Sorghum Hybrid Parents Research at ICRISAT–Strategies, Status, and Impacts

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Introduction

Sorghum (*Sorghum bicolor* L. Moench) is the first self-pollinated cereal staple crop, wherein heterosis has been commercially exploited to improve its productivity. Although the heterosis was demonstrated as early as 1927 in sorghum (Conner and Karper 1927), its commercial exploitation was possible only after the discovery of a stable and heritable cytoplasmic-nuclear male-sterility (CMS) mechanism (Stephens and Holland 1954). This CMS system has been designated as A_1 (*milo*). Since then a large number of hybrids have been developed and released/marketed for commercial cultivation in Asia, the Americas, Australia and Africa. The hybrids have contributed significantly to increased grain and forage yields in several countries. The grain productivity increased by 47% in China and by 50% in India from the 1960s to the 1990s (FAO 1960–1996), which corresponds well with the adoption of hybrids in these countries. Adoption of the first commercial hybrid (CSH 1) in India over much of the rainy season sorghum area, while local varieties are confined to fairly narrow specific environmental niches stands testimony to the wide adaptability of hybrids over varieties (House et al. 1997). Currently, over 95% of the sorghum area is planted to the hybrids in USA, Australia and China. In India, over 85% of the rainy season sorghum area is planted to hybrids.

Considering the success of CMS-based hybrid technology in sorghum, continued research investments have been made on hybrid parents [male-sterile (A-) (seed parents) and restorer (R-) lines] and hybrid development in sorghum improvement programs of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the National Agricultural Research systems (NARS). ICRISAT, located at Patancheru, Andhra Pradesh, India, was established in 1972 with a global mandate to improve the productivity of sorghum as one of the five crops for food use in the semi-arid tropics (SAT) of Asia, sub-Saharan Africa, and Latin America. Hybrid parents' research was initiated at ICRISAT in 1978 at its headquarters at Patancheru; in 1985 at Bulawayo, Zimbabwe; in the early 1990's at its regional hub, Nairobi, Kenya; and in 1982 at Sotuba, Mali in the Western and Central Africa region. The major objectives of sorghum improvement research at ICRISAT have been to develop hybrid parents that would be useful for developing hybrids for wider adaptation in Asia, Africa, and the Americas. Since then, hybrid parents' research and hybrid development strategy at ICRISAT has undergone significant changes. The external environment, donors and NARS perceptions of changing crop requirements and opportunities, and NARS capacity are the most important factors that influenced these changes. A retrospect of the hybrid parents research would serve as a valuable guide to assess the progress, and shortfalls if any, and would help chalk out the future line of research. In this article, we have made an attempt to review the progress made in hybrid parents' research in the light of strategies followed and the impacts witnessed, and to outline the future line of sorghum hybrid parents' research at ICRISAT.

Seed parents' research at ICRISAT-Patancheru, India

Sorghum seed parents' research at ICRISAT-Patancheru can be traced in three phases: Phase I (1978-1988), Phase II (1989-1998) and Phase III (beyond 1999).

Phase I (1978-1988): During this phase, grain yield and grain quality traits and adaptation traits (particularly days to maturity) have received greater emphasis to meet region-specific requirements and match the crop season, respectively. The breeding strategy involved conversion of F_6 homozygous or breeding lines with male-sterility maintainer reaction (B-lines) derived from pedigree selection. The lines with good general combining ability (GCA) for grain yield, grain quality, desired maturity and plant height (dwarf) were converted into A-lines, using 5-6 backcrosses to a known A-line with A_1 cytoplasm. A total of 92 high yielding A-/B-lines, including 17 early maturity lines (< 66 days to 50% flowering) and 75 medium maturity lines (66 to 75 days to 50% flowering), were developed during this period.

Phase II (1989-1998): The popularity of hybrids resulted in increased area under hybrids. The commercial hybrids were highly susceptible to biotic and abiotic stresses. Therefore, incorporating resistance to biotic and abiotic constraints into hybrid parents was necessary to stabilize the yields. Therefore, a trait-based breeding approach (Figure 1) was followed to develop hybrid parents during this phase. Initially, selected individual plants (from the F_6 generation) resistant to specific biotic/abiotic stresses with the maintainer reaction within the selected high yielding families were converted into A-lines after testing for GCA. This approach not only resulted in a significant reduction in grain yield potential and resistance levels in the A-lines, but the conversion process also took a longer time (9-10 years). Therefore, a different method was conceptualized and executed in the development of A-lines. The method involved simultaneous selection for resistance to a specific biotic stress (such as shoot fly, stem borer, midge, head bug, grain mold, downy mildew, leaf blight, anthracnose, rust, and *Striga*) and abiotic stress (such as terminal drought) based on families, and for grain yield based on individual plants within the selected resistant families from the F_4 generation onwards. The selected lines with maintainer reaction were converted into A-lines with resistance to a specific biotic and abiotic stress in the shortest possible period of seven years. The trait-based method ensured retaining greater genetic diversity in the A-lines. Thus, 567 trait-based A-/B-lines (Reddy et al. 2005a) and 30 high-yielding A-/B-lines were developed at ICRISAT-Patancheru in Phase II, resulting in a total of 689 A-/B-lines being produced in Phases I and II together. Identification of A-/B-lines for soil acidity tolerance and development of appropriate genetic stocks for strategic research are some of the programs initiated during phase II, apart from trait-specific diversification of A-/B-lines.

Tolerance to acid soils: Some of the grain sorghum A-/B-lines (ICSB 604, ICSB 605, ICSB 607, and ICSB 608) were found to be tolerant to soil acidity (based on grain yield) comparable to the known resistant check, Real 60 when these were introduced and empirically screened under acid soil conditions at Carimagua, La Libertad and Matazul during 1996 to December 1999 (Reddy et al. 2004a).

Genetic stocks for strategic research: Development of appropriate genetic stocks for conducting strategic research was also given due emphasis during this phase. These included isogenic lines for dwarf *vs* tall plant types, photoperiod sensitive *vs* photoperiod insensitive, tan *vs* non-tan, glossy *vs* non-glossy, trichome *vs* non-trichome and isonuclear alloplasmic [for A_1, A_2, A_3, A_4 (Maldandi), A_4 (VZM) and A_4 (Guntur)] A-lines in nine different nuclear backgrounds (ICSB 11, ICSB 17, ICSB 26, ICSB 37, ICSB 38, ICSB 42, ICSB 88001, ICSB 88004, and ICSB 88005). While the isogenic lines are ideal materials for discerning the effects of adaptation traits (photoperiod sensitivity) and plant defensive traits (trichomes) on grain yield, the isonuclear alloplasmic A-lines are useful for assessing the effects of different CMS systems on the expression of economic traits and unraveling the inheritance of male-sterility maintenance/male-fertility restoration on all the available diverse CMS systems.

Phase III (1999 onwards): This phase marked the beginning of race-specific and alternative (non-*milo*) CMS-specific diversification of A-lines. Conversion of race-specific (*caudatum* and *guinea*) selections from F_4 generations (derived from various crosses) with male-sterility maintainer reactions into A_1 and A_2 cytoplasm-based A-lines is in progress. Similarly, selected *feterita* type F_4 progenies with male-sterility maintainer reactions are being converted into A_2 cytoplasm-based A-lines. These lines are in advanced stages of conversion into A-lines. The use of a single CMS system for hybrid development not only restricts the nuclear diversity of A- and R-lines, but also renders the hybrids to be more vulnerable to insect pests and/or disease outbreaks as is evidenced from the devastation of the Texas cytoplasm-based corn hybrids due to the outbreak of corn leaf blight disease in 1970 (Tatum 1971). Therefore, greater emphasis has been placed on the diversification of A-lines based on the alternative (non-*milo*) CMS systems (A_2, A_3 and A_4 in that order) apart from the traditional *milo* (A_1) CMS system at ICRISAT-Patancheru. The diversification of A-lines for farmer-preferred grain quality-evident traits such as white, larger and lustrous grains for postrainy season adaptation is also in progress. Diversification of A-lines for resistance to biotic stresses has been limited to shoot fly (for both the rainy and postrainy seasons) and grain mold (for the rainy season), while maintaining reasonably higher yield potential.

The initial grain yield and grain quality traits-based breeding (in phase I) and subsequent yield stabilizing plant defensive traits' (resistance to biotic stresses)-based breeding (in phases II and III) and race-specific breeding (in phase III) at ICRISAT-Patancheru, India led to the development of 732 A-/B-lines, which include A_1 CMS system-based 165 (160 old + five new) high-yielding lines, 487 biotic and abiotic stress resistant lines, and 51 A_2, 17 A_3 and 12 A_4 CMS system-based lines. All these A-/B-lines have been designated. The characteristics of these hybrid parents are available at the ICRISAT website: http:/www.icrisat.org/grep/homepage/sorghum/breeding/pedigreemain.htm.

Identification/development of A-/B-lines for multicut trait, sweet-stalk, salinity-tolerance, and grain micronutrients [iron (Fe) and zinc (Zn)] density are some of the programs initiated during phase III, apart from race-specific and trait-specific diversification of A-/B-lines. Several promising A-/B-lines for the different traits have been identified. These are: ICSB 74, ICSB 264, ICSB 293, ICSB 297, ICSB 474, ICSB 664, ICSB 731 (A_2) and SP 20656B for high forage yield and multicut ability; ICSB 213, ICSB 264, ICSB 293, ICSB 401, ICSB 405, ICSB 472, ICSB 474 and ICSB 731 for sweet stalk trait (Reddy et al. 2005b); ICSB 401, ICSB 405, ICSB 583, ICSB 589 and ICSB 707 for salinity tolerance (Ramesh et al. 2005); and ICSB 37, ICSB 38, ICSB 39, ICSB 52, ICSB 74, ICSB 418, ICSB 472 and ICSB 484 for micronutrient density (Reddy et al. 2005c).

Bold grain high-yielding A-/B-lines: Since 2000, a total of 85 new race-specific A-/B-lines (39 A_1 and 46 A_2 CMS systems-based) have been developed. The grain yield potential of some of the best *durra* bold grain B-lines (A_1) has been found to be significantly better than the control, 296B (the seed parent of several commercial hybrids) with a comparable grain size.

Resistance to shoot fly and grain mold: Following a trait-based pedigree breeding approach, A-lines with shoot fly resistance (SFR) (for both the rainy and postrainy seasons) and grain mold resistance (GMR) (for the rainy season) in a white grain background are being developed. Apart from resistance, the traits such as desired maturity, plant height and good grain quality and size are being given emphasis while breeding for SFR and GMR. To address serious concerns on the limited use of diverse resistance sources, several SFR sources such as 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 and GMR sources such as IS 18758, IS 30469, IS 40657, IS 41397, IS 41618, IS 41675, IS 41720 (not used in earlier programs) are being used to diversify A-lines for SFR and GMR at ICRISAT.

Seed parents' development for postrainy season adaptation: Sorghum improvement for postrainy season adaptation, which is unique to India, received less emphasis in the beginning. The Indian NARS have developed several hybrids for cultivation in the postrainy season. However, most of these were not acceptable to farmers as they lacked terminal drought tolerance, resistance to shoot fly and grain quality traits that are comparable to M 35-1(the most popular variety). At the behest of the private seed companies and the Indian NARS, a program for sorghum improvement for postrainy season adaptation has received new impetus, and consequently A-line development for postrainy season adaptation has been intensified at ICRISAT-Patancheru since 2000. Considering that low temperature and terminal drought tolerance and grain quality traits such as pearly white, large and lustrous grains are critical for postrainy season adaptation, variability was generated by involving several postrainy season adapted landraces such as M35-1, Gidda Maldandi, DSH 128, E 36-1, Barsizoot, Dagadi Sholapur, Dagadi local, Amaravathi local, M 35-1 selection bulks and elite varieties and maintainer lines with good grain quality traits. Several elite selections (44 from F_5 and 92 from F_4 generations) based on grain size and grain lustre and agronomic eliteness were evaluated for agronomic performance and simultaneously screened for SFR in 2005 postrainy season. Those selections with desirable agronomic and grain quality traits that are similar to those of M 35-1 will be converted into A-lines (A_1). In addition, Gidda Maldandi, which is a restorer on A_1, is being converted into A_2, A_3 and A_4-based A-lines.

Seed parents' research at ICRISAT-Bulawayo, Zimbabwe

Hybrid seed parents' research in southern Africa was carried out under the Sorghum and Millets Improvement Program (SMIP) and was initially based on the selections from the A-/B-lines received from USA and ICRISAT-Patancheru to exploit the residual variability present in the introductions (Majisu and Doggett 1972). Although selections were based on the maturity duration that matched with crop season and other traits of importance such as plant height and resistance to biotic and abiotic constraints specific to locations in southern Africa, the resultant seed parents had low grain yield due to poor adaptation. Therefore, SMIP initiated its own independent programs for developing high yielding hybrid parents with local adaptation. As a result of concerted efforts, 36 A-/B-lines designated as SDSA-/B 1 to SDSA-/B 36 were developed through four backcrosses and selections were made for maturity duration (early to medium), grain yield, and grain quality and stay-green traits. These A-/B-lines are slightly taller than the controls, slightly earlier (2%), superior in grain yield (8%) and 5 to 110% superior in milling quality. These new A-lines have been grouped into three categories: i) dwarf (<1.0 m) with broad drooping leaves, tan plants and resistant to leaf blight and sooty stripe; ii) semi-dwarf (1.0–1.6 m) with thin upright leaves, and non-tan (purple) plants, but susceptible to leaf blight and sooty stripe; and iii) semi-tall (1.7–1.9 m) with broad leaves, and tan plants but susceptible to leaf blight and sooty stripe.

Seed parents' research at ICRISAT-Nairobi, Kenya

Initially, hybrid parents' development was not a major activity of the sorghum research work at ICRISAT-Nairobi, as hybrids were not the target cultivars in most of the countries in eastern and southern Africa (ESA) region. The reasons were many. Subsistence farming (except in Sudan), informal seed production and distribution system and lack of interest by seed companies to venture into sorghum seed production were the major causes, among others. However, in the early 1990s, research was initiated to develop hybrid parents mainly by screening A-/B-lines introduced from the International Sorghum/Millet Collaborative Research Support Program (INTSORMIL), USA and ICRISAT-Patancheru, India for adaptation, earliness and grain quality traits.

Seed parents' research at ICRISAT-Bamako, Mali

Research on seed parents adapted to Western and Central Africa (WCA) by the ICRISAT-Bamako, Mali program was initiated in 1982. A set of 227 Malian landraces (consisting of 74% *guinea* landrace accessions) was assessed for fertility reaction on A_1 CMS system. A high frequency (36%) of the *guinea*-based landraces showed maintainer reaction, but there were no lines converted into A-lines at that time. Characterization of 72 *guinea*-race accessions from WCA as well as ESA and Asia was conducted in 2002-2003. This evaluation confirmed the high frequency of maintainer reaction in landrace varieties from the Sudanian zone of West Africa (33% of accessions from Burkina Faso, Mali and Senegal). In contrast, landrace varieties from the more humid Guinean zone showed complete restorer reaction (sample size of 14). With these more recent results, concerted efforts have been made to develop *guinea*-race A-lines based on A_1 CMS system by ICRISAT in collaboration with the Institut d'Economie Rurale (IER), Mali and Institut d' Etudes et de Recherches Agronomiques (INERA), Burkina Faso. The objective was to develop seed parents with acceptable grain quality and *guinea* glume and panicle characteristics, and the required photoperiod sensitivity to produce the first sorghum hybrids with adaptation to West Africa and good panicle (free threshing, good milling recovery) and grain traits (such as long storage capability).

The first *guinea* landrace A-lines were based on Malian varieties Fambe, IPS001 and CSM 219 (developed by ICRISAT), and seven inter-racial derivatives of a cross [*guinea* landrace (Bimbiri Soumale) × *caudatum* varieties] - (developed by IER). While *guinea* landrace-based A-lines are tall, photoperiod sensitive, and possess typical *guinea* grain and panicle architecture, the inter-races cross derivatives-based A-lines are dwarf, basically photoperiod insensitive and possess relatively small grain.

The development of new A-lines (on A_1 CMS system) continues with sterilization of *guinea*-core collection accessions from Burkina Faso, Senegal, Gambia, Sudan, Uganda, and Malawi by the ICRISAT program and inter-racial lines by IER. These are currently in advanced stages of conversion (in BC_4 generation). Also the first sets of progenies derived from the dwarf guinea random-mating population are being converted into A-lines. These A-lines under development will provide diversity for most agronomic traits; spanning the range of grain size (100-grain weight of 1.0 to 3.0 g), grain/glume form (*Margaritiferum* to *Conspicuum* in the Snowden classification), panicle length (30 to 60 cm) and plant height (3 to 4 m) typical of *guinea* race. Besides agronomic traits, these B-lines represent a wide range of maturity that is intended to address the needs of the Northern Sudanian zone (600 to 800 mm rainfall), the Southern Sudanian zone (800–1000 mm rainfall) and the Northern Guinean zone (1000 to 1200 mm rainfall). The lines, which flower before 15 September (along with earlier developed CSM 219A and inter-racial A-lines) are most promising for the Northern Sudanian zone, whereas those flowering between 15 and 25 September and thereafter are most promising for the Southern Sudanian and the Northern Guinean zones, respectively.

Restorer parents' research at ICRISAT-Patancheru, India

Utilization of CMS systems for hybrid development requires complementary efforts in developing restorers (R-lines). There were no planned efforts to develop restorers at ICRISAT-Patancheru, India or at its regional hubs in Africa. The improved varieties developed at ICRISAT-Patancheru were test crossed and several of them found to be restorers on the A_1 CMS system were added to restorer gene pool. Also, the pedigree selections with restorer reaction in the A-line development programs were added to the restorer gene pool, though their contribution to the restorer gene pool is limited. R-line breeding therefore, rested mainly on varietal development program, wherein grain quality traits and yield potential were given major emphasis between 1972 and 1978, and resistance to biotic and abiotic stresses between 1979 and 1988 at ICRISAT-Patancheru. The program on varietal/restorer improvement has been renewed, though on a small scale, in the last three years at ICRISAT-Patancheru.

Varietal/R-line improvement programs at ICRISAT-Patancheru led to the identification/development of 883 R-lines (873 old and 10 new) on $A_{1,}$ 146 on A_2, and three dual R-lines. All these R-lines have been designated and their characteristics are available at ICRISAT website: http:/www.icrisat.org/text/research/grep/homepage/sorghum/ breeding/main.htm. Apart from these, 36 dual-restorers on A_1 and A_2, two on A_1, A_2 and A_3, and two on A_1, A_2, A_3 and A_4 (Maldandi), A_4 (VZM) and A_4 (Guntur) CMS systems have been identified. As in the case of A-/B-lines, the available varieties/R-lines were screened for acid soil tolerance, multicut ability, sweet-stalk, salinity tolerance, and grain Fe and Zn contents as discussed in the section on A-lines development, and several promising lines have been identified. These include: tolerance to soil acidity (ICSR 110, ICSR 91012 and ICSR 93033 (Reddy et al. 2004a); multicut trait (ICSR 93024-1, GD 65239, ICSR 93025-1 and GD 65174-2); sweet-stalk (ICSV 574, ICSR 91005, ICSR 93034, ICSV 700, and ICSV 93046) (Reddy et al. 2005b); salinity tolerance (ICSR 89010, ICSR 900I7, ICSR 196, and ICSR 160) (Ramesh et al. 2005), and micronutrient density (ICSR 37, ICSR 98, ICSR 196 and ICSR 90017) (Reddy et al. 2005c).

Large grain high-yielding R-lines: The R-line development program led to the identification of 142 R-lines on A_1 CMS system since 2000. Replicated field evaluation of these new R-lines during the 2004 rainy season indicated grain yield superiority of two R-lines (ICSR 24010 and ICSR 24006), each with yields of 5.6 t ha^{-1} compared to the control, CSV 4 (4.4 t ha^{-1}), which has a similar maturity period. Apart from grain yield, the two R-lines (with 2.8 and 2.7 g 100^{-1} grains, respectively) were superior to all the three control varieties/R-lines (CSV 15, CSV 4 and RS 29) (2.3 to 2.5 g 100^{-1} seeds) for grain size as well. Further, ICSR 24001 (5.4 t ha^{-1}) and ICSR 24009 (5.4 t ha^{-1}) though not statistically different from CSV 4 (4.4 t ha^{-1}) in grain yield, were significantly superior for grain size.

Restorer parents' development for postrainy season adaptation: At ICRISAT-Patancheru, R-lines development for postrainy season adaptation was intensified in 2000. Several R-lines (40) on the A_1 CMS system were derived from the crosses involving postrainy season adapted varieties (SPV 1359, SPV 1380, NTJ 2, M 35-1 bulk selections, S 35, SPV 462, and GM 970130) and several bold and lustrous grain type breeding lines. Further, 32 selections with agronomic eliteness and good grain traits within postrainy season adapted varieties (M 35-1, Swathi), germplasm lines (IS 4504, IS 4606, IS 5631, IS 8920, and IS 33844), breeding lines (SP 76942, SP 76942, SP 76946, SP 76947, SP 76948, and SP 76951), and derivatives from SPV 462 × 296 B cross were found to be restorers on A_1 and A_2 CMS systems.

The segregating lines derived from the crosses involving postrainy season adapted varieties such as M 35-1, SPV 1359, SPV 1380, NTJ 2, and M 35-1 bulk selections were subjected to farmer and breeder selection at ICRISAT, Patancheru. The breeder and farmer selections were advanced with further selections based on grain quality traits and agronomic eliteness. Twenty-four each of breeder and farmer selections were evaluated in replicated trials at the Regional Research Station at Bijapur and ICRISAT-Patancheru in the 2004 postrainy season. Four of the farmer selections (SP 71312, SP 71324, SP 71325, and SP 71327) and five of the breeder selections (SP 71513, SP 71520, SP 71522 SP 71528, and SP 71533) had high grain yield potential, good grain size and grain lustre, stay-green trait, lodging resistance, days to 50% flowering and plant height comparable to M 35-1.

Restorer parents' research at ICRISAT-Bulawayo, Zimbabwe

In southern Africa, as was in the case of A-/B-lines, the development of R-lines was mainly based on the selections (for local adaptation, male-fertility restoration, earliness and grain quality traits) from 33 R-lines introduced from INTSORMIL and several varieties/R-lines from ICRISAT-Patancheru in 1980s. A total of 23 R-lines designated as SDSR 1 to SDSR 23 were selected from 33 introductions from INTSORMIL. The 23 R-lines were tested for four years (1992/93 to 1995/96) at Matopos and Lucydale in Zimbabwe. These R-lines, when compared with controls, gave 15% increased grain yield, were 20% shorter, had 58% harder grains, and 10% higher milling yield (Obilana 1998).

Restorer parents' research at ICRISAT-Nairobi, Kenya

In the ESA region, R-line development has been confined to screening R-lines introduced from INTSORMIL and several varieties and R-lines from ICRISAT-Patancheru for local adaptation and male-fertility restoration, besides earliness and grain quality traits.

Restorer parents' research at ICRISAT-Bamako, Mali

At ICRISAT-Bamako, Mali, several lines with restorer reaction with a range of panicle length (28 to 40 cm), 100-grain weight (1.0 to 2.9 g) and heading date (15 September to 27 October) have been identified from a sub-sample of *guinea*-core collections. A range of inter-racial R-lines have been identified by the IER-Mali program. The characterization of these lines for attributes important for R-lines such as plant height, pollen abundance, panicle architecture, etc. was initiated in 2004.

Inheritance of male-fertility restoration

The inheritance of fertility restoration depends on the specific interaction of cytoplasm and nuclear genes. Qian (1990) suggested that 1 or 2 genes control male-fertility restoration, while Lonkar and Borikar (1994) have reported that 1 to 3 genes are involved in controlling fertility restoration of A_1 CMS system. Research at ICRISAT-Patancheru has shown that the frequency of recovery of fertile plants were least on A_3 followed by A_4, A_2 and A_1 indicating that more number of genes are involved in controlling fertility restoration on A_3 than the other CMS systems (Reddy and Prasad Rao 1992). El'konin et al. (1996) concluded that two complementary dominant genes control the male-fertility of 9E CMS system. It is important to note that none of these studies are based on common nuclear genetic backgrounds and common restorer lines. Therefore, the reported differences in the number of genes involved in fertility restoration could be due to the effect of different nuclear genetic backgrounds of the A-lines, R-lines and their interactions. With the availability of isonuclear alloplasmic A-lines and common R-lines on all the available CMS systems at ICRISAT, Patancheru, the genetics of fertility restoration can now be established more clearly.

Strategic research

Apart from diversification of hybrid parents for grain and forage yields, resistance to major biotic and abiotic yield constraints, and sweet-stalk, several strategic research issues were addressed at ICRISAT-Patancheru: requirements of hybrid parents, germplasm base (races) and selection criteria of hybrid parents, relationship of mean performance of parents and crosses with combining ability and heterosis, relationship between parental diversity and heterosis, season specificity of shoot fly resistance (trichome density), and relationship between parental and hybrid performances for resistance to shoot fly and grain mold and juice yield (in sweet sorghums), forage yield and postrainy season hybrid breeding approach. The strategic research information would be useful to enhance the efficiency of sorghum improvement programs. Some of the important findings are as follows.

Shoot fly resistance: Shoot fly resistance (SFR) is needed in both the parents to develop the hybrids with reasonably higher levels of SFR. It is worthwhile to improve both the hybrid parents for SFR in separate programs. Further, seed parents for SFR should be bred for the season for which the hybrids are targeted, considering season-specific expression of trichome density (Sharma and Nwanze 1997), one of the important traits contributing to SFR.

Grain mold resistance: The probability of producing grain mold resistant (GMR) hybrids is higher if one of the parents is resistant than if both parents are grain mold susceptible or GMR. It appears therefore that the diverse and complementary individual mechanisms, each with small effects, might be acting synergistically in the hybrids leading to higher levels of GMR in the hybrids involving parents with contrasting responses to grain mold. Earlier work at ICRISAT-Patancheru indicated that different GMR mechanisms operating in hybrid parents are complementary, and result in higher levels of GMR in hybrids even when parents themselves may not be grain mold resistant, specifically when flavon-4 ols rich red-grained seed parents were crossed with hard white-grained males (Reddy et al. 2000). Thus, it might be worthwhile to breed hybrid parents for GMR in separate programs to realize hybrids with reasonably higher levels of GMR and with reasonable certainty.

Fodder/sweet sorghum hybrid development: While it might be sufficient to breed male parents for high green fodder productivity potential in order to maximize the chances of developing productive forage hybrids, it is necessary to breed both the hybrid parents for the sweet-stalk trait in order to develop sweet-stalk hybrids with high millable cane and juice yielding abilities. It has been demonstrated that the hybrids based on shoot fly resistant A-lines and landrace pollinators possess the traits required for postrainy season adaptation (such as resistance to shoot fly and terminal drought), and the grain traits (such as pearly white, lustrous and large grains) preferred by farmers (Reddy et al. 2006). This provided impetus to the private sector seed industry to develop and market hybrids with postrainy season adaptation for the first time in India.

Utilization of genetic resources

In pursuit of diversifying breeding products (122 pairs of high-yielding A-lines, 567 pairs of trait-specific A-lines, 873 improved R-lines and 1451 varieties), hybrid parent research programs at ICRISAT-Patancheru could successfully capture both racial as well as geographical diversity. Nearly 4000 germplasm accessions were utilized to generate variability of which 557 lines have contributed to the development of the elite lines referred earlier. The tropical germplasm lines originating from Asia (165) have contributed most, followed by tropical and temperate lines from Africa (162) and USA (105) (Table 1).

Table 1. Summary of origin of sorghum germplasm lines utilized to develop various categories of sorghum genetic materials (ICRISAT-Patancheru, India).

Region/country	Seed parents		Male parents/varieties		Total
	High yielding A-/B pairs	Trait-specific A-/B pairs	Restorers	Varieties[2]	
Asia	16	31	54	64	165
USA	12	25	33	35	105
WCA	1	17	24	45	87
SEA	2	8	18	30	58
ICRISAT[1]	-	6	14	30	50
South Africa	3	3	5	6	17
Australia	-	1	1	3	5
Latin America	-	2	2	-	4
Unknown	1	4	22	39	66
Total	35	97	173	252	557

[1] Breeding materials; [2] Most of the varieties are restorers on A_1 CMS system

These germplasm lines largely belonged to d*urra* (80) (predominantly represented by Asia) and *caudatum* (48) (predominantly represented by Africa) among the basic sorghum races and the *guinea-caudatum* (71) (predominantly represented by Africa) and the *durra-caudatum* (45) (predominantly represented by Asia and Africa) among the hybrid races (Table 2). Genetic diversity in the breeding products is essential for sustainable on-farm production.

Table 2. Race-wise distribution of sorghum germplasm accessions used for developing various categories of sorghum genetic materials (ICRISAT-Patancheru, India).

Race	Number of accessions				Total
	Seed parents		Improved		
	High yielding A-/B-lines	Trait specific A-/B-lines	Restorers	Varieties[1]	
Bicolor (B)		1	10	1	12
Caudatum (C)	3	7	16	22	48
Caudatum- bicolor (CB)	-	5	6	14	25
Durra (D)	6	13	31	30	80
Durra- bicolor (DB)	1	1	4	9	15
Durra -caudatum (DC)	5	5	11	24	45
Guinea (G)	-	2	2	7	11
Guinea-caudatum (GC)	3	10	19	39	71
Guinea- durra (GD)	2	1	2	3	8
Guinea -*kafir* (GK)	1	-	1	2	4
Kafir (K)	4	4	8	6	22
Kafir-bicolor (KB)	1	1	-	1	3
Kafir- caudatum (KC)	-	1	2	1	4
Kafir durra (KD)	5	6	5	4	20
Unclassified	19	25	56	89	189
Total	50	82	173	252	557

[1] Most of the varieties are restorers on A_1 CMS system.

Though several resistant germplasm sources were used to develop grain mold and shoot fly resistant A-/B-lines, only a few germplasm lines have contributed to the final products (Table 3). However, in the newly developed (after 2000) grain mold and shoot fly resistant maintainer lines and the restorer and the varieties that are in the advanced stages of conversion into male-sterile lines (on A_1 and A_2), the higher proportion of the germplasm lines have contributed to the final products (Table 4). The formation of the core collection (Grenier et al. 2001) helped enhanced utilization of these genetic resources. The proposed formation of a mini-core collection (about 10% of the core collection) following the strategy of Upadhyaya and Ortiz (2001) is expected to further enhance the utilization of these genetic resources.

Table 3.The germplasm diversity captured in established and designated grain mold and shoot fly resistant A-/B-lines (ICRISAT-Patancheru, India).

Trait	Number of lines	No. of germplasm lines initially involved	No. of germplasm lines finally contributed
Grain mold resistance	58	197	12
Shoot fly resistance (rainy season adaptation)	28	96	18
Shoot fly resistance (postrainy season adaptation)	27	96	12

Table 4.The germplasm diversity captured in grain mold and shoot fly resistant A-/B-lines (that are in advanced stages of conversion) and in newly-developed high yielding restorers and varieties (ICRISAT-Patancheru, India).

Trait	Number of lines	No. of germplasm lines initially involved	No. of germplasm lines finally contributed
Grain mold resistance	12	16	8
Shoot fly resistance (rainy season adaptation)	31	13	9
Shoot fly resistance (postrainy season adaptation)	30	5	5
Restorers	10	28	26
Varieties	10	28	24

Hybrids development, evaluation and release/marketing

The ultimate worth of the hybrid parents would be known only after making hybrid combinations and testing them in several locations and years in the target regions for critical adaptation traits and resistance to major insect-pests and diseases. The traits such as early maturity, grain yield, and grain quality-evident traits (such as white, medium large grains with semi-corneous endosperm) were given major emphasis in the initial years of hybrid development and testing programs in India and Africa. In Nigeria, red colored grains were also given preference while developing hybrids for brewing purposes. Subsequently, considering the demand for dual-purpose cultivars especially in India, fodder yield was also given due importance during the hybrid testing process apart from grain yield and quality and maturity traits. Yield stabilizing traits such as resistance to *Striga* and stem borer in Africa and resistance to grain mold and shoot fly in India are the other traits that received greater emphasis in hybrid development and testing programs in recent years. Of late, in India, hybrid development for postrainy season adaptation is given more emphasis than ever before. Early maturity and grain quality-evident traits such as white, large and lustrous grains with semi-corneous endosperm (suitable for *chapathi/roti* making) coupled with resistance to shoot fly and lodging, apart from grain and fodder yields, were the important traits considered during selection, while developing and testing of hybrids for postrainy season adaptation in India.

All the hybrids developed and released/marketed so far both in India and Africa are all based on A_1 CMS system. Given the stability of male-sterility, availability of sufficient number of restorers, and *per se* performance and heterosis in hybrid combinations comparable to A_1 CMS system (Reddy et al. 2005a), it is expected that there would be a greater use of A_2 CMS system in future. A_4 (M) is the next priority CMS system for utilization (owing to its relatively higher levels of shoot fly resistance) (Dhillon et al. 2005), once sufficient numbers of restorers are identified and heterosis for economic traits over the standard check varieties/hybrids is demonstrated. The hybrid-testing program involves synthesizing new combination of hybrids to be evaluated each year and progressively reducing their numbers each season to retain only a few unique combinations, which are truly superior to currently cultivated hybrids. As the numbers are reduced, testing becomes more precise and more extensive (more test locations). The final stages of hybrid testing include evaluation in 20 or more locations, majority in farmers' fields in larger plots and seeking farmers' opinion by arranging field days. At ICRISAT-Patancheru, several thousands of grain and dual-purpose A_1 CMS system-based hybrid combinations were synthesized and tested for their performance during 1980-1995. The selected hybrids were included in the regional or international trials and supplied to various cooperators for testing. These hybrids proved to be highly productive compared to the best varieties over the years (Table 5).

Table 5. Estimates of standard heterosis of the best hybrids over the best variety in different regions in International Sorghum Varietal and Hybrids Adaptation Trials (ISVHATs) over the years.

Region	Estimates of standard heterosis (range) of best hybrids over best varieties over the years					
	1989	1990	1991	1992	1993	1994
Asia	10.2 to 207.5	10.6 to 26.2	22.9 to 69.0	16.2 to 59.9	15.7 to 27.3	16.3 to 150.0
Southern and Eastern Africa	10.2 to 37.7	7.7[a]	3.9 to 100	12.3[a]	11.2 to 24.4	*
Western and Central Africa	7.2 to 10.9	9.6 to 19.3	9.6 to 30.4	18.1 to 28.3	29.2 to 52.5	*
Northern Africa (Egypt)	12.0[a]	*	17.3[a]	10.6[a]	19.5[a]	*
Americas	10.4 to 36.2	6.8 [a]	10.9 to 22.0	*	*	*

* Data not available; [a] Data from a single location.

Considering the increasing presence of private seed (PS) companies and their enhanced research and development capabilities, (especially in large PS companies in India) coupled with the emergence of a strong NARS programs over the years with considerable resources and staff time, helped ICRISAT at its Patancheru center in India to concentrate only on the development of the hybrid parents from 1995 onwards allowing both NARS and PS companies to develop region-specific hybrids. Several improved hybrid parents developed at ICRISAT-Patancheru were supplied to NARS in different regions (Table 6).

Table 6. Details of sorghum seed samples of A_1 CMS system-based hybrid parents and hybrids supplied to NARS (ICRISAT-Patancheru, India, 1986-2004).

Region	On request					For testing in trials/nurseries	
	A-lines	B-lines	R-lines	Total A-/B-/R-lines	Hybrids	A-/B-lines	Hybrids
Asia	12928	13240	11632	37800	1677	1148	7303
Eastern and Southern Africa	694	725	638	2057	1277	0	1517
Western and Central Africa	1509	1483	1414	4406	2360	0	3382
Americas	688	940	1274	2902	998	0	738
Total	15819	16388	14958	47165	6312	1148	12940

In the Southern African Development Community (SADC) region, more than 3000 A_1 CMS system-based hybrids were developed based on the seed parents received from ICRISAT-Patancheru and USA since 1983. Up to 1998, three of the eight SADC countries released six A_1 CMS system-based hybrid(s): Zimbabwe (ZWSH 1), Zambia (MMSH 413, MMSH 375, MMSH 1257, and WSH 287) and Botswana (BSH1). Using materials from Texas A & M and parents from ICRISAT-Patancheru, NARS Zambia developed and released a forage sorghum hybrid, FSH 22 in 1995. In the regional sorghum variety and hybrids evaluation trials, hybrids exhibited an average of 41% heterosis in 2000, 33% in 2001, 95% in 2002, and 45% in 2003 (Table 7).

Table 7: Comparative performance of A_1 CMS system-based sorghum hybrids and varieties for grain yield (t ha^{-1}) in Southern African Development Community (SADC) region (2000 to 2003).

Cultivar	2000	2001	2002	2003
Hybrids	2.65	3.84	2.51	2.20
Varieties	1.88	2.88	1.29	1.52
Average heterosis (%)	40.96	33.33	94.57	44.74

At Matopos in Zimbabwe, some of the ICRISAT-bred hybrids produced grain yield of more than 9 t ha^{-1} (while the pioneer hybrids were the next best) in 2004. All these studies clearly showed that the hybrids are the target materials for the farmers. In ECA, during the 1980s, several hybrids (A_1) were tested at Wad Medani, Sudan, and the first experimental hybrid EEH 3 was released in 1983 as Hageen Durra 1 (Ejeta 1985). One of the 22 test hybrids (ICSA 44 × Gadam el Hamam) produced grain yield of 5 t ha^{-1} while, Koboko local 2 (variety) produced 4 t ha^{-1} and Gadam el Hamam (variety) produced 2.6 t ha^{-1} at Kiboko, Kenya during 2003. In Western and Central Africa (WCA), the ICRISAT program in Nigeria also developed A_1 CMS system-based hybrids based on ICRISAT-Patancheru-bred hybrid parents during 1989-96 and the selected hybrids were included in regional testing programs. In ESA and WCA, earliness, drought tolerance and good grain quality traits were the major target traits while developing and testing the hybrids.

Although *caudatum* based-hybrids have shown better yield potential in on-farm trials in Mali, they are not an option for the predominant sorghum production zone (700+ mm rainfall) in the WCA region due to their poorly adapted grain and panicle architecture and photoperiod insensitivity, resulting in severe grain damage due to insects (more compact panicles shelter insects), grain mold and bird damage. Therefore, development of *guinea*-based hybrids offers a more logical approach to increase yield potential of sorghum in WCA, while retaining adaptive and grain quality traits required for stability of production and quality of the end product. The first ever yield trials with *guinea*-based hybrids were conducted in the West African collaborative regional hybrid trials in 2004 using the newly developed *guinea*-based A-lines. The best hybrids significantly out-yielded all the well-adapted check varieties in each location. The mean yield superiority of the 20% highest yielding hybrids over the mean yield of three well adapted *guinea* check varieties was 29% or higher in all environments except the very late-sown environment at Sotuba where it was only 11% (Table 8).

Table 8. The mean grain yield and grain yield superiority of the top 20% highest yielding hybrids relative to the mean grain yield of three well-adapted checks at four locations in WCA (2004, ICRISAT-Bamako, Mali).

Location	Sowing date	No. of top 20% hybrids	Yield of top 20% best hybrids (t ha^{-1})	Check yield[1] (t ha^{-1})	Hybrid superiority (%)
Sotuba-IER, Mali	7-July	29	1.2	1.1	11
Bengou-INRAN, Niger	5-July	7	2.6	2.0	29
On-farm-Wobougou, Mali	28-June	9	2.2	1.6	39
ICRISAT-Bamako, Mali	12-June	22	3.1	2.3	38

[1] Mean of best checks-CSM335, CSM388, and Seguetana

These hybrid parents and hybrid development programs at ICRISAT-Patancheru, led to the release/marketing of 31 A_1 CMS system-based hybrids for commercial cultivation in different regions (Table 9).

Table 9. Region-wise released A_1 CMS system-based sorghum hybrids developed using ICRISAT- Patancheru, India-bred hybrid parents or their derivatives.

Region	Number of hybrids released	Period of release
Asia	15	1986-2000
Eastern and Southern Africa	9	1983-2001
Western and Central Africa	4	1995-1997
Latin America and Caribbean	3	1978-1984
Total	31	1978-2004

The hybrid, CSH 11 developed at ICRISAT-Patancheru was released by Central Varietal Release Committee (CVRC) for commercial cultivation in India. Later, three other hybrids, CSH 14, CSH 17 and CSH 18 were developed involving derivatives of ICRISAT-Patancheru-bred B-line and R-lines bred by Indian Program and released by CVRC for commercial cultivation in India. The PS seed companies are the major beneficiaries of ICRISAT-Patancheru-bred hybrid parents (especially A-lines) in India. Over 54 hybrids based on ICRISAT-Patancheru-bred hybrid parents or their derivatives have been developed and marketed in India. Apart from India, China has derived substantial benefits from ICRISAT-Patancheru-bred hybrid parents and has developed and released several hybrids. Similarly, several hybrids have been developed and released in some African countries. Notable among these are; Hageen Durra 1 and Sheikan (*Striga* resistant) in Sudan and NAD 1 (for brewing quality) in Nigeria.

The first regional trials in West Africa with *Guinea*-race hybrids were conducted in 2004 and 2005. Yield results from 2005 with 40 hybrids combined over four environments in Mali and Niger showed significant yield increase of 40% and higher, over well-adapted landrace varieties. The mean of all hybrids on the A-line, Fambe A was 32% superior to the mean of four landrace check varieties (Table 10).

Table 10. Mean yield and range of all hybrids on each of three A lines (ICRISAT-Bamako, Mali, 2005).

	# Hybrids/ checks	Grain yield (t/ha^{-1})		
		Mean	Minimum	Maximum
Fambe A	23	2.9	2.2	3.7
IP S001A	17	2.6	1.6	3.7
IS3534A	27	2.5	1.5	3.4
Checks	4	2.2	1.8	2.5

However, its/their widespread adoption depend(s) on the farmer/producer acceptance and the availability of hybrid seed. Many a times, it has been observed that the lack of hybrid seed availability at the right time and right quantity are the constraints for hybrid adoption. While exploitation of hybrid technology is a successful story in Asia (more so in India and China) and Latin American countries, it is not so in African countries (barring Egypt and South Africa). Failure of hybrid technology in African countries has been attributed to poor seed systems of NARS coupled with limited presence of private seed companies.

Impacts

ICRISAT-Patancheru-bred hybrid parents have been more extensively exploited in Asian countries for developing high yielding hybrids than in Latin American and African countries. The greatest impact of hybrid parents has been realized in India and China. In India, more than 4 million hectares are covered by over 50 hybrids developed by NARS and the private seed companies based on ICRISAT-Patancheru-bred parental lines or their derivatives. The wide adoption of ICRISAT-PS partnership hybrids, JKSH 22 (210,000 ha in 2002) (Reddy et al. 2004b) and VJH 540 (142,000 ha in 2003) (Reddy et al. 2005d) in the rainy season in major sorghum growing states in India stands testimony to the value and utility of ICRISAT-Patancheru-bred hybrid parents. These are only illustrative examples of the use of ICRISAT-Patancheru-bred hybrid parents and the power of partnership to exploit complementary expertise between ICRISAT and the PS to develop and deliver improved products. In addition, several other ICRISAT-PS partnership hybrids such as JKSH 234, JKSH 434, MLSH 296, VIKI 540, GK 4009, and GK 4013 have been widely adopted in India. Some of the popular hybrids (Longsi 1, Jin Za No.12 and Gilaza 80) released in China between 1982 and 1996 have been developed from ICRISAT-Patancheru-bred parental lines (Reddy et al. 2004b). The adoption of hybrids in China is more than 94% (Deb and Bantilan 2003).

The popularity of PS hybrids, most of which are based on ICRISAT-Patancheru-bred parental lines or their derivatives, has triggered seed production activity in several villages in Andhra Pradesh and Karnataka states in India. It is estimated that on an average, hybrid seed production fetches US$630 ha^{-1}, about three times the income from commercial grain crops. Between 2001 and 2004, a total of 29,800 t of certified hybrid seed of ICRISAT-private sector hybrids was produced, which gave a total income of US$18.8 million to the farmers in these states. Between 1994 and 2002, seed production of the hybrid, JKSH 22, has earned farmers an average of over US$0.3 million per year in Andhra Pradesh and Karnataka states in India, and US$2.7 million per year from cultivation of JKSH 22 in Maharashtra and other sorghum growing areas in India (Reddy et al. 2004b).

Looking ahead

Genetic diversification: At ICRISAT-Patancheru**,** the *caudatum* race has been extensively exploited to develop high yielding male-sterile lines as well as restorer lines, suggesting the need to diversify hybrid parents to enhance the productivity of the hybrids. CMS-based A-lines and R-lines need to be further diversified by creating separate gene pools through crossing between *guinea*- and *durra*-based B-lines and between *caudatum*- and *bicolor/durra*-based R-lines for various traits for both the seasons in India. Of the several non-*milo* CMS systems, A_2 offers an immediate potential for diversifying CMS base of hybrid parents, and hence the hybrids. The hybrid parents' need to be further diversified with *guinea, feterita* and *bicolor* races to improve grain yield and with *dochna* types that originated in Myanmar and other higher biomass types with sweet-stalk (also brown midrib) to improve multicut forage yield potential.

Plant defensive traits: Attempts to breed for resistance to shoot fly, grain mold and stem borer have met with only partial success owing to the low levels of resistance in the available resistance sources. The development and deployment of the hybrids resistant to these major biotic constraints is expected to substantially increase the commercial yield levels considering lower incidence of grain mold, shoot fly and stem borer in farmers' fields. Given that the SFR level in the primary gene pool (eg, IS 18551; 2n=20) is low to moderate and depends on insect density (Sharma et al. 2005), the use of wild sorghums such as *S. purpureosericeum* and *S. versicolor*, the members of the section *Parasorghum,* which are known to have high levels of SFR (Bapat and Mote 1982) would not only help enhance resistance levels, but also help diversify the genetic base of the hybrid parents. Also, considering higher levels of SFR, the A_4 (Maldandi) CMS system (Dhillon et al. 2005) needs to be tapped for the development of hybrids for postrainy season adaptation. The lower restorer frequency on A_4 (Maldandi) could be increased by extensive use of Maldandi sources while diversifying A_4 (Maldandi) CMS-based A-lines. The use of Maldandi sources also ensures a moderate level of SFR, besides ensuring grain-quality traits such as pearly white, bold and lustrous grains that match with M 35-1. Gidda Maldandi with D_2 dwarf genes can be exploited to develop A-lines for postrainy season adaptation. Resistance to stem borer is also important in sweet-stalk and forage sorghum cultivars, as stalks are the main economic product. Low levels of resistance in cultivated types and the complexity of inheritance warrants the use of genetic transformation to enhance the levels of resistance to stem borer.

Considering the complexity of inheritance and operation of different mechanisms for GMR, efforts can be made to identify suitable molecular markers to enable pyramiding of the genes associated with various mechanisms in high yielding hybrid parents. Head bug damage, which is a serious yield constraint in West Africa and in India in the rainy season, promotes grain mold severity. Therefore, it might be useful to develop cultivars with dual resistance to grain mold and head bug. Substantial genetic variability for tolerance to soil salinity and acidity suggests that there is good scope for genetic enhancement of sorghum for tolerance to these abiotic stresses.

Grain micronutrient density: Considerable genetic variability, coupled with high broad-sense heritability, suggests good prospects of genetic enhancement for grain iron (Fe) and Zinc (Zn) density through conventional breeding complemented by molecular breeding.

Exploring and establishing heterotic groups: As the long term success of hybrid breeding depends on maintaining distinct parental pools that produce hybrids with high heterosis, a priority activity is characterizing patterns of heterosis in the diverse sorghum germplasm adapted for each target condition. Studies are underway with *guinea*-race germplasm.

Summary

Sorghum is the first self-pollinated cereal staple crop, wherein heterosis has been commercially exploited due to the availability of a stable and heritable CMS system to improve its productivity. Considering the success of CMS-based hybrid technology in sorghum, continued investments have been made on sorghum hybrid parents and hybrid development research at ICRISAT-Patancheru, India. Hybrid parents' research at ICRISAT's regional hubs in Africa is still in its infancy, but is moving ahead. The Hybrid parents' research at ICRISAT has under gone several changes as guided by the external environment, donor and NARS perceptions, NARS capacity and changing crop requirements and opportunities. The trait-based breeding approach followed at ICRISAT resulted in a large number of trait–specific seed parents and R-lines and/or varieties, which have been shared with NARS scientists. This approach enabled capturing both racial and geographical diversity and hence the trait-based A-lines and R-lines retained substantial genetic diversity, which is essential for sustainable crop production. These hybrid parents were evaluated for soil acidity and salinity tolerance, multicut trait, sweet-stalk trait, and grain Fe and Zn density and several promising A-/B-lines for the different traits have been identified. The hybrid parents developed at ICRISAT's African locations have good potential for developing hybrids adapted to regional production environments. Apart from hybrid parents, the sharing of appropriate genetic materials for conducting strategic research and the information on strategic research findings have helped improve sorghum improvement efficiency of both ICRISAT and NARS. ICRISAT-Patancheru-bred hybrid parents have been more extensively exploited in Asian countries compared to Latin American and African countries. The NARS have developed and released/marketed several hybrids based on ICRISAT-Patancheru-bred hybrid parents after extensive testing. The greatest use of hybrid parents has been realized in India and China. New frontiers of research such as identification of genes from wild species for shoot fly resistance and genetic engineering option for stem borer resistance, molecular breeding to complement conventional breeding for resistance/tolerance to grain mold, low temperature, soil salinity, soil acidity and grain Fe and Zn deficiency and deploying them to improve hybrid parents and improvement of seed parents for sweet-stalk trait are proposed.

Acknowledgements: The grants from ICRISAT-Private Sector Sorghum Hybrid Parents Research Consortium, Organization of Petroleum Exporting Countries (OPEC) fund for International Development, HarvestPlus project, Sehgal Family Foundation in partial support of sorghum hybrid parents' research and Rockefeller Foundation are gratefully acknowledged. We are thankful to Bettina Haussmann, Senior Scientist (Pearl Millet Breeding) for her critical inputs and comments, which helped improve the quality of the manuscript.

References

Bapat DR and **Mote UN.** 1982. Sources of shoot fly resistance in sorghum. J. Maharashtra Agric. Univ. 7: 238-240.

Conner AB and **Karper RE.** 1927. Hybrid vigor in sorghum. Texas Experiment Stations Bulletin no 359. Texas A&M University, Texas, USA.

Deb UK and **Bantilan MCS.** 2003. Impacts of genetic improvement in sorghum. Pages 183–213 *in* Crop variety improvement and its effect on productivity—The Impact of International Agricultural Research (Everson RE and Gollin D eds.), Wallingford, UK: CABI Publishing.

Dhillon MK, Sharma HC, Reddy BVS, Ram Singh, Naresh JS and **Zhu Kai.** 2005. Relative susceptibility to different male-sterile cytoplasms in sorghum to shoot fly, *Atherigona soccata.* Euphytica 144: 275-283.

Ejeta G. 1985. Overcoming problems encountered in production, distribution and adoption of hybrid sorghum seed in the Sudan *in* La Produccion de la semilla de sorgo en America Latina (Guiragosian V, Paul C and Peterson G, eds), CIMMYT Londres 90, Apdo, 6-641, Mexico CP 06600D.F Mexico.

El'konin LA, Kozhemyakin VV and **Ishin AG.** 1996. Nuclear-cytoplasmic interactions in restoration of male fertility on "9E" CMS-inducing cytoplasm. International Sorghum and Millets Newsletter 37: 52-53.

FAO (Food and Agriculture Organization). 1960-96. FAO Production Year Book 1960-1996. Food and Agriculture Organization of United Nations, Rome, Italy.

Grenier C, Bramel PJ and **Hamon P.** 2001. Core collection of the genetic resources of sorghum: 1. Stratification based on eco-geographical data. Crop Science 41: 234–240.

House LR, Verma BN, Ejeta G, Rana BS, Kapran I, Obilana AB and **Reddy BVS.** 1997. Developing countries breeding and potential of hybrid sorghum. Pages 84-96 *in* Proceedings of the International Conference on Genetic Improvement of Sorghum and Pearl Millet, Lubbock, Texas, USA, 22-27 Sep 1996. Lincoln, Nebraska, USA. Collaborative Research Support Program on Sorghum and Pearl millet 97-5.

Lonkar SG and **Borikar ST**. 1994. Inheritance of A_1 and A_2 cytoplasmic genetic male sterility in sorghum. J. Maharashtra Agric. Univ. 19: 450.

Majisu BN and Dogget H. 1972. The yield stability of sorghum varieties and hybrids in East Africa environments. East Africa Agricultural Forest J. 1972:179-192.

Obilana AB. 1998. Sorghum improvement: International Sorghum and Millets Newsletter 30: 4 -17

Qian ZQ. 1990. Discussions on the inheritance of A_1 cytoplasmic male sterility and the establishment of differentiating line for restoring genotype in sorghum. Hereditas 12: 11-12.

Ramesh S, Reddy BVS, Reddy PS, Hebbar M and **Ibrahim M.** 2005. Response of Selected Sorghum lines to Soil Salinity-Stress under Field Conditions. International Sorghum and Millets Newsletter 46: 14-17.

Reddy BVS, Bandyopadhyay R, Ramaiah B and **Ortiz R.** 2000. Breeding grain mold resistant sorghum cultivars. Pages 195-224 *in* Technical and Institutional Options for Sorghum Grain Mold Management (Chandrashekar R, Bandyopadhyay R and Hall AJ eds.). Proceedings of an international consultation, 18-19, May 2000, Patancheru, Andhra Pradesh, India: International Crops research Institute for the Semi-Arid tropics.

Reddy BVS and **Prasad Rao KE**. 1992. Breeding new seed parents: Breeding non-*milo* restorer lines. Pages 63-64 *in* Cereals Program, ICRISAT Annual Report 1991, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Reddy BVS, Ramesh S and **Gowda CLL.** 2005d. Forging Research and Development Partnerships with Private Sector at ICRISAT-Sorghum as a Case Study. International Sorghum and Millets Newsletter 46: 6-10.

Reddy BVS, Ramesh S and **Longvah T.** 2005c. Prospects of Breeding for Micronutrients and β-carotene-Dense Sorghums. International Sorghum and Millets Newsletter 46: 10-14.

Reddy BVS, Ramesh S and **Ortiz R.** 2005a. Genetic and Cytoplasmic-Nuclear Male-sterility in Sorghum. Plant Breeding Reviews 25: 139-172. John Wiley & Sons, Inc., New Jersey, USA.

Reddy BVS, Ramesh S, Reddy PS, Ramaiah B, Salimath PM and **Rajashekar Kachapur.** 2005b. Sweet Sorghum-A Potential Alternative Raw Material for Bio-ethanol and Bio-energy. International Sorghum and Millets Newsletter 46: 79-96.

Reddy BVS, Ramesh S and **Reddy PS.** 2004b. Sorghum Breeding Research at ICRISAT-Goals, Strategies, Methods and Accomplishments. International Sorghum and Millets Newsletter 45: 2-12.

Reddy BVS, Rangel AF, Ramaiah B and **Ortiz R.** 2004a. A research and network strategy for sustainable sorghum production systems for Latin America. Pages 139-148 *in* Sorghum Genetic Enhancement: Research Process, Dissemination and Impacts (Bantilan MCS, Deb UK, Gowda CLL, Reddy BVS, Obilana AB and Evenson RE, eds), Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Reddy BVS, Ramesh S and **Reddy PS.** 2006. Sorghum Genetic Resources, Cytogenetics, and Improvement. Pages 309-363 *in* Genetic Resources, Chromosome Engineering and Crop Improvement, Cereals, Volume 2 (Singh RJ and Jauhar PP, eds), CRC Press, Taylor & Francis Group, Boca Raton, Florida, USA, 442 PP.

Sharma HC and **Nwanze KF.** 1997. Mechanisms of Resistance to Insects in Sorghum and Their Usefulness in Crop Improvement. Information Bulletin no. 45. Patancheru 502 324, Andhra Pradesh, India: ICRISAT. 51 pp.

Sharma HC, Reddy BVS, Dhillon MK, Venkateshwaran K, Singh BU, Pampapathy G, Folkertsma RT, Hash CT and Sharma KK. 2005. Host Plant Resistance to Insect Pests in Sorghum: Current Status and Future Priorities. International Sorghum and Millets Newsletter 46: 36-43.

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

Tatum LA. 1971. The southern corn leaf blight epidemic. Science 171: 1113-1116.

Upadhyaya HD and **Ortiz R.** 2001. A mini core subset for capturing diversity and promoting utilization of chickpea genetic resources in crop improvement. Theoretical and Applied Genetics 102: 1292-129

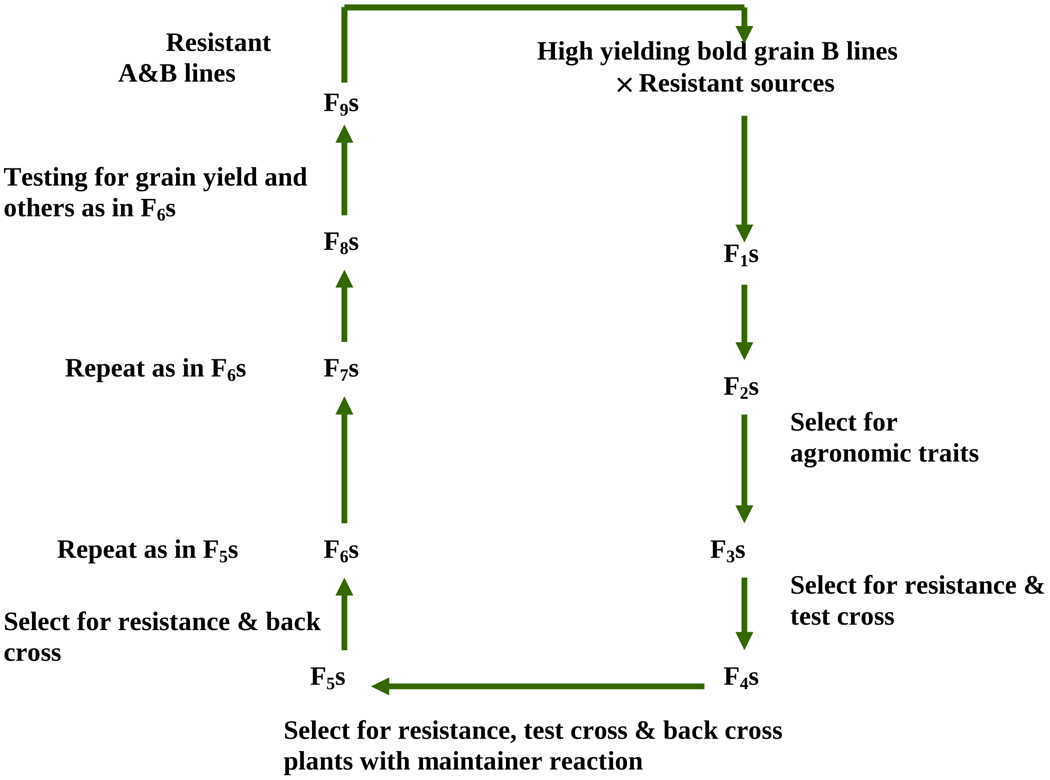

Figure 1: Method of breeding for sorghum male-sterile lines resistant to yield constraints.