Postrainy season sorghum: Constraints and breeding approaches

Belum VS Reddy[1]*, P Sanjana Reddy[2], AR Sadananda[3], Elango Dinakaran[1], A Ashok Kumar[1], SP Deshpande[1], P Srinivasa Rao[1], HC Sharma[1], Rajan Sharma[1], L Krishnamurthy[1] and **JV Patil[2]**

1. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India
2. Directorate of Sorghum Research, Rajendranagar, Hyderabad 500 030, Andhra Pradesh, India
3. Vibha Seeds, Madhapur, Hyderabad 500 081, Andhra Pradesh, India

*Corresponding author: b.reddy@cgiar.org

Citation: Reddy BVS, Sanjana Reddy P, Sadananda AR, Dinakaran E, Ashok Kumar A, Deshpande SP, Srinivasa Rao P, Sharma HC, Sharma R, Krishnamurthy L and Patil JV. 2012. Postrainy season sorghum: Constraints and breeding approaches. Journal of SAT Agricultural Research 10.

Introduction

Sorghum (*Sorghum bicolor*) is the fifth most important cereal crop in the world. Different types of sorghum are recognized. These are: grain sorghum, dual purpose (grain and fodder) sorghum, fodder sorghum, forage sorghum and sweet stalk sorghum. Also two types of sorghums are noted based on the season of adaptation; these are rainy (wet) season or postrainy (dry) season sorghum. There are two distinct sorghum growing seasons in India, *kharif* (rainy season; June–October) and *rabi* (postrainy season; October–January). In India, the grain productivity is about 1.2 t ha^{-1} in the rainy season, and about 0.8 t ha^{-1} in the postrainy season whereas the global grain productivity of sorghum is 1.4 t ha^{-1} (FAOSTAT 2011). The grain sorghum requirements for these two seasonal adaptations are quite diverse due to different agroclimatic conditions (Rana et al. 1997). There has been a significant decline in area under grain and dual purpose sorghum during the rainy season due to grain molds, but the area has remained stable in the postrainy season where mostly dual purpose sorghums are cultivated.

This review deals with postrainy (dry) season sorghum production constraints and breeding approaches in India. Due to their excellent grain quality, the postrainy season sorghums are used mainly for food purpose in India. Several varieties such as Phule Yashoda, Phule Anuradha, Phule Chitra, Parbhani Moti and Parbhani Jyothi have been released in the recent past by the All India Coordinated Sorghum Improvement Project (AICSIP). However, M 35-1, a landrace selection from Maldandi cultivated by the farmers traditionally in these areas for several hundred years, was selected nearly 75 years ago, and is still dominating the postrainy season tracts (Maharashtra, Karnataka and Andhra Pradesh) in India. There is a pressing need to develop and transfer to growers high-yielding grain and dual purpose sorghum cultivars with superior grain quality and with adaptation to postrainy season to break the yield plateau, which has resulted due to the major constraints, viz, water availability/drought, shoot fly, aphids and charcoal rot.

Major production constraints

The low grain productivity in the postrainy season sorghum in India is due to both biotic and abiotic constraints coupled with low genetic variability among the postrainy season sorghums. Much of the area cultivated during the postrainy season is under landraces that have a poor yield potential. Moreover, sorghum is grown under receding soil moisture after the cessation of the rains. So, end of season moisture stress is a major production constraint. Further, low temperature tolerance early in the season, response to photoperiod sensitivity (short day length), flowering and maturity irrespective of temperature fluctuations and sowing dates (thermo-insensitivity), tolerance to shoot fly and aphids among insects, and charcoal rot and rust among diseases and grain quality traits (bold lustrous grain with thin pericarp) are critical for the postrainy season crop (Reddy et al. 2010). The landrace M 35-1 has all these characters that are required for the postrainy season adaptation.

Apart from these constraints, the challenge of global warming, no or low rainfall, increased cooler nights, availability of alternate suppliers and shift from subsistence to market oriented agriculture – all influence the need for sorghum improvement in the postrainy season. The important traits that need to be focused in breeding sorghum for the postrainy season are discussed.

Photoperiod sensitivity and temperature insensitivity
Sowing of postrainy season sorghum in India starts from first week of September and extends up to first week of November depending upon the rainfall pattern. This season is characterized by reduced sunshine hours and cooler nights which affect the crop growth and productivity. Sorghum is a short-day plant, and variation in the response to photoperiod and temperature determines its adaptation to the wide range of environments in which it is grown (Craufurd et al. 1999). So, it is important to know the behavioral genetics of sorghum response to day length and temperature. As sorghum originated near the equator in northeastern Africa, it is sensitive to day length and temperature (Miller 1982). Miller et al. (1968) established that sorghum has a critical photoperiod of 12 h and classified some cultivars into groups that had higher critical photoperiods, including a class which does not respond (insensitive). When the day length becomes short (12 h or less), the sorghum plant differentiates from vegetative to reproductive growth when the rains diminish in tropical areas of Africa and India. During December, the critical photoperiod decreases up to 10.5 h and temperature to 5°C from 24°C. A study was conducted during 2010 postrainy season at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru under HOPE (Harnessing Opportunities for Productivity Enhancement) project using ten popular sorghum varieties to assess the flowering response under different dates of sowing. The results showed that rainy season adapted genotypes like ICSB 52 and ICSR 149 took more time to mature in later dates of sowing, whereas Phule Vasudha and SPV 1359 were stable varieties and did not respond to photoperiod. Parbhani Jyothi and Dagadi Solapur showed photoperiod sensitivity and temperature insensitivity by flowering late in first date of sowing and early in third date of sowing (Fig. 1). Thus, it emphasizes the need to practice season specific selection while breeding for postrainy season cultivars.

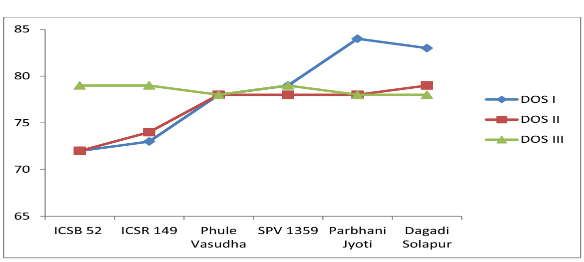

Figure 1. Time to 50% flowering (days) in sorghum genotypes at different sowing dates at ICRISAT, Patancheru, postrainy season 2010. [Note: DOS (date of sowing) I: 01.10.2012; DOS II: 15.10.2012; DOS III: 30.10.2012.]

Photoperiod sensitivity and temperature insensitivity are the two factors that are required for satisfactory yield during postrainy season. Photoperiod sensitivity appears to be a key feature that helps adjust flowering to occur at a particular period irrespective of planting time and plays an important role to secure the level and quality of harvests (Vaksmann et al. 1996). Therefore, better understanding of the genetic basis will facilitate the transfer of photoperiod sensitivity from local or landrace to high yielding backgrounds. The *Ma3* gene is one of six genes (*Ma1* to *Ma6*) that regulate the photoperiodic sensitivity of flowering in sorghum. The *ma3R* mutation causes a phenotype that is similar to plants that are known to lack phytochrome B, and *ma3* sorghum lacks a 123-KD phytochrome that predominates in light-grown plants and that is present in *non-ma3* plants (Childs et al. 1997). *Ma1* encodes a pseudo response regulator protein 37 (PRR37) that activates expression of the floral inhibitor Constans and represses expression of the floral activators Early Heading Date 1, Flowering Locus T, *Zea mays* Centro radialis 8 and floral induction in long days. The expression of SbPRR37 is light dependent and regulated by the circadian clock. In short days, the evening-phase expression of SbPRR37 does not occur due to darkness, allowing sorghum to flower in this photoperiod (Murphy et al. 2011). In future, identification of markers linked to their 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. However, tolerance to early and mid-season cold temperature is needed for increasing production in temperate and tropical sorghum production areas around the world, where the plants experience cold stress during emergence and/or anthesis. Tolerant genotypes show increased seedling vigor, resulting in greater biomass and grain yield in both cold and dry environments. As sorghum cultivars adapted to warm climates, prevalence of low soil temperature reduces germination and causes slow seedling emergence and growth. Significantly higher grain yields have been obtained by simply raising soil temperature during early growth stages (Adams 1962, 1970). Sorghum cultivars that produce more leaves (Quinby et al. 1973) had delayed floral initiation (Caddel and Weibel 1971, Quinby et al. 1973), and were found to be male sterile (Downes and Marshall l97l, Singh 1977) when low temperatures occur at anthesis. Exposure of whole sorghum plants to cold (5°C) or exposure of shoots only to a range of low night temperatures (5–15°C) reduced the rate and extent of stomatal opening and photosynthesis in the succeeding day (Pasternak and Wilson 1972). Cold-tolerant cultivars had 6 to 10°C lower optimum temperature requirements and 20–25%

higher respiration rates than cold-susceptible sorghum (Eastin 1976). Lower air and soil temperature occurs at different times during the growing season: (i) at the beginning of the season, causing poor germination and slow growth; (ii) at the end of the season, reducing grain-fill rate and perhaps reducing grain yield and quality; (iii) regularly or sporadically throughout the growing season, which may cause total crop failure. By planting short-duration cultivars and manipulating the planting date, severe damage under the former two conditions could be avoided. However, for the later condition, maximum cold tolerance must be derived by breeding resistant cultivars. At Patancheru, during postrainy season 2010, a date of sowing experiment was conducted to study the mechanisms of reproductive cold tolerance in postrainy season adapted sorghum cultivars. The results revealed that the genotypes like Dagadi Solapur, SPV 1411 and M 35-1 that were not seemingly affected by cold, as indicated by higher seed set percentage, higher mean panicle weight and higher panicle harvest index (data not shown here). Therefore the size of the panicle, panicle harvest index and the good grain filling can help in categorizing genotypes for their reproductive period cold reaction. However, variability for cold tolerance and its inheritance is to be fully understood for improving this trait.

Terminal drought tolerance

Terminal drought tolerance in sorghum has polygenic inheritance and hence selection is very effective for the traits governing it. The characters associated with terminal drought tolerance are non-senescence or delayed senescence, less lodging and charcoal rot tolerance.

Stay-green. Stay-green (non-senescence or delayed senescence) under moisture stress is considered as an important trait for sustaining yield under stress during grain filling (Borrell and Hammer 2000, Sanchez et al. 2002). Additionally, stay-green is an important factor in sustaining a positive nitrogen balance in sorghum (Borrell and Hammer 2000). Non-senescence is under relatively simple genetic control and can readily be improved by conventional or molecular breeding. Yet at the same time, non-senescent genotypes retain more photosynthates in their leaves and stems, whereas rapid leaf senescence may be indicative of reserve mobilization to the grain under stress (Borrell and Hammer 2000, Yang et al. 2001). However, it is quite obvious that when severe stress occurs during grain filling, even a non-senescent leaf cannot function indefinitely, and photosynthesis is bound to be drastically reduced. The only possible mechanism that would still allow some grain filling in a standing dehydrated plant is stem-reserve mobilization. On the other hand, there is an obvious advantage to stay-green in plants that are devoid of any effective capacity for stem-reserve utilization for grain filling under stress, such as in the normal 3-dwarf sorghum plant that is in wide use (Blum et al. 1997).

Studies by several authors starting from 1998 to 2012 (Sabadin et al. 2012) have identified several genomic regions of sorghum associated with pre- and post-flowering drought tolerance using several donors such as B 35, QL 41 and SC 56. Another donor parent for stay-green, E 36-1, a cultivar of Ethiopian origin, has also been used to map QTLs for the stay-green trait in two RIL (recombinant inbred line) mapping populations from which a total of seven QTLs were identified (Haussmann et al. 2002), with three of them being common to both populations. So, overall, six sources of the stay-green trait (B 35, E 36-1, QL 41, SC 56, SC 283 and SDS 1948-3) have so far been used for the identification of QTLs for this phenotype, and QTLs have been identified on all 10 sorghum linkage groups. Breeders at Patancheru selected six candidate QTLs for the stay-green trait from donor B 35, using published results including *Stg1*, *Stg2*, *Stg3*, and *Stg4* reported by Subudhi et al. (2000), Sanchez et al. (2002) and Harris et al. (2007) as well as additional QTLs on SBI-01 (*StgA*) and SBI-02 (*StgB*), and initiated marker-assisted backcross to transfer these QTLs into a number of genetically diverse, tropically-adapted elite sorghum varieties of Asia, Africa and Latin America, having a range of drought tolerance (Hash et al. 2003).

Recurrent parents included highly senescent *rabi* adapted *durra* variety R 16, 2-dwarf tan white-grained *caudatum* variety ISIAP Dorado, and 2-dwarf tan white-grained sweet-stemmed *caudatum* sister-line varieties S 35 and ICSV 111. Several of the stay-green QTLs identified have been validated in different backgrounds (Harris et al. 2007, Kassahun et al. 2010, Vadez et al. 2011). Recently, the stay-green QTL *Stg1* in sorghum has also shown its capacity to enhance water uptake in senescent S 35 background (Vadez et al. 2011). However, the effect of *Stg1* was not visible in R 16 background. This highlights the importance for future research on stay-green to precisely decipher the mechanisms involved, and whether any of these mechanisms is already available in target recipients. In most sorghum improvement programs globally, E 36-1 and B 35 have been extensively used for developing hybrid seed parents (B-lines) and pollen parents (R-lines) and cultivars (Reddy et al. 2009). Several stay-green hybrid seed parents and pollen parents were evaluated for stay-green and grain yield potential during the 2003 postrainy season at Patancheru. Some of these B- and R-lines are better than the stay-green source, E 36-1, for stay-green and grain yield under terminal drought

(Table 1). These hybrid parents have good potential for developing stay-green hybrids.

Charcoal rot tolerance. Charcoal rot of sorghum caused by the fungus *Macrophomina phaseolina* is a root and stalk rot disease of great destructive potential in most sorghum growing regions. *Macrophomina phaseolina* is a common soilborne, non-aggressive and plurivorous pathogen that attacks plants whose vigor has been reduced by unfavorable growing conditions (Das et al. 2008). Improved, high-yielding cultivars under good management tend to be very susceptible to the disease (Mughogho and Pande 1984). Drought stress is the primary factor that predisposes sorghum to charcoal rot. In diseased roots and stalks, *M. phaseolina* is often associated with other fungi, suggesting that the disease is of complex etiology (Fig. 2).

The seed parents, pollen parents, preliminary hybrids, advanced hybrids and varieties were evaluated for charcoal rot tolerance under HOPE project at Patancheru during 2010 postrainy season. Test lines were artificially inoculated by inserting toothpick infested with inoculum of *M. phaseolina* into the second internode of the stalk at 10 days after 50% flowering. Irrigation was withheld at 50% flowering to ensure adequate soil moisture stress to facilitate disease development and the data recorded for percentage soft rot, number of nodes infected and length of infection at physiological maturity (25–35 days after inoculation). The lines with <1 internode infection, <5 cm length of infection and <10% soft rot were considered resistant to charcoal rot. Charcoal rot infection in the advanced hybrids ranged from 0.3 internode (ICSA 84 × SPV 1411) to 3.4 internodes (ICSA 20 × ICSR 93009) and soft rot ranged from 6% (ICSA 675 × SPV 1411) to 100% (ICSA 20 × ICSR 93009) (Table 2). Based on number of nodes infected, infection length and percentage soft rot, two hybrids (ICSA 675 × SPV 1411 and ICSA 675 × ICSV 700) appeared tolerant to charcoal rot with <1 internode infection, length of infection <5 cm and <10% soft rot whereas the hybrid ICSA 20 × ICSR 93009 was highly susceptible to charcoal rot.

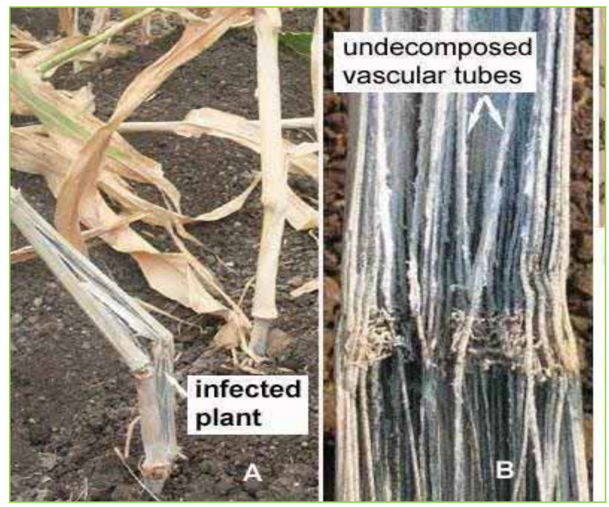

Figure 2. Charcoal rot (*Macrophomina phaseolina*) infected sorghum plant at ICRISAT, Patancheru during postrainy season 2010.

Table 1. Performance of selected ICRISAT-bred sorghum stay-green B- and R-lines at ICRISAT, Patancheru during 2003 postrainy season.

Line	Grain yield (t ha^{-1})	Stay-green score[1]	Time to 50% flowering (days)	Plant height (m)	100-seed weight (g)
ICSB 371	4.54	1.8	70	1.5	2.71
ICSB 375	3.50	2.0	71	1.7	3.14
ICSB 405	3.79	1.8	72	1.1	3.21
ICSB 677	3.58	2.0	74	1.0	3.33
ICSV 21004	4.10	2.5	77	1.5	3.67
ICSV 21005	4.90	2.5	76	1.5	3.69
ICSV 21011	5.29	2.5	73	1.6	3.29
ICSR 21002	5.75	3.0	76	1.7	3.71
296B	2.56	2.5	78	1.0	3.06
E 36-1	2.80		65	1.5	3.71
SE±	0.36	0.43	0.87	0.05	0.17
LSD (5%)	1.10	1.30	2.68	0.15	0.53
CV (%)	14.26	23.57	1.68	5.31	7.58

1. Scored on a scale of 1 to 5 at harvest, where 1 = >75% green, 2 = 51–75%, 3 = 26–50%, 4 = 10–25% and 5 = <10% green.

Shoot fly resistance

Shoot fly, *Atherigona soccata*, is one of the important constraints in the postrainy season sorghum in Asia. Shoot fly females lay eggs singly on the lower surface of sorghum leaves of 5- to 20-day-old seedlings. The larva migrates to the growing point and kills it, resulting in the drying of the central leaf, which is then called dead heart. To breed cultivars for shoot fly resistance, a season specific selection is needed. Since resistance to shoot fly in sorghum is apparently a complex trait, such traits as trichome density, leaf glossiness, number of eggs laid (oviposition non-preference) and seedlings with dead hearts have been used as selection criteria for shoot fly resistance. At Patancheru two such RIL populations derived from crosses 296 B × IS 18551 and BTx 623 × IS 18551 segregating for shoot fly resistance were used for QTL mapping studies across several screens. Among several mechanisms of resistance to shoot fly, the non-preference for oviposition (a component of which includes leaf trichome density and leaf glossiness) has been extensively exploited in breeding programs, and also genetically mapped in QTL mapping studies. Two major QTLs, each for glossiness (on SBI-05 and SBI-10) and trichome density (on SBI-09 and SBI-10), were consistently detected across screens and across both mapping populations. The glossiness QTL mapped on SBI-05 and SBI-10 contributed >50% and 17% of total phenotypic variation across several screens and populations. Similarly, QTL for trichome density (for both upper and lower leaf surface) mapped on SBI-10 accounted for >30% phenotypic variation (Folkertsma et al. 2003, Hash et al. 2003, Deshpande et al. 2006). These QTLs were further validated by marker-assisted backcrossing in two recurrent parent backgrounds (296 B and BTx 6233) in a multi-season screening for shoot fly resistance (Deshpande et al. 2010). Jayanthi (1997) established that the resistant B-lines bred for rainy season adaptation showed better expression for trichome density in rainy season than in postrainy season, although there were genotypic differences (Table 3). Moreover, reverse trend was observed in case of shoot fly resistant B-lines bred for postrainy season adaptation. Similar results were observed in hybrids based on the A-lines bred for a particular seasonal adaptation (Table 4). These results indicated season-specific expression of B-lines and hybrids for trichome density suggesting that the seed parents for shoot fly resistance should be bred for the season for which the hybrids are targeted.

Reddy et al. (2006) demonstrated the responses to shoot fly infestation by producing shoot fly resistant hybrids and exposing them to shoot fly pressure. Seventeen A-lines (14 shoot fly resistant and 3 susceptible lines) were crossed with 13 R-lines (9 resistant and 4 susceptible) to obtain 221 hybrids in 2003 postrainy season. All the 221 hybrids along with 17 female parents, 13 male parents, one resistant control (IS 18551) and one susceptible control (DJ 6514) were

Table 2. Performance of advanced sorghum hybrids for charcoal rot tolerance at ICRISAT, Patancheru during postrainy season 2010.

		Infected nodes (no.)		Length of infection (cm)	
Pedigree	Soft rot (%)	Inoculated	Control	Inoculated	Control
ICSA 84 × SPV 1411	39	0.3	0.0	2.5	0.0
ICSA 675 × SPV 1411	6	0.4	0.3	3.0	2.8
ICSA 702 × SPV 1411	19	0.6	0.2	7.4	2.3
ICSA 38 × SPV 422	58	1.4	0.0	17.9	0.0
ICSA 502 × SPV 422	39	1.8	0.0	18.0	0.0
ICSA 675 × ICSV 700	6	0.4	0.0	4.1	0.0
ICSA 88001 × M 35-1-19	17	0.9	0.4	8.0	5.0
ICSA 88001 × IS 33844-5	28	1.0	0.4	6.7	3.6
ICSA 20 × ICSR 93009	100	3.4	0.2	39.2	1.1
ICSA 563 × ICSR 93030	17	0.6	0.0	4.8	0.0
8712	24	0.7	0.0	6.5	0.0
XSR 401	6	0.9	0.3	5.0	2.5
CSH 15R	0	0.1	0.3	0.4	3.0
M 35-1	22	1.0	0.5	8.5	3.7
SPV 1411	29	1.1	0.0	12.4	0.0
296B	19	0.4	0.0	1.6	0.0
Mean	27.4	0.9	0.2	9.1	1.5
SE (m) ±	15.1	0.4	0.2	3.6	1.5
LSD (P <0.05)	43.6	1.1	0.5	10.5	4.5

evaluated in replicated trial for shoot fly resistance at Patancheru during rainy season 2004. The hybrids were classified into R × R, R × S, S × R and S × S categories based on the shoot fly infestation response criterion of the parents. The estimates indicated that the probability of producing shoot fly resistant hybrids is higher from R × R category followed by R × S category of crosses compared to that from other categories (S × R and S × S) (Table 5). Thus, it is clear from the results that shoot fly resistance in both parents or at least in seed parents is required to realize hybrids with reasonably higher levels of shoot fly resistance. The males, being selections from landraces, were less susceptible to shoot fly than the females. Similar results were obtained by Reddy et al. (2010) and Ashok Kumar et al. (2011). Hence, it is essential to improve seed parents for shoot fly resistance.

Grain and fodder quality

Apart from grain yield, grain quality, fodder yield and fodder quality are important as the postrainy season sorghum has been widely used as food and fodder unlike rainy season sorghum. Entire harvest of the postrainy season sorghum grains is used for human consumption due to its excellent grain quality. Consumers prefer highly lustrous sorghum grains with bold globular shape without beak (Neil and Rao 1999). This has been reflected in breeding efforts in the recent years at ICRISAT, Patancheru. The grain quality traits in the hybrids are also influenced more by the seed parent (Ashok Kumar et al. 2011). Further, the pollen parents can be selected readily from the available postrainy season cultivars, as most of them are good restorers. Hence, developing seed parents with improved grain quality traits should be more emphasized in hybrid breeding programs than the pollen parents. Through concentrated breeding efforts, nine highly lustrous elite seed parents are in pipeline for postrainy season adaptation at Patancheru. This grain quality generally known as “Maldandi quality”, an attribute of M 35-1, the landrace selection, which is widely grown needs to be further studied in depth both at physio-chemical level as well as genetics level, to understand this complex trait, so as to develop a breeding strategy in developing genotypes suitable for postrainy season with acceptable grain quality. Use of Parbhani Moti and Barshizoot in the hybridization programs helps in realizing improved lines with preferred grain quality attributes. Fodder yield and quality can be improved by simple selection, since the nature of gene action is additive and additive × additive epistatic interaction for these traits. Apart from fodder yield, the quality characters such as palatability stem nutrients/sugars and juiciness (Blümmel et al. 2009), in-vitro organic matter digestibility, crude protein, acid detergent lignin and anti-nutritional factors should be considered (Srinivasa Rao et al. 2010). Thin stalk with sugars enhances the palatability and digestibility of sorghum fodder. There is little correlation between yield and quality and stay-green trait will also improve the fodder quality.

Table 3. Season specificity for shoot fly resistance in sorghum maintainer lines (A_1) in 1996 at ICRISAT, Patancheru[1].

Line[2]	Trichome density (no. mm^{-2}) Rainy season	Trichome density (no. mm^{-2}) Postrainy season
SFR B-lines bred for rainy season adaption		
SPSFR 94002B	51.7	16.5
SPSFR 94003B	46.3	43.0
SPSFR 94001 B	80.6	63.4
SPSFR 94031B	71.0	43.3
Mean	62.4	41.5
CD (*P* = 0.05)	9.01	9.22
SFR B-lines bred for postrainy season adaption		
SPSFPR 94001B	34.2	116.4
SPSFPR 94002B	43.8	78.7
SPSFPR 94005B	20.6	29.5
Mean	32.9	74.9
CD (*P* = 0.05)	9.01	9.22

1. Source: Jayanthi (1997).
2. SFR = Shoot fly resistant.

Table 4. Season specificity expression of A_1 CMS system-based sorghum hybrids for trichome density during 1996 at ICRISAT, Patancheru[1].

Hybrids[2]	Trichome density (no. mm^{-2}) Rainy season	Trichome density (no. mm^{-2}) Postrainy season
Based on SFR A-lines bred for rainy season (RBR CMS) adaptation		
RBR CMS × RBR	50.30	49.85
RBR CMS × SBR	22.55	11.76
Based on SFR A-lines bred for postrainy season (PRBR CMS) adaptation		
PRBR CMS × RBR	49.80	67.37
PRBR CMS × SBR	25.71	30.06
PRBR CMS × PRLR	42.25	50.27

1. Source: Jayanthi (1997).
2. SFR = Shoot fly resistant.

Early breeding approaches

Introduction and pedigree selection

For the past several years, breeding programs attempted to introduce landrace collections from various sources from postrainy season areas and confined to either selection among themselves or pedigree selection in the crosses made among themselves. Since the variability is limited the improved selections resembled more or less the landraces or their selection like M 35-1. As a result there is very little improvement achieved.

Heterosis for grain and fodder

Considering the low productivity and stagnated heterosis levels in postrainy season sorghum, there is a pressing need to break the yield plateau. According to Rao (1970), there is no significant heterosis in postrainy season sorghum and hence for a long time to come, major sorghum genetic enhancement efforts were directed towards developing varieties for postrainy season. The postrainy season hybrids were mostly based on females and males. However, experiments at Patancheru from 1981 to 1987 recorded significant heterosis in postrainy season sorghum (Reddy and Stenhouse 1994) (Table 6) indicating the feasibility of hybrids development for postrainy season. To inherit all the required characters for postrainy season adaptation into the hybrids, the landrace hybrid approach was developed by Reddy and Stenhouse during 1994. It essentially involves selection for efficient restorers within the postrainy season landraces based on single plant test crosses and using them as males in producing the landrace hybrids with the established rainy season adapted female parents. According to Reddy and Stenhouse (1994), variability for restoration is enormous within the postrainy season landraces/released varieties (Table 7). Similarly, heterosis is high in hybrids obtained from crosses of landrace (*durra-caudatum*) based males and *caudatum* based females rather than *durra* based females (data not shown). Also, *durra* × *durra* hybrids more often have seed set problems in the postrainy season when temperatures are low.

Based on the landrace hybrid approach, several landrace hybrids were developed and tested during 1993–94. But these hybrids, although superior to M 35-1 for grain yield lacked shoot fly tolerance and grain quality traits, in particular grain luster because females were susceptible to shoot fly and lack grain characteristics needed. So, it is important to develop females with resistance to shoot fly and with bold lustrous grain like in M 35-1.

Table 5. Shoot fly resistant (SFR) A_1 CMS system-based sorghum hybrids (in different categories of crosses) during 2004 at ICRISAT, Patancheru.

Category of the crosses[1]	No. of hybrids	Mean dead heart (DH) (%)	No. of hybrids with DH ≤50%	Probability that the SFR hybrids with DH ≤50% belongs to the category
R × R	126	32.28	120	0.95
R × S	56	53.61	23	0.41
S × R	27	61.24	1	0.04
S × S	12	68.73	0	0.00
Total	221		144	

1. Female and male parents with DH ≤50% were classified as resistant (R); female and male parents with DH >50% were classified as susceptible (S).

Table 6. Superiority of the selected five each of sorghum varieties and hybrids over M 35-1 for grain yield in postrainy season at ICRISAT, Patancheru.

Type of trial	Planting	No. of trials	Grain yield ($t\ ha^{-1}$) for selected entries	Superiority (%) over M 35-1
Varieties	Normal[1]	15	3.6	22
	Late[2]	4	3.1	20
Hybrids	Normal[1]	13	3.7	64
	Late[2]	5	3.1	45

1. Sowing in September–October during 1981–87.
2. Sowing in November during 1983–87.

Table 7. Variability for restoration in sorghum postrainy season landraces, ICRISAT, Patancheru during postrainy season 1993–94[1].

	A_1 cytoplasm					A_2 cytoplasm				
	Progenies (%)				No. of progenies tested	Progenies (%)				No. of progenies tested
Pollinators	R	B	P	Seg		R	B	P	Seg	
Swathi	97	0	1	2	129	96	2	0	2	56
M 35-1	61	20	11	8	70	60	22	12	6	50
Muguthi	84	2	9	5	106	86	2	10	2	43
IS 18361	97	1	1	1	111	96	0	0	4	57
IS 18372	95	1	1	3	141	99	0	0	1	79
Mean	65	17	9	8	82	56	32	7	4	52

1. R = Male fertile/restorer; B = Male sterile/maintainer; P = Partially fertile; Seg = Segregating for R/B/P.

Some of the recently developed shoot fly resistant high-yielding hybrid parents (ICSA 29001 to ICSA 29006) are promising for the hybrid development programs (Ashok Kumar et al. 2008, 2011). Most sorghum experts in India suggest to focus on development of heterotic hybrids for postrainy season even if the grain quality is not exceptionally good. In recent years, ICRISAT developed hybrids using the landrace hybrid approach. The selected hybrids belong to *caudatum* based females and with *durra* type restorers except SPV 422 which is more of *caudatum* type. ICRISAT bred hybrids, ICSA 502 × SPV 422, ICSA 38 × SPV 422 and ICSA 84 × SPV 1411 performed well across the three locations, viz, Parbhani, Rahuri and Patancheru during postrainy season 2010 for grain yield and other adaptation features and out-yielded the controls (CSH 15R and M 35-1). The hybrid ICSA 84 × SPV 1411 has excellent grain traits and resistance to shoot fly like M 35-1. The hybrid ICSA 675 × SPV 1411 has tolerance to stalk rot. The private sector hybrids (8712 and XSR 401) have both shoot fly resistance and stalk rot tolerance.

Ideotype specific to the season

Productivity depends not only on the moisture availability but also on the soil types under which it is grown and the genotypes used. Much of the postrainy season sorghum is grown on residual and receding soil moisture on shallow and medium-deep soils. Among the several strategies suggested to yield improvement of postrainy season sorghum, multidisciplinary approach was one of them. Donald (1968) proposed the ideotype approach to plant breeding in contrast to the empirical breeding approach of defect elimination and selection for yield per se. Ideotype breeding involves defining a crop production environment, designing a plant model, from morphological and physiological traits known to influence performance in that environment, and combining these traits into one plant type. Germplasm lines suitable to both the soil conditions and also to specific soils were identified by Pawar et al. (2005). Under shallow soils, the genotypes were shorter, flowered and matured early while in medium-deep soils, mean leaf area, grain number and 1000-grain mass, grain and fodder yields were higher (Rafiq et al. 2003). The varieties like Phule Maulee and Phule Chitra were released for regions of Maharashtra with medium soil depth, Phule Anuradha for shallow soils and Phule Vasudha for deep soils of Maharashtra. These have been performing well in specific soil situations. Therefore, there is a need for the development of varieties adapted to specific soil situation in postrainy season to enhance production and productivity levels. On comparison of yield attributes and physiological traits of Phule Chitra with M 35-1, a widely cultivated postrainy season variety with broad adaptation and Phule Maulee, a variety suitable for medium soils, the ideotype was reflected in the higher per day grain and fodder productivity, higher harvest index, greater ear head exertion, higher relative water content and slow leaf senescence. Hence, while breeding for new varieties adaptable to medium soils, these traits have to be focused.

Current breeding approaches at ICRISAT

Diversification of restorers

Development of restorers based on individual plant selections test cross will be continued. Further, diversification of restorers will be brought about by crossing the postrainy season released cultivars (mostly *durra* type) with exotic germplasm from highlands of Eastern Africa that are genetically diverse compared to postrainy season landraces from India. Diversity analysis using markers like DArTs, and SSRs revealed that the *durra* germplasm lines from Cameroon, Ethiopia, Yemen and Eritrea are different from the landraces from India and these are being used to develop new variability and exploit it through selection. Thus, restorers should be more of *durra* type, characterized by bold size.

Diversification of maintainers

As indicated earlier, these should have base germplasm more of *caudatum* type that is required to provide needed diversity when hybrids are developed with the restorers that are more of *durra* type. The available male-sterile lines need to be improved for the traits referred above in particular resistance to shoot fly and charcoal rot, grain luster, size and shape. Recently, aphids are also becoming a serious pest. So the seed parents should be bred for resistance to aphids as well. Regular pedigree method followed by backcrossing for conversion into male-sterile lines coupled with screening for various traits is being followed. Secondly, the selected landraces and cultivars are introgressed into ms_3 based dwarf elite *caudatum* population to develop postrainy season improved maintainer population that will offer opportunity for selection of maintainers with the needed traits. Thirdly, introgression of ms_3 genes (dwarf and *caudatum* based) into postrainy season adapted cultivars such as Swathi, Phule Anuradha and Dagadi Solapur (which are maintainers) and others like Phule Vasudha, Parbhani Moti, Phule Chitra, Muguthi, M 35-1, and Barshizoot (which segregate for maintainer reaction) – all tall – has been initiated at Patancheru wherein the dwarf and male-sterile plants in backcross F_2 populations are used for backcrossing to the respective recurrent parent (postrainy season adapted cultivars, such as M 35-1 or Barshizoot or SPV 1411). After two to three backcrosses coupled with selection, the dwarf male-fertile plants will be identified in BC_2/BC_3 F_2 populations and test crossed to identify the maintainers for conversion into male-sterile lines (Fig. 3). These ms_3 gene introgressed versions of postrainy season adapted landraces and open-pollinated varieties can be used for improving shoot fly resistance and stay-green QTLs through marker-assisted backcrossing. Similarly it can be used for restorer line diversification, as developing F_2s with exotic *durra* lines becomes very easy. This will help hasten the process of cultivar improvement by accumulating favorable alleles for various target traits in same genetic backgrounds.

Fourthly, genome wide selection approach is being employed in $F_{2:3}$s of crosses involving dwarf B-lines and lustrous tall lines like Barshizoot, M 35-1, M 35-1-19,

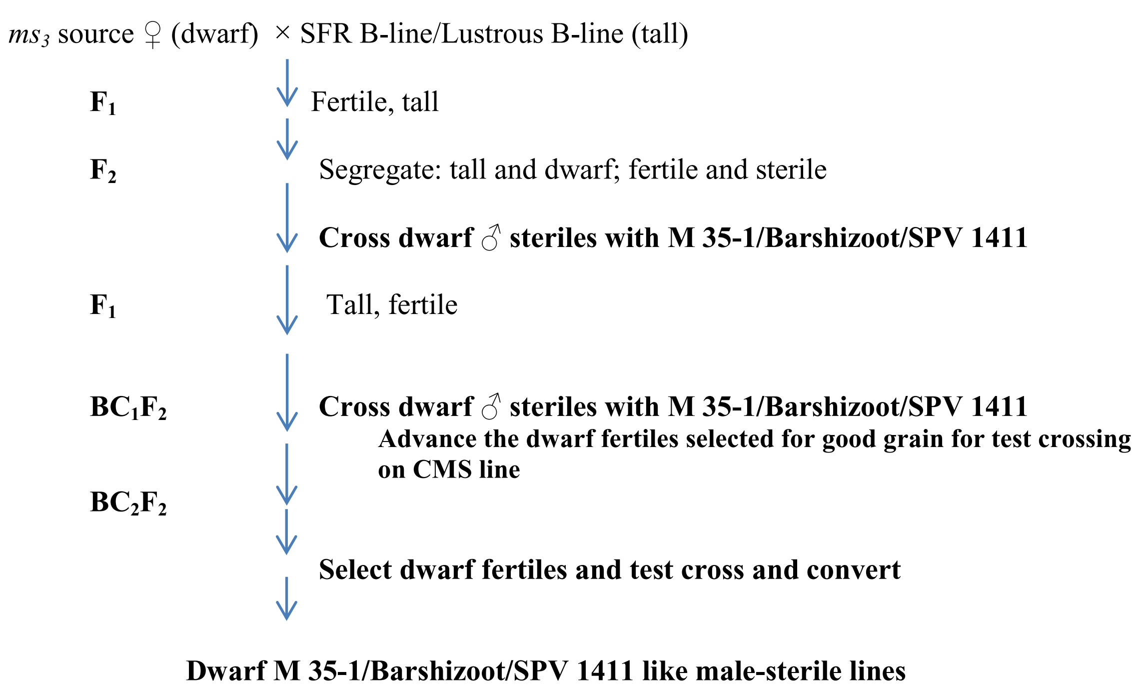

Figure 3. Developing dwarf postrainy season female lines using ms_3 gene.

Phule Chitra and SPV 1411 for selecting grain attributes like size, shape, luster, etc. This work may help unravel the "Maldandi type" grain quality by providing the information on genetics of various traits that define the quality in postrainy season. Thus the diversified restorer and maintainer pools are subjected to selection for various traits that are associated with postrainy season adaptation. Further, hybrid parents will be selected for combining ability under various conditions and along with the ideotype traits that helps in selecting specific ideotypes for producing the desirable hybrids for various postrainy season conditions.

Summary

Due to erratic rainfall distribution, there is an increase in population pressure and degradation of natural resources in rainfed regions and semi-arid tropics. 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. Sorghum, cultivated in rainy and postrainy seasons in India, has great production potential. Postrainy season sorghum harvest, both grain and fodder fetches high market prices because of high quality and is preferred as food and feed.

The improved postrainy season sorghum genotypes are not popular with farmers as they do not match M 35-1 for shoot fly resistance and drought tolerance. In this paper, constraints and the research in these areas that have impact on the adaptation of sorghum for postrainy season are examined. Also, the breeding approaches followed are described. The landrace pollinator based hybrid approach is described and some of the hybrids with high level of heterosis for grain yield and with some of the critical traits required for postrainy season adaptation are presented. Finally new breeding approaches that are being followed at ICRISAT are delineated for diversifying the restorers and maintainers for developing the hybrid parents and for producing heterotic hybrids for postrainy season adaptation (different soil depths). Small quantities of these lines will be available on request from ICRISAT, Patancheru.

Acknowledgment. Financial support provided by the ICRISAT-Private sector Sorghum Hybrid Parent's Research Consortium (SHPRC) and Bill and Melinda Gates Foundation in the form of HOPE Dryland Cereals Project is gratefully acknowledged.

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