop and disseminate sorghum hybrids with high micronutrient density. A total of 66 commercial sorghum cultivars developed by public sector and private sector partner organizations in India were assessed for grain Fe and Zn contents and promising cultivars identified [47] (**Table 7**).

6. Sweet Sorghum for Ethanol Andanimal Feed

Sweet sorghum is a multi-purpose crop that yields food, fodder and fuel. It is being used for syrup and ethanol production in U.S.A (http://nssppa.org/Sweet_Sorghum_FAQs.html verified on 12th July 2011) EU (http://esse-community.eu/ verified on 12th July 2011), China, Philippines, Mali, India and other countries. 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 22SS, the first sweet sorghum hybrid released in India, was based on the ICRISAT-bred female parent ICSA 38. Strategic research at Indian national program and ICRISAT indicated that ethanol production in Indiausing sweet sorghum is cost-effective and its cultivation gives 23% additional income to farmers compared to the grain sorghum [50]. There are minimal food-fuel tradeoffs in sweet sorghum but season-specificity exists. Hybrids are the cultivar options, as hybrids are high-yielding, flower early and less photoperiod-sensitive compared to the varieties. ICRISAT, along with

Table 7. Mean performance of the commercial sorghum cultivars (Set I) for grain Fe and Zn contents at ICRISAT-Patancheru, India during 2008 and 2009 postrainy seasons.

Hybrid name	Seed source	Fe content ($mg \cdot kg^{-1}$)			Zn content ($mg \cdot kg^{-1}$)		
		2008	2009	Mean	2008	2009	Mean
NSH 703	Nuziveedu Seeds, Hyderabad	50	38	44	36	28	32
GK 4035	Ganga Kaveri Seeds, Hyderabad	57	31	44	46	19	33
Mahabeej 703	MSSCL, Akola	53	33	43	36	22	29
NSH 702	Nuziveedu Seeds, Hyderabad	49	37	43	37	28	32
8562	Bayer Bio Sc., Hyderabad	51	31	41	37	23	30
Mahabeej 704	MSSCL, Akola	48	31	40	34	19	26
KDSH 1179	Krishidhan Seeds, Jalna	48	30	39	31	22	27
BSH 45	Biostadt Mh Seeds, Aurangabad	48	29	39	32	22	27
Madhura-SS hybrid	Nimbkar Seeds, Paltan	52	25	39	43	21	32
Mahabeej 7	MSSCL, Akola	52	25	39	33	18	26
GK 4009	Ganga Kaveri Seeds, Hyderabad	46	30	38	36	17	27
Hi-jowar 52	Biostadt Mh Seeds, Aurangabad	42	33	38	28	22	25
PSV 2 (variety)	ARS, Palem	47	28	38	36	16	26
CSH 25	MAU, Parbhani	53	27	37	35	19	25
8340	Bayer Bio Sc., Hyd	47	27	37	29	20	25
KDSH 209	Krishidhan Seeds, Jalna	48	28	36	31	22	26
PSV 1 (variety)	ARS, Palem	47	26	36	31	17	24
BSH 47	Biostadt Mh seeds, Aurangabad	42	28	35	26	19	23
GK 4044	Ganga Kaveri Seeds, Hyderabad	43	26	33	32	16	22
8568	Bayer Bio Sc., Hyderabad	37	23	30	29	17	23
Controls							
PVK 801 (variety)		55	30	43	41	20	30
CSH 16 (hybrid)		50	32	41	34	22	28
Mean		48	29	39	34	20	27
SE ±		2.86	1.85	2.76	2.09	1.44	2.00
CD (5%)		8.39	5.27	7.84	6.13	4.10	5.68

Table 8. Nitrogen, neutral detergent fiber (NDF), *in vitro* digestibility (all in % of dry matter) and mega joule (MJ) of metabolizable energy content and voluntary feed intake and changes in live weight in bulls fed a marketed commercial sorghum stover-based feed block (CFB), an experimental sweet sorghum bagasse/stripped leaves-based feed block (SLB) and 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}

its partners, is working on sweet sorghum ethanol value chain development including the supply chain management through a combination of centralized and decentralized models for commercial ethanol production [51]. Sweet sorghum when fed directly as forage was found to have high daily intake and higher digestibility in large ruminants (cows and buffaloes) [52]. 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 extraction of juice) can be used as animal feed without chemical or physical upgrading (**Table 8**) [53].

7. Future Plans

In addition to the biotic and abiotic challenges, presumed climate change effects influence the sorghum area and its importance globally. Climate change will modify the length of the growing period across the sorghum regions, but this can be mitigated by the 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 have shown 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 beoriented towards 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. More collaboration is required between ICRISAT and NARS partners across the globe in this endeavor. Harnessing the synergies of public- and private-sector agencies assume higher importance to ensure better impacts of genetic enhancement in farmers' fields.

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