Hybrid Parents Research at ICRISAT

International Crops Research Institute for the Semi-Arid Tropics

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Abstract

Hybrid cultivars in maize revolutionalized agriculture in many countries, leading to substantial and sustained increase in production and productivity in the past five decades. This success was emulated by other crops, including sorghum and pearl millet. Recent discovery of cytoplasmic-nuclear male sterility (CMS) system in pigeonpea is paving way for the possible release of hybrid cultivars to increase productivity and production of this crop as well.

This book has attempted to review the hybrid parents research at ICRISAT, to provide the available research information and knowledge to the global research and development community. The introductory chapter gives an overview of the evolution of hybrid parents research in sorghum, pearl millet and pigeonpea at ICRISAT, including the rationale and priority setting for conducting research on various aspects of hybrid parents. Individual chapters on sorghum, pearl millet and pigeonpea detail the historical aspects of research and development, changes in research priority to cope with user needs and research developments, and providing the latest scenarios for hybrid options. These crop chapters also contain research results and knowledge generated on various CMS systems and their usefulness in hybrid breeding, including efforts to diversify the CMS systems to prevent any future disease or insect pest epidemics.

Public-private partnership is emerging globally. ICRISAT is a pioneer in enhancing this partnership to ensure that seed of hybrid cultivars is available to the resource-poor farmers at reasonable costs.

The implication and relevance of ICRISAT's hybrid parents research globally has been discussed.

Hybrid Parents Research at ICRISAT

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Contents

Foreword

Agriculture is the backbone of development in many countries, especially in the developing countries. Agricultural scientists and farmers have fed the world population over the millennium, averting disasters in several countries. Similar to other fields of research, innovation has played a major role in increasing production and productivity of many agricultural commodities. The concept of hybrid cultivars was one such innovation that has revolutionized the productivity and production of many staple food crops, fruits and vegetables. Hybrids in maize have significantly contributed towards food security in several developing countries. The success of hybrid cultivars of sorghum in many countries globally, and pearl millet in India, has been remarkable in the past 30–40 years. ICRISAT can claim some credit in enhancing the productivity of pearl millet and sorghum, especially in India and China (sorghum).

In the initial years of ICRISAT's establishment (late-1970s and early-1980s), the major emphasis was on developing improved populations and composites, and open-pollinated varieties (OPVs). However, with the rapid development of hybrid seed industry in Asia (particularly in China, India and Thailand), and the comparatively higher grain yield (25–30% more than OPVs) and better adaptation to diverse climatic areas, ICRISAT-India (and to some extent ICRISAT programs in sub-Saharan Africa) re-oriented the sorghum and pearl millet improvement programs to breed hybrids. In Asia, the breeding programs focused on developing improved breeding lines and parental lines of potential hybrids, and delegating the responsibility for development, testing and release of hybrids to the public sector institutions and private sector seed companies. Because of the proactive role of national program partners and private seed companies, the hybrid development research bloomed, and is now a billion dollar industry in India. In sub-Saharan Africa, although ICRISAT programs were involved in developing and promoting adapted and high-yielding hybrid combinations, hybrids are yet to make a mark in this region except for sorghum hybrids in Nigeria.

Research on hybrids in pigeonpea is a more recent development. Genetic male sterility (GMS) system in this crop was discovered in 1978. ICPH 8, the first hybrid (based on GMS), was released in 1991. Subsequently, 6 more hybrids were released by Indian national programs. However, the hybrids did not become popular because of the difficulties in hybrid seed production and high cost of hybrid seed. With concerted efforts, ICRISAT scientists (in partnership with Indian NARS) were able to identify four cytoplasmic-nuclear male sterility (CMS) systems. The breeding material and technology for hybrid seed production has been shared with the national program scientists in both public and private sectors. It is likely that high-yielding pigeonpea hybrids will be available to farmers in next two years.

This technology is especially significant in the context of adaptation of these crops to diverse environments and their potential values in crop diversification and enhancement of system productivity. Apart from the grain values of these crops, they are also important for their forage values.

This book reviews ICRISAT's research efforts in sorghum, pearl millet and pigeonpea hybrid parents development and provides insights into the future. It is hoped that the information presented in this book will be useful to the agricultural research and development community globally for enhancing production and productivity of sorghum, pearl millet and pigeonpea.

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1. Evolution of Hybrid Parents Research

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The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has a mandate to contribute to improved and sustainable agricultural production in the semi-arid tropical regions of the world through integrated genetic and natural resource management (IGNRM) technologies. Sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), and pigeonpea (*Cajanus cajan*) are the three of its five mandate crops. Sorghum is the most important crop, cultivated on about 45 million ha in Asia and Africa. Asia cultivates 11 million ha with India having the largest area (9 million ha) in the world. Pearl millet is cultivated on 26 million ha in Asia and Africa. In India, it is cultivated on 10 million ha, which is >80% of the total pearl millet area in Asia, and largest in the world. Pigeonpea is cultivated on 4.1 million ha globally, with India having the largest area (3.2 million ha). Thus, considering the large area under these crops in India and the diverse agro-ecologies in which they are cultivated, it is assumed that hybrid parents research at ICRISAT in India will have direct implications on increasing the productivity and stability of these crops in several parts of Asia, with spill-over effects in parts of Africa that have similar agro-ecological adaptations.

Pearl millet is a highly cross-pollinated crop with protogynous flowering and wind-borne pollination mechanism, which fulfils one of the essential biological requirements for hybrid development. Sorghum is a predominantly self-pollinated crop, but use of male sterility leads to complete cross pollination in sterile plants, through wind-borne pollen, thus making it behave like a cross-pollinated cop. Pigeonpea, like sorghum, is also a predominantly self-pollinated crop, but insect-borne pollination and male sterility lead to complete cross-pollination in male-sterile plants. High degree of outcrossing leads to open-pollinated varieties (OPVs) and hybrids as the two cultivar options in pearl millet where heterosis can be exploited to enhance the productivity of this crop. However, OPVs permit only partial exploitation of heterosis. In sorghum and pigeonpea, hybrids provide the only option for the exploitation of heterosis. In all three crops, hybrids have about 20–30% grain yield advantage over varieties (Reddy et al. 2004).

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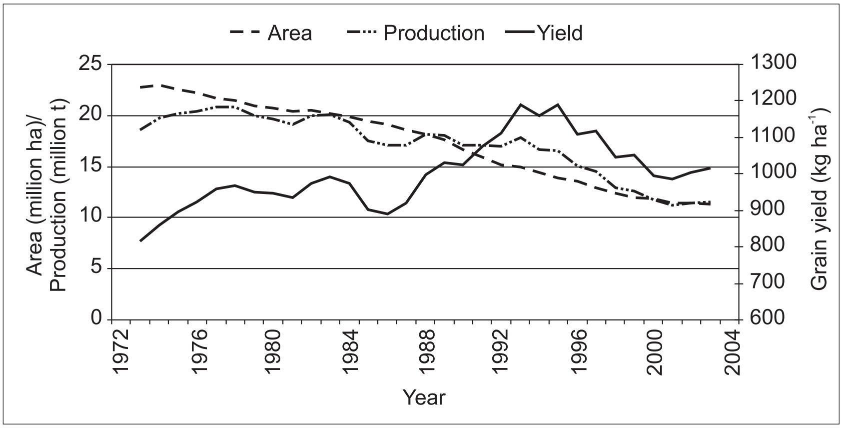

Figure 1.1. Three-year moving average for sorghum area, production and grain yield in Asia.

Hybrid parents research on sorghum at ICRISAT, Patancheru, India has made some contributions to enhancing the productivity of this crop in Asia (Fig. 1.1). The greatest impact of this research, however, has occurred in India, where development of high-yielding hybrids (based largely on ICRISAT-bred materials) and their large-scale adoption played a major role in enhancing its productivity from 650 kg ha^{-1} of grain yield during mid 1980s to 800 kg ha^{-1} during 2000–04, registering 23% gain in productivity (Fig. 1.2). Pearl millet hybrids, mostly developed from ICRISAT-bred parental lines and improved

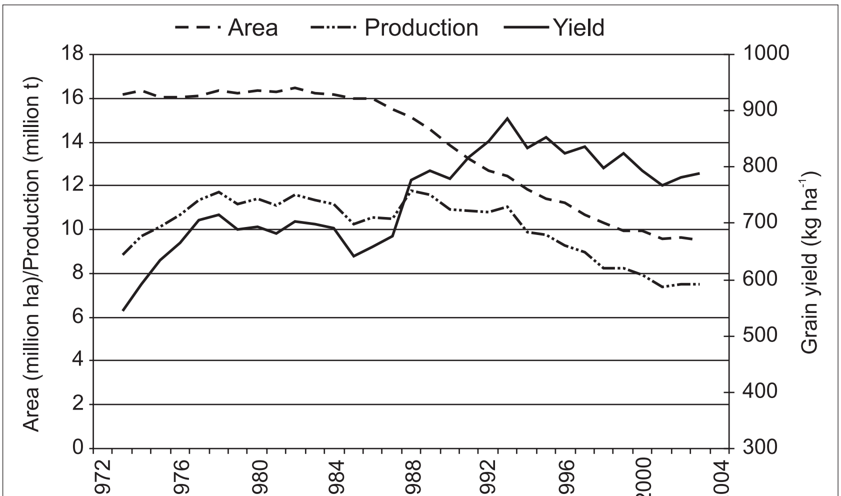

Figure 1.2. Three-year moving average for sorghum area, production and grain yield in India.

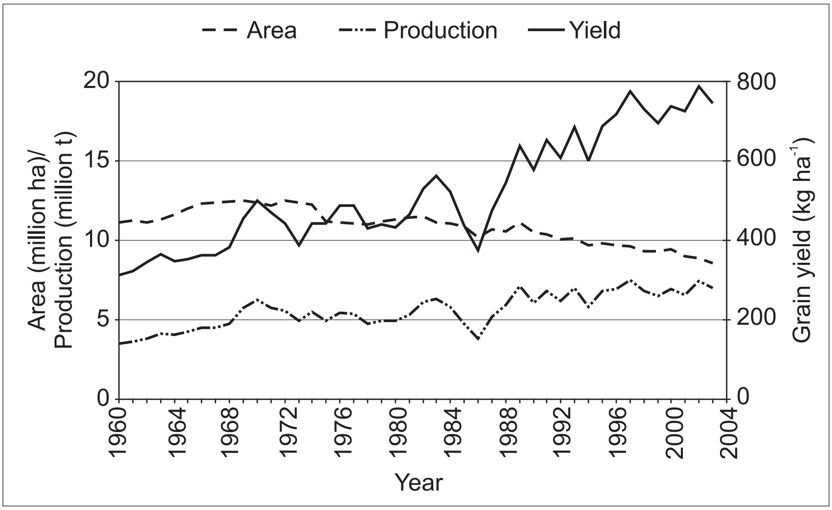

Figure 1.3. Three-year moving average for pearl millet area, production and grain yield in India.

germplasm, have made even greater contributions to productivity enhancement as reflected in grain yield increase from 450 kg ha^{-1} during mid 1980s to 750 kg ha^{-1} during 2000–04 (66% increase) (Fig. 1.3). These productivity gains have led to increased production despite decline in cultivated area under these crops. In case of pigeonpea, there has been no adoption of hybrids because there have been no commercial hybrids produced, and productivity has been stagnant in India (Fig. 1.4). In case of both sorghum and pearl millet, the observed increase in productivity perhaps has not been only due to the adoption of high-yielding hybrids. Adoption of improved crop management technologies have also contributed to these yield gains, though hybrid seed may have worked as a catalyst for the adoption of improved management practices.

Much before ICRISAT was established in 1972, availability of commercially exploitable cytoplasmic-nuclear male sterility (CMS) systems in sorghum and pearl millet led to hybrid development and their adoption in early 1960s. However, considering the relatively higher cost of seed of hybrids as compared to OPVs, complexity of hybrid parents development and their commercialization, and the perceived wider adaptation potential of OPVs as compared to hybrids, ICRISAT laid major emphasis on the development of improved populations and OPVs both in sorghum and pearl millet. With the rapid development of sorghum and pearl millet hybrid seed industry in India,

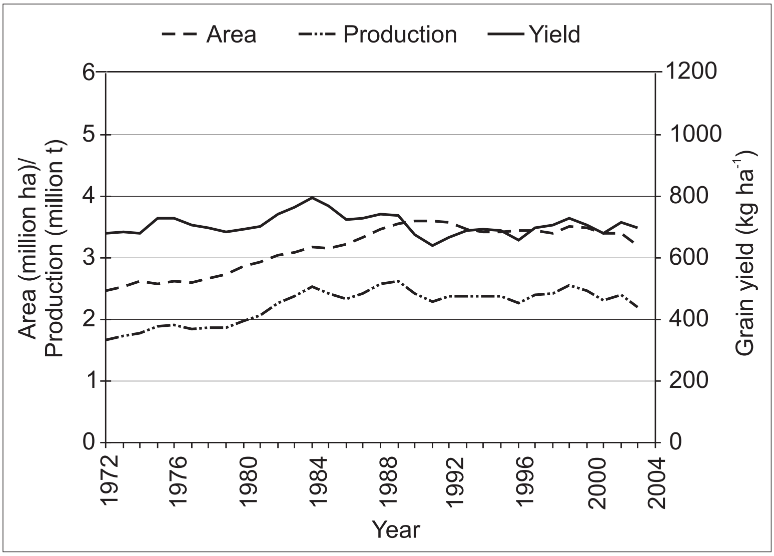

Figure 1.4. Three-year moving average for pigeonpea area, production and grain yield in India.

which is a major single country in the world cultivating both sorghum and pearl millet, and the evidence that hybrids in both crops have 25–30% yield advantage over OPVs, ICRISAT-Patancheru center gradually reoriented the genetic improvement programs of both crops to align with the cultivar priority of the public and the private sector seed industry. ICRISAT also visualized a comparative advantage and more effective utilization of its resources in restricting its role to the germplasm introgression, and development of improved breeding lines and parental lines of the potential hybrids. Development, testing and release of hybrids was delegated to the public and private sector programs, particularly in India.

ICRISAT scientists realized the greater complexities involved in breeding seed parents (male-sterile lines or A-lines) than in breeding pollen parents (restorer lines or R-lines). It was also realized that genetic diversification of hybrids with high yield potential was being hampered more due to the lack of diverse and productive seed parents than due to the lack of restorer parents. There was a widely felt need for cytoplasmic diversification of A-lines to prevent any disease or insect pest epidemics that could result from cytoplasmic uniformity arising from a single CMS system deployment in hybrids. These considerations guided the hybrid parents research to place greater emphasis on seed parents development than on restorer parents development. ICRISAT took lead in assembling the CMS sources from various research centers and conducting its own search for new CMS sources. These were characterized for their relative usefulness in breeding seed parents, and utilized for seed parents development. Thus, while all the commercial hybrids both in sorghum and pearl millet currently grown in India and elsewhere are based on A-lines having the A_1 CMS system, alternative CMS systems (the A_2 CMS system in sorghum, and A_4 and A_5 CMS systems in pearl millet) were used to develop a diverse range of A-lines. Considerably greater emphasis has recently been placed in using these alternative CMS systems both for cytoplasmic and genetic diversification of A-lines.

In pigeonpea, ICRISAT played a leading role in developing a hybrid breeding technology by using a genetic male sterility system (Saxena et al. 2005b). It was soon realized that high seed production cost was a major barrier in the commercialization of pigeonpea hybrids, and this can be overcome by the CMS system. Intensive search at ICRISAT for CMS sources led to the identification of several CMS sources from related wild species, but not all of these proved commercially viable due to either instability of the male sterility of A-lines, or low frequency of R-lines and their partial fertility restoration behavior. The breakthrough finally came with the identification of an A_4 CMS source in a cross-compatible wild relative, *Cajanus cajanifolius* (Saxena et al. 2005a), which has been shown to have stable male sterility and high frequency of restorers with excellent fertility restoration (except at low temperatures during flowering). This CMS source is now extensively being used in breeding A-lines of potentially commercial hybrids. While there may be no need to search for any more CMS sources in sorghum and pearl millet, the search for alternative CMS sources in pigeonpea will continue until at least one more commercially viable CMS source comparable to or better than the A_4 source has been discovered. Initially, pigeonpea research will be focused on development of experimental hybrids to demonstrate the usefulness of parental lines and commercialization potential of hybrids. Once this objective has been achieved, research on this crop will follow the pattern similar to that in sorghum and pearl millet, ie, restricting its role to the development and dissemination of a diverse range of parental lines and improved germplasm.

High grain yield potential of the parental lines per se is as important as their high grain yield potential in hybrids, ie, general combining ability (GCA). This attribute must be combined with their resistance to key important diseases and insect pests, tolerance to abiotic stresses, and farmer-acceptable grain and stover quality. These requirements vary considerably across the three crops, and thus have received varying levels of attention in the breeding programs of these crops. For instance, the grain and fodder quality requirements in pearl millet are not that stringent as those in sorghum. Also, pearl millet does not suffer from as many diseases and insect pest problems as do sorghum and pigeonpea. Further, pearl millet is much less affected by the photo-thermal variations than sorghum and pigeonpea. While many of the yield, adaptation and quality aspects were addressed in the initial years of the programs, they were later narrowed down to fewer aspects of greater importance and to those where the probability of success was considered to be high.

Hybrid parents research in sorghum placed greater emphasis for rainy season than for postrainy season because the former had relatively larger cultivated area, the yield potential was higher, the germplasm diversity was larger, and grain and fodder quality requirements were relatively less stringent. Similarly, in pearl millet, breeding for relatively better-endowed environments received greater research attention because of larger area under such environments, and greater probability of success. In pigeonpea, highest priority was given to medium maturity as the area under this maturity duration is highest, the germplasm base to address this duration is large, and the hybrids based on the A_4 CMS system have complete male fertility restoration. In sorghum, breeding for biotic stresses was narrowed down to grain mold (among the diseases) and to shoot fly (among insect pests), while in pearl millet it was narrowed down to downy mildew disease. In pigeonpea, wilt and sterility mosaic have continued to receive highest priority among the diseases. For pigeonpea hybrid technology to succeed and be adopted on large scale by farmers, resistance to pod borer (*Helicoverpa armigera*) will have to be incorporated into hybrids. Significant progress has been made through conventional approaches in breeding for resistance to downy mildew in pearl millet, and wilt and sterility mosaic in pigeonpea, with modest gains made in breeding for resistance to grain mold and shoot fly in sorghum.

ICRISAT has been pursuing trait-based breeding of parental lines in all three crops, for several reasons. The user-demand has almost always been for certain traits or trait combinations, be it germplasm or improved breeding materials. Some of the most common traits included in the seed request are maturity, plant height, head type, grain size, shape and color, and resistance to certain diseases and pests (including specific pathotypes/races). These traits are important for farmers' acceptance of hybrids and relatively easy to breed due to relatively greater heritability and hence efficient selection in a single-location evaluation nursery. Studies conducted in four trait-specific pearl millet trials have shown significant and high positive correlation between the agronomic scores of grain yield and measured grain yields, indicating that visual evaluation of grain yield potential is fairly effective, particularly as a discarding procedure. When applied over successive generations of selection and generation advance, this procedure also permits selection for yield stability.

As far as the genetic improvement for GCA is concerned, apart from the critical choice of an effective tester (still remains debatable), GCA evaluation is a resource-consuming breeding operation, which must be conducted multilocationally to be effective. ICRISAT does not have access to multilocational test facilities for conducting combining ability trials. Further, there is evidence from numerous studies both in sorghum and pearl millet that either there is no correlation between per se performance of the lines and their GCA, or the correlation is positive and significant. The implication of the former case is that when high GCA lines are equally likely to occur in a wide range of yield classes, then why not look for them in high-yielding lines. The implication of the latter case is that high GCA lines are more likely to occur in high-yielding lines, so then why not select first for line yield (easier and more cost-effective to evaluate than GCA evaluation) and then later evaluate for combining ability [both GCA and specific combining ability (SCA)]. In fact, most breeding programs in the commercial seed industry sector use restorers of their best hybrids for testing the combining ability of their seed parents, and vice-versa. This is done in tandem, which is basically the genetic improvement for SCA. However, this approach is effective when the breeding of parental lines of hybrids is targeted for a specific ecoregion. In case of ICRISAT with an international mandate, and with a responsibility to generate a diverse range of breeding materials adapted to diverse ecoregions, no single tester can reliably select lines with high CGA that are suitable to various ecoregions. This would imply using different testers on both male and female sides, and thus requiring expanded research base beyond the available resources.

Conventional breeding approaches have proved successful in generating a diverse range of breeding lines and parental lines of potential hybrids, which have been extensively used by the public and private sector breeding programs. This is reflected in more than 70 hybrids of pearl millet under cultivation in India, of which about 60 are based on ICRISAT-bred male-sterile lines, or on proprietary parental lines developed from the ICRISAT-bred improved germplasm. Similarly, more than 60 hybrids of sorghum are under cultivation in India, of which at least 50 are based on ICRISAT-bred parental lines, or on proprietary parental lines developed from ICRISAT-bred improved germplasm. Some of the more intractable problems such as drought tolerance in sorghum and pearl millet and shoot fly in sorghum are being addressed through marker-assisted selection (MAS), and genetic management of pod borer can be most effectively done through the application of transgenic technology. Use of disease screening nurseries has been effective in breeding for resistance to downy mildew in pearl millet, and wilt and sterility mosaic in pigeonpea. However, MAS has proved effective in pyramiding resistance genes for downy mildew in pearl millet, leading to the development of a resistant version (HHB 67-2) of an extra-early-maturing and highly popular commercial hybrid (HHB 67) that has recently been showing signs of increasing susceptibility to this disease. The biotechnological approach to genetic enhancement is increasingly being integrated with the mainstream conventional breeding, where it enhances the speed and precision of breeding with good probability of success and acceptable cost-effectiveness.

New research areas have recently emerged in hybrid parents research, in response to emerging challenges and opportunities. These relate to forage research on all three crops to address the increasing requirement for green fodder for a growing livestock population; micronutrient enrichment research in sorghum and pearl millet to address nutritional security; sweet sorghum research for biofuel production to address the energy security; salinity tolerance research in sorghum and pearl millet to enhance productivity of these crops in the traditional saline areas and to position them for new niches in non-traditional saline lands; and vegetable pigeonpea for dietary diversification and income generation.

Pigeonpea hybrid parents research is progressing remarkably and will achieve the same success as in sorghum and pearl millet. One of the key factors behind these successes has been strong partnerships with both public and private sectors, which have made more effective use of comparative advantages arising from complementary resources and skills. The synergy generated from these partnerships has enhanced the pace and scale of research impacts. This partnership itself has evolved over time, from unstructured collaboration to structured partnership, and the creation of ICRISAT-Private Sector Hybrid Parents Research Consortia (Gowda et al. 2003), which have grown from nine seed companies joining sorghum and pearl millet consortia in 2000 to 34 seed companies being members of the consortia of sorghum, pearl millet and pigeonpea in 2006.

Since most of ICRISAT's research on the hybrid technology of these crops has been done at Patancheru, the research results are mostly relevant to Asia region. However, the approaches followed and the research results (both strategic and applied) will have implications for developing hybrid research programs on these crops in Africa and elsewhere. For instance, efficient screening procedures for various stress factors, CMS systems and their restorers discovered at ICRISAT, or discovered elsewhere but characterized for their potential at ICRISAT, would have global implications. The breeding approaches followed for trait prioritization and genetic enhancement, evolution of relative emphasis on hybrid development and hybrid parents research vis-à-vis comparative advantages with the national agricultural research systems (NARS) and private sector research, and partnership development will also have implications for other hybrid breeding programs. The applications of these results and approaches to the African regions are likely to benefit from an objective analysis of the research and development needs in the different regions of Africa. For instance, single-cross hybrids are the only adoptable hybrid cultivars of pearl millet in India. Such cultivars may not be the right starting point for hybrid development in the African regions on account of the seed production cost, and greater vulnerability of such cultivars to downy mildew and panicle diseases. Research conducted in the African regions has shown that topcross and inter-population hybrids with 20–30% grain yield advantage over the higher-yielding parental populations can be produced. Thus, the initial thrust should be more on topcross and inter-population hybrids. Development of fully male-sterile populations to satisfy the developmental need of inter-population hybrids has been a concern. Feasibility of breeding fully male-sterile population has clearly been demonstrated (Rai et al. 2000), thus paving the way for evaluating the yield potential of commercial inter-population hybrids. The availability of the more stable A_4 and A_5 CMS sources with high frequency of maintainers provides the mechanism for rapid conversion of any productive population into its male-sterile version.

Some of the African regions having adaptation requirements similar to those of the Indian agro-ecologies may directly benefit from the hybrid parents and elite breeding lines developed at ICRISAT-Patancheru. This applies to pearl millet and pigeonpea materials for eastern and southern Africa (ESA) and to sorghum materials for ESA region as well as for western and central Africa (WCA). The three chapters that follow present a strategic review rather than a complete listing of the hybrid parents research work on these crops at ICRISAT.

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2. Pearl Millet Hybrid Parents Research: Approaches and Achievements

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The protogynous flowering in pearl millet (*Pennisetum glaucum*) makes it a highly cross-pollinated crop with outcrossing rate of over 85%. The outbreeding system makes open-pollinated varieties (OPVs) as the natural cultivar state of this species. Pearl millet displays high degree of heterosis for grain yield (Virk 1988). The OPV option, however, allows for only partial exploitation of heterosis. Sustainable improvement in grain yield through OPVs faces a major dilemma. On one hand, crosses between morphologically similar genotypes/varieties generate little genetic variability to sustain significant genetic gains, though they permit rapid development of OPVs with acceptable morphological uniformity. On the other hand, crosses between dissimilar types create more heterotic F_1s and large variability in the subsequent generations for sustainable genetic improvement, but populations derived from such crosses also reduce the pace of developing OPVs with acceptable morphological uniformity. Hybrid route provides an excellent opportunity to use dissimilar parental lines to harness heterosis to its maximum possible extent, and yet produce a cultivar with high degree of morphological uniformity. The breeding system and extent of heterosis, and availability of stable cytoplasmic-nuclear male sterility (CMS) and its fertility restorers, have made the hybrid option commercially viable in pearl millet.

In the recent years, especially since late 1990s, there has been a significant decline in research efforts related to OPV development at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India and elsewhere in the country, primarily because of the greater attention paid to hybrid development due to yield superiority of hybrids over OPVs, and also because of the significant positive (and now increasingly dominant) roles of private sector in hybrid technology upgradation and transfer. Considering the limited impacts made through OPV breeding in the African regions, and

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a realization that not much headway in pearl millet productivity gains can be expected unless private sector gets involved in technology upgradation and seed business, hybrid development efforts are likely to increase in these regions.

Applied hybrid parents research at ICRISAT-Patancheru has made significant contributions to enhancing hybrid cultivar diversity and increasing the productivity of this crop in India. Some of the breeding products from this research may have direct applied value for hybrid development mostly in India, and also in similar agro-ecoregions elsewhere. The strategic research results have the potential of contributing to more efficient hybrid development strategies globally.

The purpose of this review is to summarize, in a strategic context, the approaches that have been followed, the results that have been achieved, and the impacts that have been made and are likely to occur. Considering the relatively longer history and the depth of research, this review covers mostly the research done at ICRISAT-Patancheru. Implications of these results and those on alternative hybrid options for hybrid breeding in the African regions are also presented.

Advantages/disadvantages of hybrids

Grain yield advantage of hybrids over varieties

Open-pollinated varieties are developed and maintained by random mating, which permits no control over recombination within the populations. Since OPVs remain in a state of flux, reorganization of variability with each seed increase generates arrays of new recombinants, risking the possible break up of co-adapted complexes within the populations and in population crosses. This may be one reason for the lack of sustainable genetic gains for grain yield through OPVs of acceptable uniformity in maize (*Zea mays*) research programs in USA (Fig. 2.1).

The history of genetic progress for grain yield with OPVs based on the indigenous germplasm of pearl millet in India is similar to the progress made with OPVs of maize in USA. With the establishment of ICRISAT, rapid progress was made in breeding high-yielding OPVs of pearl millet. But this became possible because of radically different and more productive germplasm introduced from the western and central Africa (WCA) region as exemplified by WC-C 75 that was developed from the World Composite

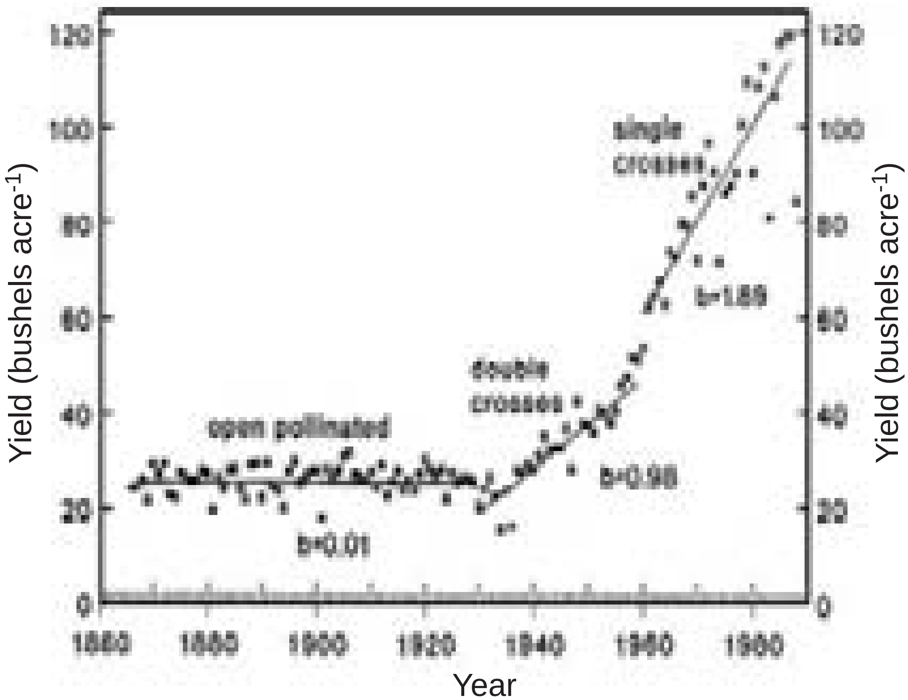

Figure 2.1. Maize yield and kinds of cultivars from the civil war to the present. [Note: b values (regressions) indicate gain in bushels per year.] (Source: Troyer 1990)

introduced from Nigeria, and ICTP 8203 that was developed from an *iniari* germplasm introduced from Togo. Although the eastern and southern Africa (ESA) region may directly benefit from such introductions from WCA and ICRISAT-Patancheru, similar opportunities with the introduced germplasm may not be available to the WCA region as these introduced germplasm are likely to be poorly adapted in the WCA region. Though comparative assessments were never made, it is likely that these two OPVs (WC-C 75 and ICTP 8203) differed from their respective populations more with respect to morphological uniformity and downy mildew (DM) (caused by *Sclerospora graminicola*) resistance than for grain yield. The sustainability of grain yield improvement through OPVs remained largely uncertain in India. It was this realization that reinforced increased attention for pearl millet hybrid program in India. A similar shift in hybrid research, albeit at a greater pace, may be required for the African regions, considering just the modest yield gains that could be achieved through more than 20 years of OPV research.

The first commercial pearl millet grain hybrid HB 1, developed at Punjab Agricultural University (PAU), Ludhiana and released in India in 1965, had twice as much grain yield as the then improved OPVs (Athwal 1965). This demonstration of hybrid potential boosted the struggling hybrid program that had remained confined mostly to heterosis studies and development of chance hybrids. At the time when all the hybrid research centers in India were working on hybrids and significant yield gains were being achieved, ICRISAT research largely opted for OPV development, following both synthetics and composite approaches. The guiding principles behind this cultivar strategy were: (i) ICRISAT research would complement the efforts of the national agricultural research systems (NARS) by providing genetically diverse and improved populations from which NARS could develop parental lines of potential hybrids; (ii) high-yielding OPVs competitive to hybrids were possible, and technologies for OPV development and seed production were technically easier and more economical than for hybrids; (iii) OPVs would be less vulnerable than hybrids to diseases; and (iv) being heterogeneous, OPVs would have more stable yield and be more widely adapted than hybrids, serving the institute's wider mandate beyond India.

The first ICRISAT-bred OPV (WC-C 75) released in 1982 was apparently supportive of some of the notions mentioned above. This variety gave 99% of the grain yield and 120% of the dry fodder yield of then most popular hybrid BJ 104 in the All India Coordinated Pearl Millet Improvement Project (AICPMIP) trials conducted in 110 (locations × year) environments (Andrews et al. 1985). Based on the success of this variety, which was grown on about 1.2 million ha at the peak of its popularity and had high level of DM resistance in the field (<2% disease incidence), several research programs in India took up OPV breeding. Results from extensive AICPMIP trials that tested hybrids and OPVs in the same experiments, however, showed that hybrids, in general, had about 25% grain yield advantage over the improved OPVs of comparable height and maturity, and 5–6% less dry fodder yield than OPVs (Table 2.1). Further, the highest-yielding hybrids generally produced 30% more grain yield than the highest-yielding OPVs. Based on these results, there was a downtrend in OPV breeding in India and as ICRISAT also took a policy decision not to breed finished products (mostly OPVs), the cultivar development research in India got almost all geared to breeding hybrids. To be in tune with the NARS research priority, ICRISAT-Patancheru gradually

Table 2.1. Grain and dry fodder yield of hybrids and open-pollinated varieties (OPVs) of pearl millet in AICPMIP joint hybrid and population trials in India.

	Mean grain yield (kg ha^{-1})		Mean dry fodder yield (t ha^{-1})	
Year	Hybrids[1]	Best hybrid[2]	Hybrids[1]	Best hybrid[2]
1996	1775 (24)	2213 (31)	3.1 (–6)	3.5 (–5)
1997	1676 (10)	2047 (26)	3.4 (3)	4.0 (8)
2000	1117 (26)	1449 (40)	2.0 (5)	2.1 (5)
2001	1917 (27)	2191 (30)	2.9 (–17)	3.6 (3)
Mean	1621 (22)	1975 (32)	2.9 (–4)	3.3 (3)

1. Figures in parentheses indicate superiority (%) over OPVs.
2. Figures in parentheses indicate superiority (%) over best OPV.

phased out its OPV breeding research and now almost entirely concentrates its efforts on hybrid parents research.

In the African regions, development of OPVs continues to be the primary objective for several reasons that include: (i) seed production ease and economy; (ii) relatively less vulnerability to diseases such as DM, smut [*Moesziomyces penicillariae* (syn. *Tolyposporium penicillariae*)], and ergot (*Claviceps fusiformis*); and (iii) absence of an organized seed industry. The limited work done on hybrids, however, has shown evident grain yield advantage of hybrids over OPVs in the absence of diseases in the Southern African Development Community (SADC) region (Monyo 1998). Topcross and inter-population hybrids evaluated in the WCA region have shown up to 81% grain yield advantage (Ouendeba et al. 1993) and up to 23% stover yield advantage over OPVs. Thus, the hybrid research emphasis in these regions has been on the topcross and inter-population hybrids, which being genetically more heterogeneous than single-cross hybrids, are less vulnerable to DM, ergot and smut. The critical need for regionally adapted seed parents research has been recognized in both the African regions for a successful hybrid development program.

Disease resistance

Downy mildew is the most destructive disease of pearl millet, especially in single-cross hybrids. The two most-widely cultivated OPVs (WC-C 75 released in 1982 and ICTP 8203 released in 1988) had very high levels of DM resistance (<2% incidence) at the time of their release. There was no decline in their DM resistance levels even 17–20 years after their cultivation. In contrast, the DM resistance of single-cross hybrids lasts generally 4–8 years. This requires frequent replacement of hybrid cultivars. However, considering the official release of 2–3 hybrid cultivars every year, apart from marketing of the truthfully labeled hybrids from the private sector, the hybrid replacement is not such a big problem in India. In the initial phase of the hybrid program when only 2–3 hybrids were available for entire India, there used to be frequent DM epidemics (Fig. 2.2). However, much stronger hybrid programs in the country (both public and private sector) supported by hybrid parents research at ICRISAT-Patancheru have resulted in phenomenal hybrid cultivar diversity with more than 70 hybrids currently in the market. The hybrid parents research at ICRISAT-Patancheru has a major focus on DM resistance that involves both greenhouse and field screening of breeding lines, and monitoring the performance of advanced breeding lines through multilocational testing and their hybrids through on-farm DM survey (Singh 1995, Hash et al. 1999, Thakur and Hash 2004). In addition to genetic resistance, seed treatment with the systemic fungicide metalaxyl provides protection from DM until flowering time. The large cultivar diversity, improved genetic resistance and use of seed fungicide have prevented recurrence of the DM epidemics that occurred during 1970–90. Since the hybrid cutlivar programs of this size are not likely to be in place in the African regions in the near future, the frequent cultivar replacement strategy for DM management is not a likely option. The strategy for this region should be to strengthen DM resistance breeding program [supported by marker-assisted selection (MAS)] and implement alternative hybrid options.

Smut and ergot of pearl millet are of secondary importance. Hybrids have been shown to be more prone to infection to these two diseases than are the OPVs, primarily because the latter have the advantage of pollen-based escape mechanism (Thakur et al. 1983, Thakur 1989). Seed parents breeding research did succeed in developing male-sterile lines (A-lines) with high levels of resistance to ergot (Rai et al. 1998a) and smut (Rai et al. 1998b), but it was also observed that breeding hybrids and their parents for resistance to these two diseases (especially ergot) was much more difficult than it was for DM. The research conducted during the process of breeding ergot and smut resistant seed parents also showed that (i) it is not the A_1 cytoplasm per se but the cytoplasm-induced male sterility that makes A-lines and their hybrids more susceptible to these two panicle diseases (Rai and Thakur 1995, 1996); (ii) genetics of these two diseases, especially ergot resistance, is complex; and

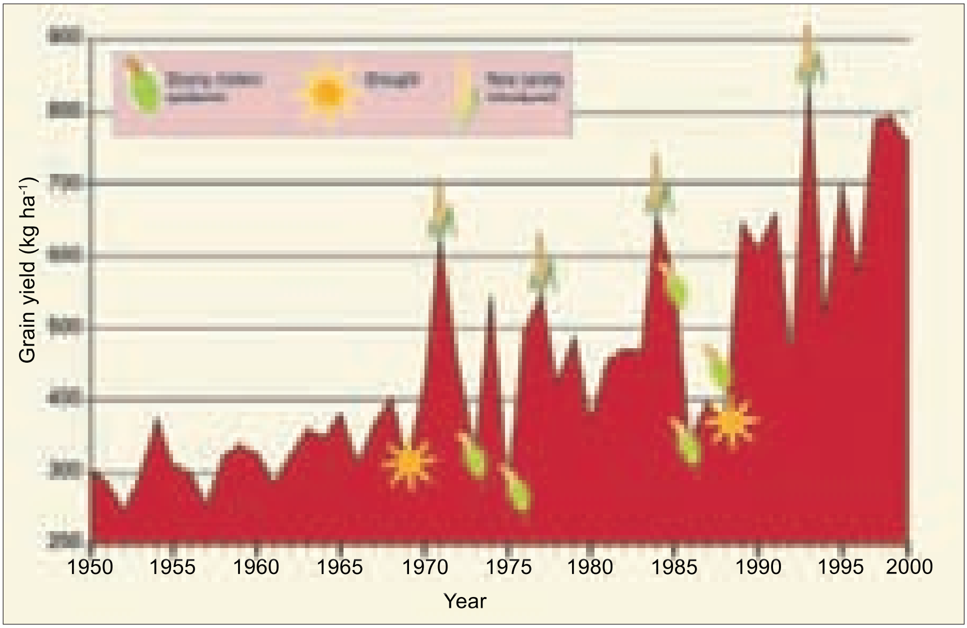

Figure 2.2. Boom and bust cycle of pearl millet production caused by downy mildew epidemics and drought in India.

breeding resistant hybrids would require having both parental lines resistant to these diseases; (iii) resistant sources for both diseases were limited and often in agronomically poor background, especially for ergot resistance; and (iv) these two diseases are not of widespread nature and are of infrequent occurrence. Based on these considerations, ergot and smut resistance breeding received much lower priority in NARS and at ICRISAT, and it was gradually phased out. Nevertheless, it is possible to breed ergot and smut resistant hybrids by deploying resistance genes in both parental lines, and then backing it up with improved levels of male fertility restoration in hybrids. Incorporation of these two aspects in the hybrid breeding program will obviously have negative impact on genetic improvement for characters of primary importance (eg, grain and stover yield and DM resistance).

Commercialization

Private seed companies in India have emerged as the most dominant and reliable force in the commercialization of hybrid breeding products. Seed yield of OPVs is about 2–3 times more than hybrid seed yield (yield of

A-lines). Yet, fewer seed companies find OPV seed production attractive enough for three obvious reasons:

1. OPVs are public goods, available to anybody and everybody, thus impinging on the exclusivity of the seed companies' products and resulting in low sale price of the seed;
2. Variability in OPVs does not permit clear-cut brand names which can be identified with companies' products; and
3. Since the farmer-saved seed can be used in the subsequent years, companies find it difficult to gauge demand and formulate their production plans.

Seed production and marketing, however, is only part of the story impacting on commercialization of cultivars. Since OPVs are public goods, the public sector institutes have to follow the full process, starting from population improvement to OPV development to OPV testing and release. In case of hybrids, public institutes would do better (as does ICRISAT) to restrict themselves to hybrid parents development, leaving hybrid development, testing and release to the private sector. This strategy broadens the research and development partnership base in which both sectors play their respective roles in areas where they have distinct comparative advantage as well as complementary skills and resources; and thus generate the synergy that enhances the pace of technology development and adoption. This type of partnership is lacking in the African regions because (i) hybrids with commercially viable and consistent grain yield advantage over the OPVs have not yet been identified; and (ii) private seed companies have yet to assess the size of hybrid markets and the profitability of hybrid seed production and marketing.

Seed parents research

Geographical and trait focus

The initial ICRISAT strategy, parallel to that in India, has been to address relatively better-endowed environments, and it continues to be so. The obvious reasons for these were: (i) greater reliability of results (low trial CV) and fewer crop failures, thus increasing the breeding efficiency; (ii) greater probability of producing high-yielding hybrids, which, by nature, are more responsive and perform better under improved productivity conditions; and (iii) relatively more progressive farmers and farming systems, leading to rapid cultivar adoption. This strategy has paid well and is reflected in rapid hybrid adoption, greater hybrid cultivar diversity, and larger area under hybrid cultivation (see section Impact). Development of hybrids with high and stable grain yield in more marginal environments, where there is greater poverty and fewer livelihood options, should ideally receive higher priority from socioeconomic point of view. However, development of high-yielding and farmer-adoptable hybrids for such environments is a greater challenge for the reasons just opposite to those mentioned for relatively better-endowed environments, and thus should initially be a subject of experimentation in feasibility. This has been the basic approach followed in most of the breeding programs in India and also at ICRISAT.

It is common to find that heterosis is better expressed in high productivity environments. Six populations adapted to arid zone of Rajasthan and their topcross hybrids made on each of the three A-lines were evaluated in five environments in Rajasthan with varying productivity levels. Results showed that most hybrids had about 50% grain yield advantage over their respective population parents, and the mean heterosis of all the hybrids was almost negligible in the environments that had less than 1000 kg ha^{-1} of grain yield (Fig. 2.3). However, in the environments exceeding this productivity level, most hybrids had more than twice as much grain yield as their respective population parents, with the mean heterosis of all hybrids being about 50%. In a study conducted in the WCA region, no such relationship was observed between the magnitude of heterosis for grain yield and the productivity levels of the environments. Thus, there is a need to synthesize a large body of data available from such experiments to examine how general these results are, as this pattern would have implications for targeting the environments for which hybrids might be developed on priority basis.

In the WCA region, the higher importance of pearl millet in the Sahelian zone could mean a stronger research focus for this zone. On the other hand, the higher rainfall and prospects of rapid adoption of hybrids for production system intensification in the Sudanian zone might imply greater research emphasis for this zone. Given the resources constraint, it is clear that the entire WCA agro-ecologies cannot be addressed. The simple rule may be to address those agro-ecologies where the probability of success in terms of hybrid development and adoption may be higher. However, pearl millet has greater concurrence with sorghum (*Sorghum bicolor*) and early-maturing maize cultivars/hybrids in this zone. With an effective marker-assisted genetic

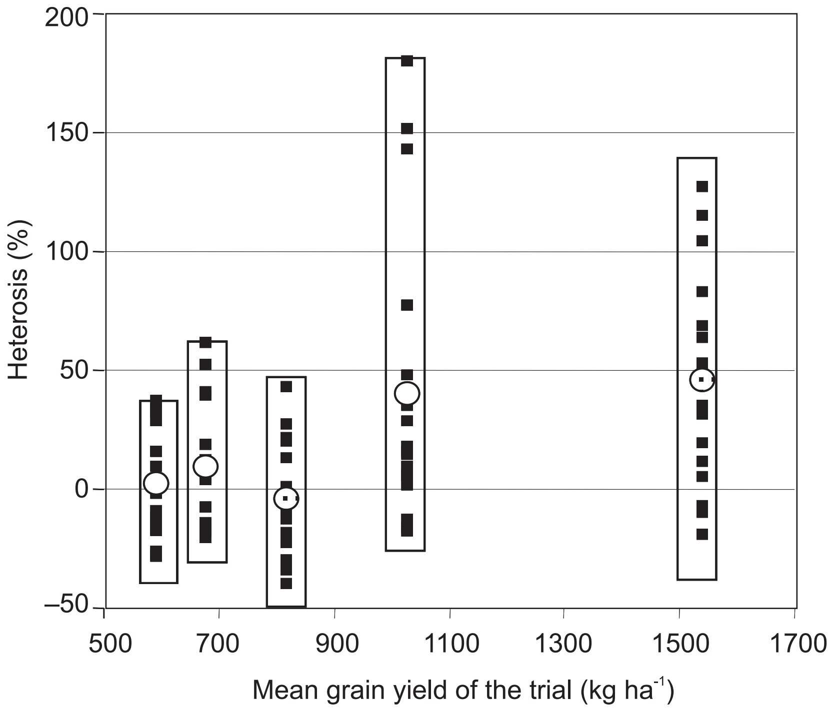

Figure 2.3. Heterosis in pearl millet topcross hybrids for grain yield in relation to productivity levels of test environments in Rajasthan, India.

manipulation of photoperiod sensitivity as a key adaptation trait and regional integration of breeding programs, it might be possible to address both zones.

Drought is the most serious among the abiotic constraints, affecting pearl millet productivity worldwide, while DM is the most serious among the biotic constraints. Based on a holistic view comprising considerations such as: (i) effectiveness of screening methodologies; (ii) extent of genetic variation and agronomic backgrounds in which the target traits are available; (iii) heritability of the target trait and nature of character association; (iv) geographical scale and the frequency of the occurrence of the constraint; and (v) probability of success in breeding high-yielding and farmer-acceptable cultivars, all hybrid programs in India (including ICRISAT) gave highest priority to breeding for DM resistance. Drought resistance breeding remained largely a strategic research issue. This trend continues even today, and is likely to be so for a long time until effective breeding approaches such as MAS and transgenics are shown to be reasonably effective to be integrated in the mainstream breeding. In the WCA region, however, locally adapted landraces will be used as the basic breeding materials to enhance drought resistance.

Hybrid programs in India and at ICRISAT-Patancheru accorded highest priority to grain yield and DM resistance combined with maturity duration, mostly in the range of 75–85 days, as per the agro-ecological requirements. Breeding for DM resistance has also been accorded high priority, next to grain yield, based on the consideration that there have been several epidemics of this disease on pearl millet hybrids in India as mentioned earlier. Due to growing importance of pearl millet stover for fodder purposes, there has been considerable emphasis in recent time on breeding for high stover yield. Apart from the evident quality traits both in the grain (size, shape, color) and stover (less rust, thinner stem, lodging resistance) that receive some attention, consideration of any other quality traits in hybrid breeding has been negligible in all the programs. Grain and stover yield along with DM resistance will also be high priority traits in both African regions (ESA and WCA). The parasitic weed, *Striga hermonthica*, stem borer (*Coniesta ignefusalis*) and head miner (*Heliocheilus albipunctella*) are the additional biotic constraints that cause significant yield losses to pearl millet productivity in the WCA region, and thus ideally should be accorded high priority for genetic improvement of resistance to these pests. Considering the genetic complexities of resistance, relatively fewer sources of resistance and low resistance levels available mostly in the unproductive genetic backgrounds, and relatively inefficient screening techniques, significant genetic improvement of resistance and its cost-effectiveness remains an open question. This perhaps calls for the crop management options as the most probable route for the management of these pests. Longer panicles with thicker stems are the other traits, which are more preferred in the African regions than in Asia. Another character of high priority could be photoperiod sensitivity, which plays a significant role in adaptation. But the effect of this trait on the breeding speed through generation turnover, and geographical adaptation range of hybrids or OPVs bred in a certain set of environments needs to be examined.

Search, characterization and use of CMS systems

CMS search

Large-scale deployment of the single A_1 CMS source during the 1960s in all the hybrids had raised a concern regarding their potential vulnerability to insect pests and diseases. As a result, continuing efforts were made to search for alternative CMS sources. This led to identification of A_2 and A_3 CMS sources from genetic stocks and their derivatives (Athwal 1961, 1966), and A_v and A_4 CMS sources from *P. glaucum* ssp *monodii* (=*violaceum*) accessions (Marchais and Pernes 1985, Hanna 1989). Research at ICRISAT led to the identification of Ghana and Botswana CMS sources in germplasm accessions from these countries (Appa Rao et al. 1989), and A_{egp} and A_5 CMS sources from gene pools (Sujata et al. 1994, Rai 1995). Based on the differential male fertility restoration patterns of hybrids, it has been established that the A_1, A_2, A_3, A_v, A_4 and A_5 were distinctly different CMS systems. In these studies, A_{egp} had been found to be similar to A_1 in that all the pollen parents used as the testers that produced sterile hybrids on A_1 also produced sterile hybrids on A_{egp}, but a high proportion of those producing fertile hybrids on A_1 also produced sterile hybrids on A_{egp}.

Basic features of available CMS systems and their commercial potential

Figure 2.4. Partial pollen shedding panicle of pearl millet.

Commercial viability of a CMS system for seed parents development depends on the stability of male sterility, frequency of maintainers in a wide range of breeding materials, nature of character association and inheritance of male sterility, all of which influence seed parents breeding efficiency. Although all the commercial hybrids today continue to be based on the single A_1 CMS system, it has been observed that all the A-lines involved in these hybrids produce varying, albeit low, frequency of pollen shedders (Fig. 2.4), which is influenced by the genetic backgrounds of A-lines and the environments in which they are grown. About 40 years of research with the A_2 and A_3 CMS systems, mostly at PAU, Ludhiana (where these CMS sources were discovered), failed to produce an A-line with stable male sterility comparable to A_1-system A-lines.

Stability of male sterility. A systematic research was initiated at ICRISAT to address the basic questions related to seed parents breeding efficiency of various CMS sources. First, it was shown that for a valid comparison of the stability of male sterility of different CMS systems, studies must be conducted with isonuclear A-lines (ie, different cytoplasm in the common nuclear genetic background) to overcome the effect of cytoplasm × nuclear interaction, if any (Rai and Hash 1990). This was followed up with the development of isonuclear A-lines in the genetic background of 81B. In an evaluation of A-lines during the rainy and summer seasons at Patancheru, $81A_1$, $81A_4$ and $81A_v$ had no pollen shedders, while there were 5–7% pollen shedders in $81A_3$ and 12–23% pollen shedders in $81A_2$ (Table 2.2). This showed that the A_2 and A_3 CMS systems had highly unstable male sterility. These results were based on a study of 128–239 plants of A-lines in each CMS system. However, in a breeder seed production plot of $81A_1$ a low frequency of pollen shedders was observed. Thus, another study was conducted with larger number of plants (355–1618 plants of each A-line) and in six environments (rainy season, early summer and late summer plantings for two years at Patancheru). Results of this study showed that male sterility of $81A_1$ and $81A_v$ had similar low frequency of pollen shedders (0–0.6% in $81A_1$ and 0.1–0.8% in $81A_v$), while $81A_4$ and $81A_5$ had no pollen shedders (Table 2.3).

Table 2.2. Pollen shedders in isonuclear A-lines of pearl millet during rainy and dry seasons in 1991 at ICRISAT, Patancheru, India.

	Number of plants		Pollen shedders (%)	
A-line	Rainy season	Dry season	Rainy season	Dry season
$81A_1$	147	239	0	0
$81A_2$	178	219	12	23
$81A_3$	171	247	5	7
$81A_4$	128	139	0	0
$81A_v$	195	222	0	0

Source: Rai et al. (1996).

Table 2.3. Pollen shedders in isonuclear A-lines of pearl millet at ICRISAT, Patancheru, India.

A-line	Number of plants[1]	Pollen shedders (%)
$81A_1$	378–1618	0.0–0.6
$81A_v$	355–1233	0.1–0.8
$81A_4$	385–1200	0.0
$81A_5$	366–1249	0.0

1. Based on six environments.
Source: Rai et al. (2001).

Since the above studies were conducted using isonulcear A-lines in just one nuclear genetic background, the question still remained as to the effect of cytoplasm × nuclear genetic background interaction in determining stability of male sterility. Thus, isonuclear A-lines with four cytoplasms (A_1, A_{egp}, A_4 and A_5) in each of the three diverse nuclear genetic backgrounds (81B, 5054B and ICMB 88004) were evaluated for pollen shedders in six environments that consisted of three planting dates (rainy season, early summer and late summer season) for two years. Results of this study showed that depending on the genetic background and environments, the frequency of pollen shedders was higher in A-line with the A_1 cytoplasm (0.0–2.5%) followed by the A_4 cytoplasm (0.0–0.3%) and the A_{egp} cytoplasm (0.0–0.1%) (Table 2.4). There were no pollen shedders in A-lines with the A_5 cytoplasm, irrespective of their genetic backgrounds or the environments in which they were grown. It was also observed that irrespective of the CMS system, plants of A-lines visually rated as pollen sterile set seed when selfed. This could result from the traces of viable pollen that escape visual assessment. Depending on the

Table 2.4. Pollen shedders[1] in isonuclear A-lines of pearl millet at ICRISAT, Patancheru, India.

Genotype	Cytoplasm			
	A_1	A_{egp}	A_4	A_5
81B	0.3–0.6	0.0–0.1	0.0	0.0
5054B	0.1–2.5	0.0	0.0–0.3	0.0
ICMB 88004	0.0–0.6	0.0–0.1	0.0–0.1	0.0

1. Based on six environments.

Table 2.5. Frequency of plants in selfed seedset class (%) in isonuclear A-lines of pearl millet during rainy season 2002 at Patancheru, India.

		Percentage of plants in selfed seedset class (%)			
CMS source	A-line	0	1–5	6–10	11–40
A_1	81A	95–100	0.0–5.0	0.0–0.3	0.0–0.3
	5054A	97–100	0.0–2.7	0.0–1.0	0.0
	88004A	99–100	0.0–1.2	0.0–0.3	0.0–0.4
A_4	81A	99–100	0.0–0.9	0.0	0.0
	5054A	97–100	0.0–2.8	0.0	0.0
	88004A	100	0.0	0.0	0.0
A_5	81A	99–100	0.0–0.2	0.0	0.0
	5054A	100	0.0	0.0	0.0
	88004A	99–100	0.0–1.0	0.0	0.0

growing environments of the A-lines and their nuclear genotype, 95–100% of the pollen-sterile plants of A-lines with the A_1 cytoplasm did not set any seed when selfed. There were up to 0.4% plants that set up to 40% seed under selfing (Table 2.5). In comparison, 97–100% plants of A-lines with the A_4 and A_5 cytoplasm did not set any seed when selfed, no more than 2.8% plants had 1–5% selfed seed set, and none set seed any more than this. Thus, on the criterion of the stability of male sterility, A_5 CMS system appeared to be most useful, followed by the A_4 and then the A_1 CMS system. Further studies were conducted to find out the sterility/fertility of plants produced from seed generated from pollen-sterile plants in various selfed seedset classes. Results showed that, in general, percentage of pollen shedders was higher in those plants that came from higher selfed seedset classes of pollen-sterile plants of A_1-system A-lines in the earlier generation (Table 2.6).

Maintainer frequency. While working with the A_1 CMS system, several of the agronomically outstanding inbred lines, especially those of shorter height (the most suitable plant type for A-lines), could not be converted into A-lines simply because they were not maintainers. This has been a significant constraint in genetic diversification of A-lines. Since the A_4 and A_5 CMS systems were found to be most stable amongst those that were found to be distinctly different from the A_1 CMS system, a diverse range of populations developed at ICRISAT-Patancheru and in the African regional programs was examined. Based on the frequency of male-sterile plants in topcross hybrids (a measure of maintainer frequency) made on $81A_1$ with Patancheru-bred populations, it was found that most of the populations had 8–35% maintainers

Table 2.6. Frequency of pollen shedders (%) in plants from different selfed seedset classes of isonuclear A-lines of pearl millet during rainy season 2002 at Patancheru, India.

		Pollen shedders (%) in plants from seedset class (%)		
Cytoplasm	A-line	1–5	6–10	11–40
A_1	81A	0	24	5
	5054A	5	36	63
	88004A	11	12	22
A_4	81A	0	–	–
	5054A	0	–	–
	88004A	–	–	–
A_5	81A	–	–	–
	5054A	–	–	–
	88004A	0	–	–

of the A_1 CMS system except ICTP 8203 that had >75% maintainers (Fig. 2.5). In A_4 CMS system, the frequency of maintainers varied from 28 to 97%, while in A_5, the maintainer frequency was highest, varying from 85 to 99%. A wider range of maintainer frequency of the A_1 CMS system, varying from

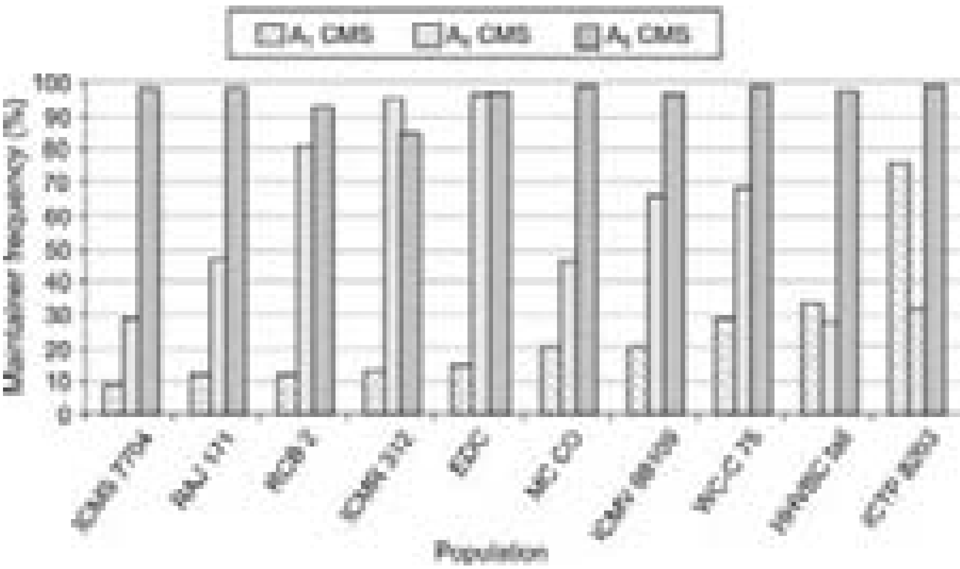

Figure 2.5. Frequency of male-sterile plants (maintainers) in topcross hybrids of $81A_1$, $81A_4$ and $81A_5$ made with diverse pearl millet populations developed at ICRISAT and evaluated during rainy season 2000 at Patancheru, India.

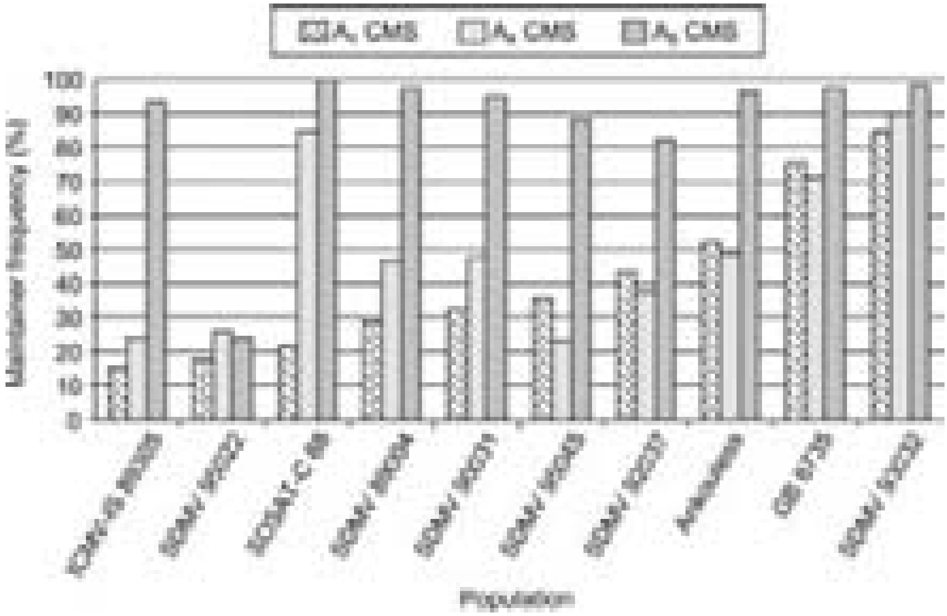

Figure 2.6. Frequency of male-sterile plants (maintainers) in topcross hybrids of 81A_1, 81A_4 and 81A_5 (made with diverse pearl millet populations developed in African regions) evaluated during rainy season 2002 at Patancheru, India.

16 to 84%, was found in the populations from the African regions, and the difference in the maintainer frequency of the A_1 and the A_4 CMS systems was smaller than in the Patancheru-bred populations (Fig. 2.6). However, the frequency of maintainers of the A_5 CMS system remained highest, varying from 83 to 100% in all the populations except SDMV 95022, which had only 23% maintainers. Based on these results, it can be concluded that the A_5 CMS system provides the greatest opportunities for genetic diversification of A-lines, followed by the A_4 and then the A_1 CMS system.

Character association. Earlier studies had established that the A_1 cytoplasm is not associated with DM susceptibility (Anand Kumar et al. 1983, Yadav et al. 1993). No such planned studies have been conducted with the A_4 and A_5 CMS systems. However, no differences have been detected between the DM incidence in maintainer lines (B-lines) and their counterpart A-lines in both the A_4 and A_5 CMS systems with respect to the Patancheru pathotype. A systematic comparison of A-/B-lines in both CMS systems and with respect to diverse pathotypes of the DM pathogen population is warranted.

Evaluation of isonuclear hybrids, developed from crosses between nine seed parents (A-lines with A_1 and A_4 cytoplasms and the counterpart B-line with the fertile cytoplasm in each of the three diverse genetic backgrounds) and five dual-restorers of the A_1 and A_4 cytoplasms, showed that the mean grain yield of hybrids with the A_4 cytoplasm was 5% less than that of the A_1-system hybrids ($P<0.05$), varying from 9% less yield during 2003 at Patancheru to identical yield during 2002 at Jamnagar (Table 2.7). A similar comparative study of isonuclear hybrids with the A_1 and A_5 cytoplasms is under way. Results from the first year of the trial showed that there was no significant difference between the mean grain yield of hybrids with the A_1 and A_5 cytoplasms (Table 2.8). The cytoplasmic effects on other traits such as plant height and time to 50% flower, though sometimes significant, have been of such small order as to be of no practical significance.

Table 2.7. Mean grain yield (kg ha^{-1}) of isonuclear pearl millet hybrids based on A_1, A_4 and fertile cytoplasms during rainy season at three locations in India.

	Patancheru		Hisar		Jamnagar		
Hybrid	2002	2003	2002	2003	2002	2003	Mean
A_1-hybrid	3920	2160	3700	1980	1660	1950	2560
A_4-hybrid	3740	1960	3450	1880	1660	1930	2440
	(95)[1]	(91)	(93)	(95)	(100)	(99)	(95)
B-hybrid	3820	2040	3360	1730	1610	1840	2400
LSD (0.05)	123	77	NS[2]	128	NS	NS	–
CV (%)	9	10	21	19	19	16	–

1. Figures in parentheses indicate yield of A_4-hybrids as percentage yield of A_1-hybrids.
2. NS = Not significant.

Table 2.8. Mean grain yield (kg ha^{-1}) of isonuclear pearl millet hybrids based on A_1, A_5 and fertile cytoplasms during rainy season 2004 at two locations in India.

Hybrid	Patancheru	Jamnagar
A_1-hybrid	2940	3030
A_5-hybrid	2920	2930
	(99)[1]	(97)
B-hybrid	2940	2760
LSD (0.05)	122	145
CV (%)	12	14

1. Figures in parentheses indicate yield of A_5-hybrids as percentage yield of A_1-hybrids.

Genetic improvement of maintainer and restorer frequencies. Genetics of male sterility (or male fertility restoration), whether simple or complex, has a direct bearing on the efficiency of genetic improvement of these traits. The simpler the inheritance the greater the selection response. Saying it differently would mean that the greater the selection response the simpler the inheritance. While a major study on the genetics of several CMS systems, including the A_1 and A_4 CMS systems, is nearing completion, a bi-directional recurrent selection for fertility and sterility reactions of the A_1 and A_4 CMS systems was conducted for five cycles in Early Smut Resistant Composite II (ESRC II) and for three cycles in the OPV Raj 171.

Male-sterile lines $81A_1$ and $81A_4$ were used as testers to evaluate the fertility and sterility reactions of plants of these populations in their testcrosses. Recurrent selection bulks of these populations (in the maintainer and restorer streams and with respect to A_1 as well as A_4 CMS system) along with the original bulks of both populations were crossed onto A_1 and A_4 system male-sterile lines in three genetic backgrounds ($81A_1$ and $81A_4$, $5054A_1$ and $5054A_4$, and $ICMA_1$ 88004 and $ICMA_4$ 88004). The resulting topcross hybrids were evaluated for the frequency of male-sterile plants (a measure of maintainer frequency). Results of the topcross hybrids made on $81A_1$ and $81A_4$ showed that two selection cycles in ESRC II were effective in rapidly increasing the frequency of maintainers from 25% in the C_0 bulk to 92% in the C_2 bulk with respect to the A_1 CMS system, and from 42% in the C_0 bulk to 99% in the C_2 bulk with respect to the A_4 CMS system (Fig. 2.7). Similarly, the frequency of restorers increased from 75% in C_0 bulk to 96% in the C_3 bulk with respect to the A_1 CMS system, and from 58% in the C_0 bulk to 97% in the C_2 bulk with respect to the A_4 CMS system.

In Raj 171, one cycle of selection increased the frequency of maintainers from 18% in C_0 bulk to 98% in the C_1 bulk with respect to the A_1 CMS system, and from 49% in the C_0 bulk to 99% in the C_1 bulk with respect to the A_4 CMS system (Fig. 2.8). Similarly, one cycle of selection for fertility restoration increased the frequency of restorers from 82% in the C_0 bulk to 99% in the C_1 bulk with respect to the A_1 CMS system, and from 51% in the C_0 bulk to 96% in the C_1 bulk with respect to the A_4 CMS system. Broadly speaking, the results showed that both CMS systems were equally effective in genetic improvement of both populations for fertility restoration as well as for sterility maintenance reaction. Results of topcross hybrids made on the A_1 and A_4 system A-lines in the genetic background of 5054B and ICMB 88004 also had similar patterns.

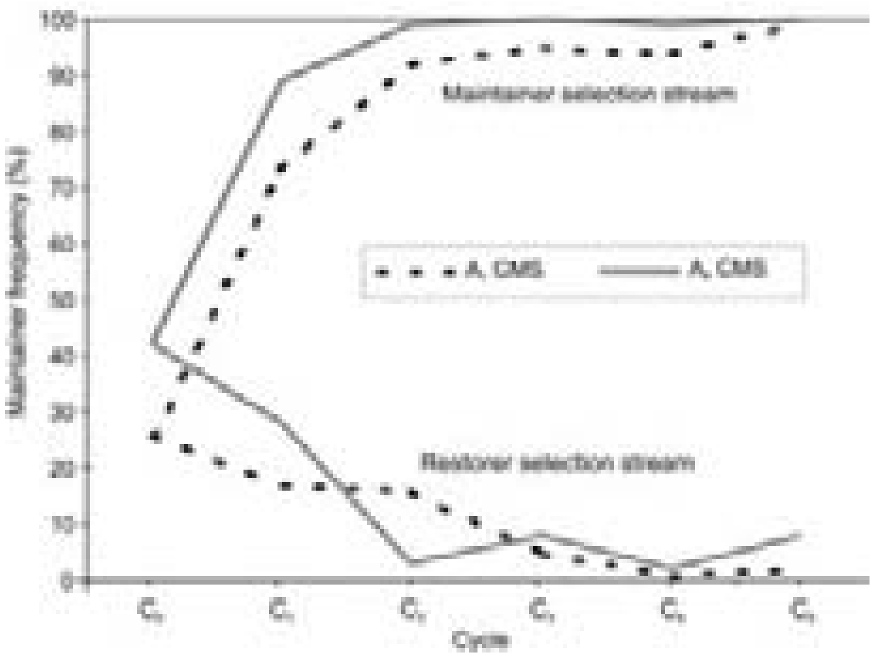

Figure 2.7. Frequency of male-sterile plants (maintainers) in pearl millet topcross hybrids of 81A_1 and 81A_4 made with recurrent selection cycle bulks of ESRC II during rainy season 2004 at Patancheru, India.

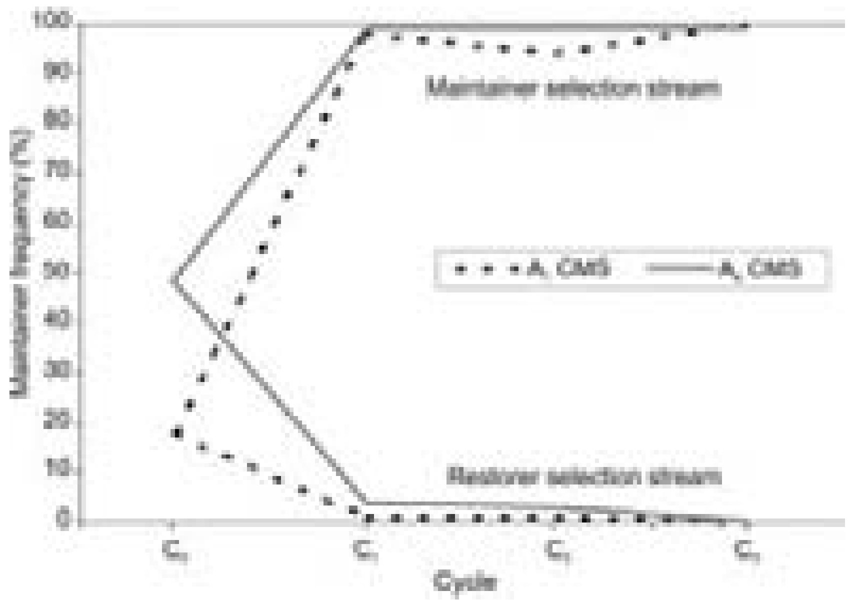

Figure 2.8. Frequency of male-sterile plants (maintainers) in pearl millet topcross hybrids of 81A_1 and 81A_4 made with recurrent selection cycle bulks of Raj 171 during rainy season 2004 at Patancheru, India.

Genetic changes in grain yield and agronomic traits associated with recurrent selection for fertility and sterility reaction. While selecting for male fertility restoration and sterility reaction in ESRC II and Raj 171, the question remained whether this caused any changes in grain yield and agronomic traits. For this, the cycle bulks were evaluated for grain yield and agronomic traits. Separate replicated trials were conducted for ESRC II and Raj 171 during the rainy season 2004 at Patancheru. The ESRC II trial consisted of 21 bulks (C_0 bulk, and five bulks each for the restorer and maintainer stream of each of the two CMS systems). Similarly, Raj 171 trial consisted of 13 bulks. In ESRC II, selection either for fertility restoration or for sterility maintenance had no adverse effect on grain yield with respect to the A_1 CMS system or for sterility maintenance reaction with respect to the A_4 CMS system. There were indications of significant decline in grain yield in the C_4 and C_5 restorer bulks of the A_4 CMS system. Changes in other traits such as time to flower, plant height, panicle length, tillering ability and seed mass were not significant. Results from Raj 171 trial also showed that recurrent selection for fertility/sterility traits with respect to either of the two CMS systems had no adverse effect on grain yield and agronomic traits. Use of the A_4 and A_5 CMS systems can enhance the efficiency of seed parents breeding in the African region as well, where lack of adapted seed parents (high grain yield and DM resistance) with farmer-acceptable grain quality remains a major bottleneck in hybrid development. Use of these CMS systems would be especially more effective in breeding male-sterile populations for developing inter-population hybrids. In fact, the A_4 CMS system has been demonstrated to be effective in breeding a male-sterile population at ICRISAT-Patancheru (Rai et al. 2000a).

Prioritization of CMS systems for use in seed parents development

Considering the three key attributes of the CMS systems for their applied values as mentioned above, the highest priority should be on breeding A-lines with the A_5 CMS system followed by the A_4 CMS system, and gradual phasing out of the A_1 CMS system. However, the research thrust continues to be on breeding A-lines with the A_1 cytoplasm as a high proportion of the restorers of this CMS system in all the hybrid programs in India and elsewhere cannot restore the fertility of hybrids made on A-line based on the A_4 CMS system. Almost none will restore the fertility of hybrids based on the A_5-system A-lines. Thus, the second priority has been on breeding A-lines with the A_4 cytoplasm and last priority with the A_5 cytoplasm (Table 2.9).

As more productive restorers of these two new cytoplasms are developed, the top priority will eventually be on the A_5 cytoplasm, followed by the A_4 cytoplasm. A beginning has been made in this direction as reflected in the increasing proportion of A-lines with the A_5 cytoplasm, followed by the A_4 cytoplasm, which are at various stages of their development (Table 2.10).

Table 2.9. Cytoplasmic diversification of pearl millet A-lines developed at ICRISAT.

	No. of designated A-lines			
Period	Total	A_1 cytoplasm	A_4 cytoplasm[1]	A_5 cytoplasm[1]
1976–85	4	4	0	0
1986–95	27	27	1	0
1996–2004	68	33	31	4
Total	99	64	32	4

1. Does not include 34 A-lines, which are yet to be designated.

Table 2.10. Genetic diversification of A-lines in pearl millet during rainy season 2004.

	No. of lines			
Development stage	B-line	A_1-line	A_4-line[1]	A_5-line[2]
Designated lines	99	62	33	4
Advanced backcross (BC) stage	97	30	69	2
Initial BC stage	157	83	100	62

1. 34 additional B-lines converted into A_4-lines but not yet designated.
2. 34 additional B-lines at BC_1 stage of conversion into A_5-lines.

B-line breeding

Germplasm utilization

A detailed analysis of the extent to which the germplasm accessions and composites have been evaluated and used in seed parents development, and advanced breeding lines have been generated is yet to be done. The analysis of the parentage of 95 maintainer lines (B-lines) of the counterpart designated A-lines shows that 17 of these B-lines were developed either directly from selection in germplasm accessions or in composites (Table 2.11).

Table 2.11. Germplasm use in designated A-/B-lines of pearl millet developed during **1986–2004.**

A-/B-lines category	No. of A/B pairs	Remarks[1]
Germplasm	3	All three from *iniari* germplasm
Composites	14	6 composites, HHVD BC (5)
Germplasm × Breeding lines	56	19 lines/accessions, 843B (35), 81B (16), ICMB 89111 (12)
Composites × Breeding lines	9	3 composites, 843B (6)
Breeding × Breeding lines	13	Largely 843B (6), 81B (5) and ICMB 89111 (3)
Total	95	

1. Figures in parentheses indicate the number of times a parental line of hybrid has been used in the parentage.

Further, 65 B-lines involved germplasm accessions or composites as one of the parents in their parentage. Thus, a total of 82 B-lines (86%) involved germplasm or composites at least as one of the parents in their parentage. Among seed parental lines, 843B, reputed for its early maturity, large seed size, dwarf height, good tillering and good combining ability, was involved as one of the parents in 47 (49%) of the B-lines, followed by 81B in 16 B-lines and ICMB 89111 in 15 B-lines. It should be noted that ICMB 89111 itself involves 843B as one of the parents in its parentage. This shows substantially wider genetic base of designated pearl millet A-/B-lines.

Line breeding

High grain yield potential of A-lines, both per se as well as in hybrids (ie, combining ability) is the most important consideration in seed parents breeding. Thus, high yield potential is the first target trait for which selection is made visually and in unreplicated nursery. High yield, however, must be achieved in combination with other agronomic and farmer-preferred traits, if the lines and hybrids are to be accepted by the seed industry and the farmers. Some of the traits in hybrids common to all the environments include lodging resistance, compact panicles and good exertion, and seed set. Traits that have regional preferences include various maturity types, plant height (grain vs dual-purpose hybrids), tillering ability, seed color and seed size. Thus, trait-based breeding approach is followed as most of these agronomic traits have high heritability, for which visual selection during generation advance that takes advantage of the two contrasting crop seasons at Patancheru is fairly effective. These traits in the parental lines are expressed in hybrids to varying levels, depending on the corresponding traits in the pollen parents. The A-lines must also have complete and stable male sterility and B-lines must have profuse pollen production ability across the seasons and sites.

The first planting of F_2 populations and composites/OPVs generally has 500–1000 plants, with replanting of the outstanding populations in the subsequent seasons. Pedigree breeding is followed generally up to F_7/S_5 stage after which bulk breeding is carried out in lines that have attained high levels of uniformity for morphological traits and DM resistance. At least one DM screening of breeding lines will have been completed by the time the F_7/S_5 breeding stage is reached. At each inbreeding stage, about 30–50% breeding lines that are not found acceptable on the multiple-trait criteria are discarded. However, lines found outstanding for even one trait are selected for further use in the crossing program. F_5/S_3 onwards, selected lines continue to be evaluated in the plantings done according to parentage, but highly selected lines from various populations are also classified into trait-specific groups. This planting/evaluation plan allows for some sort of replicated evaluation of the highly selected lines, and it also allows for more effective comparative evaluation/selection of lines in trait-specific compact blocks.

Selection for DM resistance

Periodic evaluation of progenies for DM resistance during the course of inbreeding and selection runs concurrent to agronomic evaluation to ensure that lines [B-lines and restorer lines (R-lines)] finally produced are resistant to this disease. Initially, field DM nursery was used for screening. But this has not been always very effective because of uncertain and variable effects of weather on disease development. The greenhouse facilities for maintaining diverse pathotypes, and their use for seedling screening at ICRISAT-Patancheru, however, has proved very effective with consistent results and provision for mass screening of breeding lines round the year (except for two months each in winter and hot summer). Results show that an unreplicated single-pot screening of breeding lines (approximately 30–40 seedlings per line) is highly effective for rejecting the susceptible lines as the correlation between single-pot screen and 2-pot screen for DM incidence is highly significant ($r = 0.75^{**}$) (Rai et al. 2004).

Trait-specific breeding lines are evaluated for DM resistance against pathotypes from the region for which the lines are targeted. However, breeding lines in some trait-specific groups (eg, early maturity, medium seed size, and average tillering with long panicles) are evaluated in successive steps against more than one diverse pathotypes because of the wider requirements of such materials. It has been found that selection for resistance to one pathotype is effective, to some extent, in selecting for resistance to another diverse pathotype. For instance, about 500 progenies from the Extra-early dwarf B-composite had been screened against two diverse pathotypes (Jalna and Durgapura). From amongst the lines that belonged to 0–10% DM incidence class against Durgapura pathotype, about 54% had <10% DM incidence against Jalna pathotype (Table 2.12). From amongst the lines that had 21–30% DM incidence against Durgapura pathotype, only about 29% lines had <10% DM incidence against Jalna pathotype. This selection strategy has proved useful in breeding A-lines having resistance to multiple pathotypes of DM. For instance, of the 72 A-lines designated and disseminated during 2000–03, six were resistant to five diverse pathotypes (Patancheru, Jalna, Jamnagar, Durgapura and Jodhpur) against which the screening was done, 23 to four pathotypes, 31 to three of the pathotypes, and 12 to two of the pathotypes (Table 2.13).

Table 2.12. Extra-early dwarf B-composite pearl millet progenies with resistance to two diverse pathotypes of downy mildew (DM) pathogen under glasshouse conditions.

DM incidence (%) class (Durgapura pathotype)	No. of progenies tested	Percentage progenies in DM incidence (%) class against Jalna pathotype			
		0–10	11–20	21–30	>30
0–10	174	54	18	7	20
11–20	68	43	22	19	16
21–30	48	29	31	8	31
>30	203	33	20	15	33

Plant type and morphological diversity

Since the beginning of the pearl millet improvement research at ICRISAT, d_2 dwarf plant height has emerged as the most dominant plant type concept in seed parents breeding. This has several operational advantages: (i) provides the option for breeding hybrids of varying heights; (ii) provides greater control on seed yield and quality by reducing the danger of lodging which can occur under high-management seed production conditions; and (iii) allows for much rapid

Table 2.13. Nature of multiple pathotype[1] resistance of pearl millet A-line developed during 2000–03 at ICRISAT, Patancheru, India.

Multiple pathotype resistance	Number of A-lines
Resistance to any five pathotypes	6
Resistance to any four pathotypes	23
Resistance to any three pathotypes	31
Resistance to any two pathotypes	12

1. Patancheru, Jalna, Jamnagar, Durgapura, Mysore and Jodhpur pathotypes.

detection and efficient roguing of off-types and pollen shedders in A-lines. It is common to hear breeders searching for A-lines with basic morphological features specific to A-lines of some successful commercial hybrids, but with improvement in certain traits such as seed size, panicle size and compactness, and seed yield. Those common and prevailing plant type choices are considered in the breeding programs to test their potential. The designated A-lines represent considerable morphological diversity for the agronomic traits. In view of the increasingly important role of the stover, ICRISAT seed parent development program is well positioned to address this emerging trend with most of the materials being in the medium (46–55 days to flower) to mid-late (56–60 days to flower) maturity groups (Table 2.14). Being an international center with a global mandate, ICRISAT explores new plant types such as A-lines with long panicles (30–80 cm compared to standard normal of 10–20 cm), eg, ICMA 04777 (Fig. 2.9); thick panicles (40–50 mm compared to standard normal of 20–30 mm diameter);

Figure 2.9. Pearl millet ICMA 04777, a male-sterile line with long panicles.

Table 2.14. Frequency distribution of designated pearl millet B-lines for various traits[1].

Character	Class/ No. of lines	Frequency distribution in class					
Time to 50% flower (days)	Class	≤40	41–45	46–50	51–55	56–60	61–75
	No. of lines	2	20	42	31	3	1
Plant height (cm)	Class	60–75	76–90	91–105	106–120	121–135	136–150
	No. of lines	10	26	21	18	17	7
Panicle length (cm)	Class	10–15	16–20	21–25	26–30	31–35	36–40
	No. of lines	37	49	7	5	0	1
Panicle diameter (mm)	Class	15–20	21–25	26–30	31–35	36–40	--
	No. of lines	4	33	44	16	2	
1000-seed mass (g)	Class	≤8	8.1–10.0	10.1–12.0	12.1–14.0	14.1–16.0	--
	No. of lines	9	38	44	7	1	
No. of panicles plant^{-1}	Class	1.0–2.0	2.1–3.0	3.1–4.0	4.1–5.0	--	--
	No. of lines	25	50	18	6		

1. Controls:
81B: Time to 50% flower 54 days; plant height 90 cm; panicle length 23 cm; panicle diameter 20 mm; 1000-seed mass 6.3 g; no. of panicles plant^{-1} 2.8.
843B: Time to 50% flower 39 days; plant height 78 cm; panicle length 14 cm; panicle diameter 23 mm; 1000-seed mass 8.8 g; no. of panicles plant^{-1} 23.7.

and large seed size (17–20 g of 1000-seed mass compared to standard normal of 9–12 g), eg, ICMA 04888 (Fig. 2.10).

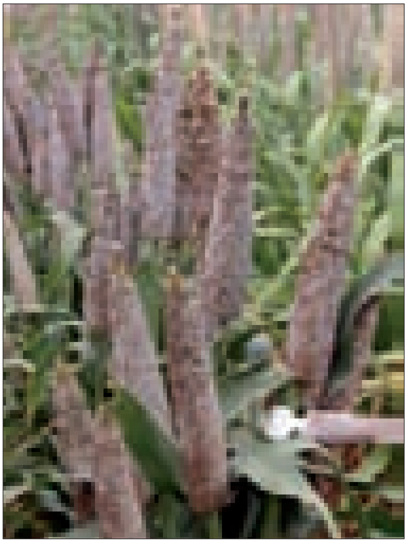

Figure 2.10. Pearl millet ICMA 04888, a male-sterile line with large seeds.

GCA testing

While breeding for high general combining ability (GCA) is an important aspect of hybrid parents development, there are several plant performance aspects that are equally and even more important, are relatively easy to breed for (as mentioned earlier), and hence these have received higher priority. These include high grain yield levels of the lines per se (especially A-lines), lodging resistance, compact panicles, good exsertion, acceptable seed size, shape and color, acceptable height and maturity, complete and stable male sterility of A-lines, high levels of male fertility restoration ability of R-lines, good pollen shedding in B-lines and R-lines, flowering synchrony between A-lines and R-lines, and high levels of resistance to DM (and other diseases and pests, if these are of serious nature in the target region). These traits are important in developing farmer-acceptable hybrids. Most of these are also important at the seed production level itself as they relate to seed production economy, and it is from this viewpoint that these traits have become increasingly more important in recent time.

A summary of six line × tester studies (Rai and Virk 1999) showed that there was no correlation between the grain yield of the lines per se and their GCA (Table 2.15). A similar summary of six diallel crosses showed that in two studies there was no correlation between the two, while in four studies the correlation was positive and significant. Thus, high general combiners are equally likely or even more likely to occur in lines with high grain yield per se than in any other yield group. Considering the seed production economy and high probability of producing high-yielding hybrid, it is prudent that seed parents possess both high yield per se as well as high GCA. Early generation testing of lines at the F_4/F_5 inbreeding stage is conducted in those programs,

Table 2.15. Correlation between performance per se and general combining ability for grain yield in pearl millet line × tester and diallel crosses.

No. of lines/ inbred lines	Correlation coefficient[1]	Reference
Line × tester crosses		
5 × 21	0.07	Tyagi et al. (1975a)
4 × 19	–0.08	Phul et al. (1976)
6 × 16	0.21	Pethani and Kapoor (1984)
6 × 8	–0.40	Maciel et al. (1987)
6 × 8	–0.54	Maciel et al. (1987)
5 × 10	–0.03	Patel and Kukadia (1988)
Diallel analyses crosses		
20	0.75**	Upadhyaya and Murty (1971)
9	0.25	Phul et al. (1973)
10	0.38 (0.17)	Tyagi et al. (1975b)
16	0.68**	Tyagi et al. (1978)
12	0.79** (0.87)**	Singh et al. (1980)
9	0.69**	Navale et al. (1993)

1. Figures in parentheses indicate correlation coefficient for F_2 generation; ** Highly significant at 0.01 probability level.
Source: Rai and Virk (1999).

which have complementary sets of breeding materials for seed parents and restorer parents development, and conduct research on materials with relatively much narrow genetic base (eg, private seed companies and NARS) and for specific target regions.

A-line development

In A-line breeding, development of productive B-lines with combinations of numerous agronomic and adaptation traits is the most difficult part of the program. Once this has been achieved, conversion of B-lines into A-lines is a rather straightforward exercise. Several questions, however, arise that relate to efficiency and cost-effectiveness of the conversion process.

Conversion stage

Conversion of potential B-lines into A-lines is initiated once it has been ascertained that they meet the multiple criteria of yield potential, agronomic traits, DM resistance and high levels of morphological uniformity. Normally, at least three generations of progeny-based evaluations (ie, at least up to F_5/S_3) must precede before undertaking them for conversion into A-lines, which translates to about two years × two seasons of prior field evaluation on plot basis. In very exceptional cases (either exceptional performance or any urgency to save critical time), a progeny with outstanding performance can be put into A-line conversion scheme at an earlier inbreeding stage.

Conversion method

Since highly uniform B-lines are used for conversion, crosses and backcrosses are made on line basis rather than on individual plant basis during generation advance. Following this method, it has been observed that normally there is neither significant variability within B-lines for agronomic and adaptation traits nor any variability within the F_1 and backcross progenies for male sterility, thus eliminating any need for within-plot selection. This method of conversion of B-lines into A-lines also reduces unnecessary work needed while dealing with sister A/B pairs in plant × plant backcross conversion scheme, and allows for the maintenance of greater diversity for the equivalent resources used in plant × plant crossing scheme. Even with the use of advanced generation B-lines for conversion, lines found to have produced fully sterile F_1s sometimes produce backcross progenies with low frequency of pollen shedders. First, such cases are very rare. Second, unless the B-line is truly outstanding, plant × plant crossing in backcross progenies is not done, and those backcross/B-line pairs are eliminated from the crossing program.

Selection during conversion process

During the conversion process, selection continues, but more among the B-lines than within the B-lines, especially during the advanced backcross stages. Generally, there is about 20% rejection of the B-lines and their corresponding F_1 and backcross progenies at each backcross stage (Fig. 2.11).

Each plant in the F_1 and backcross progenies is also selfed (using the tiller panicle) to score for and confirm complete sterility. One or two generations of backcross time can be saved by selecting plants in the backcross progenies that have greater resemblance to the basic plant morphology of the recurrent parent. This, however, would require planting larger plots of the backcross progeny (say 80–100 plants rather than the customary 20–25 plants) to make the selection more effective.

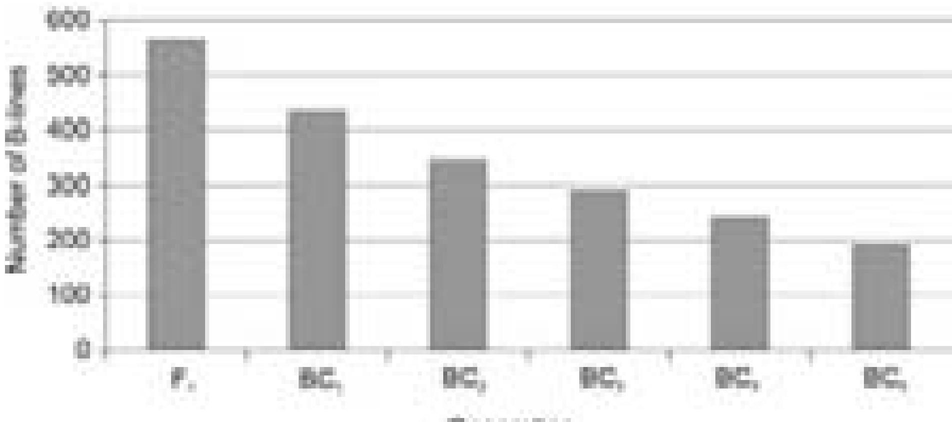

Figure 2.11. Number of pearl millet B-lines retained at various backcross (BC) stages of their conversion into A-lines (1995–2002).

A-/B-lines designation

Since 1988, pearl millet A-/B-lines developed at ICRISAT-Patancheru have been designated with a five-digit number, where the first two digits refer to the year in which they are made available for use in testing experimental hybrids, followed by three digits (the same number in triplicate). Thus, ICMA/B 99444 refers to the fourth A/B pair produced in 1999 and ICMA/B 01222 refers to the second A/B pair produced in 2001. At ICRISAT-Patancheru, normally 5–7 A/B pairs are produced and designated every year, but not more than 9 pairs in any one year. These A/B pairs are designated after rigorous screening of the B-lines for DM resistance to five diverse pathotypes under high disease pressure (80–90% disease incidence in the susceptible check in the greenhouse seedling inoculation). Normally 15–20 B-lines of the counterpart candidate A-lines selected on the basis of agronomic performance and morphological diversity are subjected to DM screening and those eligible for designation must be resistant (<10% DM incidence) to at least two pathotypes. This designation system has been operationally found quite useful, especially in terms of seed request and in recall during the selection process in seed parents progenies. This designation system, developed for a historical reason, can be simplified to three-digit system.

The B-line counterparts of 34 designated A_1-system A-lines have been converted into A_4-system A-lines. Also, the same 34 B-lines are also being converted into A_5-system A-lines. These A-lines with the A_4 and A_5 cytoplasms are yet to be designated, following a rational system for which the decision is yet to be taken. The simplest procedure would be to retain the same five digit numbers already assigned to the A_1-system A-lines, with the CMS system subscript attached to the new CMS versions (eg, $ICMA_4$ 00999 for the A_4-system A-line with ICMB 00999 genotype that is involved in A_1-system A-line ICMA 00999).

Characterization

Since only 5–7 A/B pairs are generated every year, characterization of B-lines for grain yield and agronomic traits per se is done once in 2–3 years, in replicated trials and for at least two seasons at Patancheru. To start with, almost all the designated B-lines have been characterized for grain yield and other agronomic traits in trait-specific trials conducted at Patancheru in 2–3 year × season environments. Several of these lines have shown higher yield potential with maturity comparable to or even earlier than the commercial control line 81B

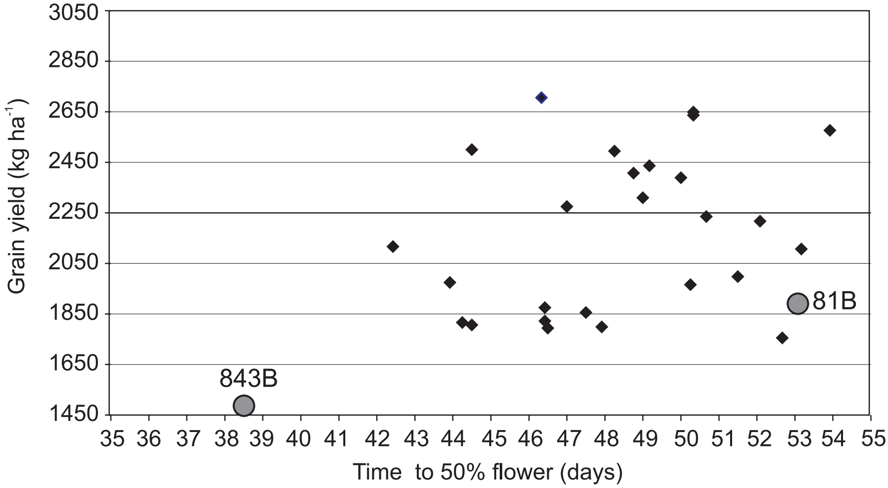

Figure 2.12. Distribution of pearl millet dwarf B-lines (counterpart of designated A-lines) for grain yield and time to 50% flower.

(Fig. 2.12). A similar characterization of the early-maturing B-lines has led to identification of very few lines outyielding 843B in the comparable maturity group. However, several B-lines outyielding 843B but being 2–3 days later in maturity have been identified (Fig. 2.13).

With the emerging intellectual property rights (IPR) issues, B-lines will now likely be characterized for at least two seasons before they are fully

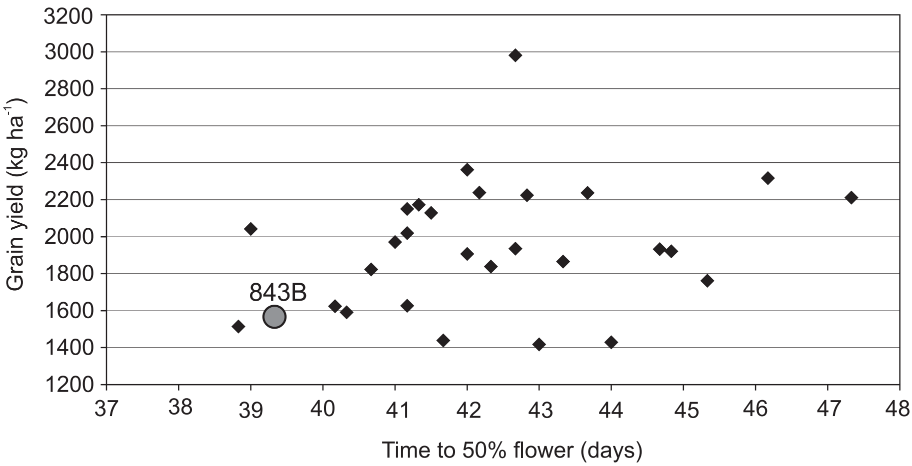

Figure 2.13. Distribution of pearl millet early B-lines for grain yield and time to 50% flower.

converted into A-lines, and both A- and B-lines will have to be characterized again for distinctness, uniformity and stability (DUS) traits. The implications of early characterization in resource use and IPR context still need to be clearly assessed. Also, targeted characterization of a few A-lines is undertaken to assess their hybrid yield potential as compared to A-lines of similar plant morphology already under commercial production. Thus, 843A has been widely used in breeding several early-maturing commercial hybrids, but of late it has been showing increased susceptibility to DM. In an attempt to breed its resistant versions, several A-lines with basic morphological traits similar to 843A were developed and evaluated for their hybrid yield potential. Two of these (ICMA 95444 and ICMA 97444) that flowered 1–6 days later than 843A produced hybrids that had similar flowering time as the hybrid of 843A (Table 2.16). Both these A-lines had much less DM incidence (17–23%) compared to 843A (94%) under high disease pressure in the greenhouse screening. Similar DM incidence patterns were observed in the hybrids of these A-lines. While the grain yield of ICMA 95444 was comparable to that of 843A, ICMA 97444 had 12% more grain yield than 843A. Similar patterns were observed in the hybrids of these three A-lines. These results showed ICMA 95444 and ICMA 97444 as promising alternatives to 843A.

Table 2.16. Performance of downy mildew (DM) resistant versions of pearl millet 843A and their hybrids.

	Grain yield (kg ha^{-1})		Time to 50% flower		DM incidence (%) in B-line[3]	
A-line	A-line[1]	Hybrid[2]	A-line[1]	Hybrid[2]	Jodhpur	Durgapura
ICMA 95444	1369	3188	44	42	23	9
ICMA 97444	1713	3478	49	44	17	12
843A (control)	1281	3117	43	42	94	87
SE± (trial)	43.9	39.0	0.2	0.1	2.3	1.8

1. Mean of seven environments.
2. Mean of eight environments.
3. Greenhouse data.

ICMA 89111 is another A-line on which two public sector hybrids have been released. ICMA 97333 was developed at ICRISAT-Patancheru as a better version of ICMA 89111. Both A-lines have similar basic plant morphology with respect to their high-tillering behavior and panicle types, but ICMA 97333 is slightly taller, takes 1–2 days more to flower, and has slightly longer and more compact panicles. Evaluation of their hybrid potential showed hybrids of ICMA 97333 outyielding the hybrids of ICMA 89111 by 3–8% with just 1 day later flowering, but being taller by 10–20 cm (means higher fodder yield) (Table 2.17). The hybrid of G 73-107 made on ICMA 97333 was DM free while the one made on ICMA 89111 had 6.5% DM incidence.

Table 2.17. Grain yield, agronomic traits and downy mildew (DM) resistance of pearl millet hybrids based on ICMA 89111 and ICMA 97333 during rainy season 2002 at Patancheru, India.

Character	ICMA 97333 × RIB 3135/18	ICMA 89111 × RIB 3135/18	ICMA 97333 × G 73-107	ICMA 89111 × G 73-107	SE±
Grain yield (kg ha^{-1})	4470	4140	3980	3860	220.4
Time to 50% flower (days)	43	42	43	42	0.0
Plant height (cm)	180	170	180	160	2.8
Panicle length (cm)	22	22	21	21	0.8
No. of panicles $plant^{-1}$	3.5	3.5	3.9	3.5	4.4
1000-seed mass (g)	8.0	8.0	11.1	9.0	0.41
DM incidence (%)	0.0	0.0	0.0	6.5	3.56

Documentation

So far, two types of documentation procedures for seed parents have been followed: one dealing with the hybrid yield potential, and the other dealing with the agronomic and adaptation traits of the lines per se. The latter has generally been done for A/B pairs which have either exceptional properties such as ergot or smut resistance, or have been under increasing commercial production with hybrid cultivation exceeding 20,000 ha. Again, with emerging IPR issues, A/B lines in the future will be documented not only for morphological DUS traits and hybrid yield potential, but some of them even for DNA-based markers. Research has recently been initiated on identification/development of breeding lines, parental lines, and improved germplasm with high levels of iron (Fe), zinc (Zn), β-carotene and salinity tolerance. Germplasm identified as outstanding in these respects will be documented on high priority basis regardless of their direct parental worth in hybrid development. Documentation of hybrid yield potential of few lines has been done to demonstrate their usefulness in hybrid breeding, as a part of the information generation exercise for utilization by NARS and the private sector.

Restorer parents research

Priority CMS systems

After a gap of 10 years, restorer parents research at ICRISAT-Patancheru was reactivated in response to requests from the Scientists' Field Day participants in 2000. Considering the high seed parents breeding efficiency with the A_4 and A_5 CMS systems, and their planned use for A-lines development, corresponding emphasis will be placed on breeding restorers of these CMS systems as well in all the ICRISAT mandate regions. So far, almost entire emphasis has been on the use of the A_1 CMS system in restorer breeding in all the regional programs in Asia and Africa, except that some of the elite breeding lines have been under conversion into their A_4 and A_5 restorer versions at Patancheru, and A_4 restorers have been introduced into 14 adapted OPVs developed in the ESA region. The low frequency of A_4 restorers observed in several WCA-bred populations point to the need for restorer development research if this CMS system (and also the A_5 CMS system) is to be used in breeding commercial hybrids.

Restorer sources of various CMS systems

Excellent restorers of the A_1 CMS system are available with the public and private sector hybrid programs in India. However, there is a serious lack of the A_4 restorers everywhere. Restorers of A_5 in elite agronomic background are rare and are yet to be developed. Excellent genetic stocks of A_4 and A_5 restorers have been developed at ICRISAT-Patancheru, which can be used for backcross breeding of R-lines of these two CMS systems. An efficient backcross breeding method (Fig. 2.14) for converting elite inbred lines into their A_4 and A_5 restorer versions has been developed. Its application has now led to the conversion of elite inbred lines (designated restorers of the A_1 CMS system) from ICRISAT-Patancheru and NARS into their A_4 restorer versions (13) and A_5 restorer versions (34), while some more are at various backcross stages of their conversion (Table 2.18). Also, moderate frequency of restorers of the A_4 CMS system has been found in most of the populations surveyed. Low frequency of restorers of the A_5 CMS system has also been found in most of these populations. Their frequency in these populations can be rapidly increased by recurrent selection.

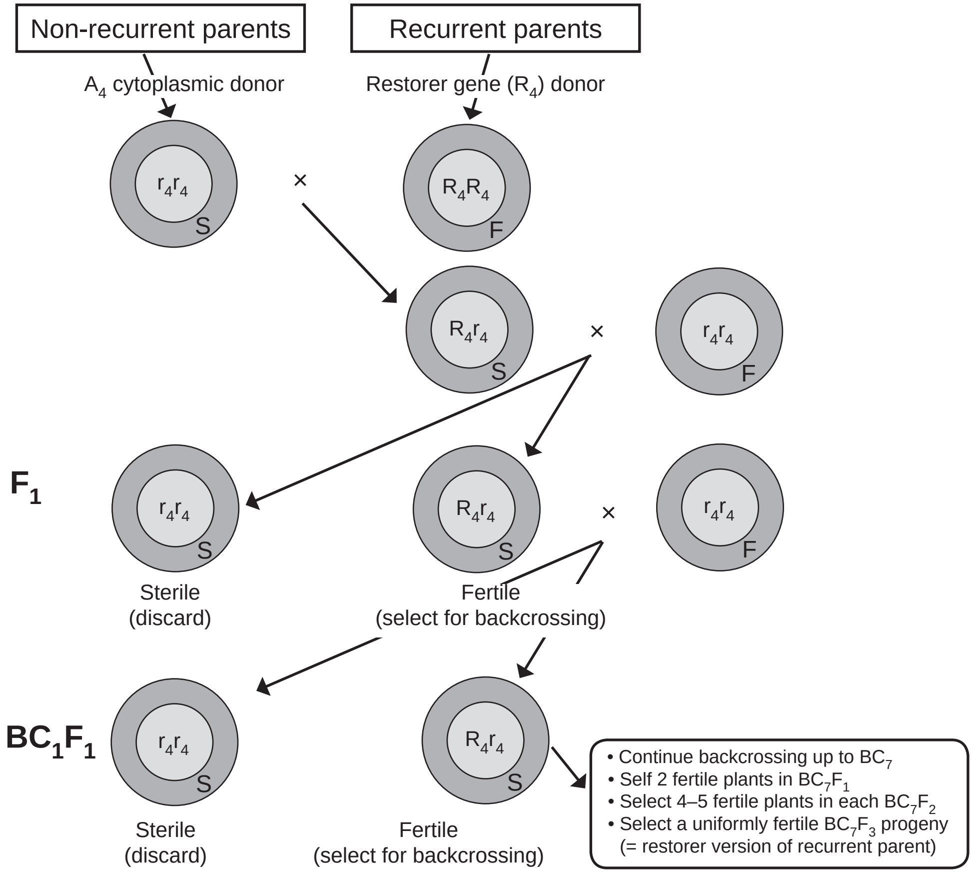

Figure 2.14. Schematic backcross procedure for breeding restorer lines of A_1 cytoplasmic-nuclear male sterility in pearl millet.

Table 2.18. Backcross breeding to develop A_4- and A_5-restorer versions of elite inbred lines in pearl millet.

	No. of inbred lines[1]	
Development stage	A_4-restorer	A_5-restorer
Backcross completed	13	34
Advanced backcrosses	7	14
Total	20	48

1. Inbred sources: ICRISAT-Patancheru (32), Mandor (8), CAZRI (Jodhpur) (2), Durgapura (2), Jamnagar (1), New Delhi (1), private seed companies (2).

Basic features

Restorer lines must produce profuse pollen that should remain viable at air temperatures as high as 42–44°C. Also, pollen parents must produce highly fertile hybrids, which confers some degree of protection from ergot and smut infection. Besides being able to produce high-yielding hybrids, the restorers should also be highly productive, which is important from the viewpoint of seed production economy. It is desirable to breed pollinators of 150–180 cm height, but no taller than the A-line, with panicle, maturity and tillering attributes that will be preferred by farmers in the hybrids. Pollinators must have acceptable level of lodging resistance and resistance to diseases (DM resistance in case of India). While heterosis for DM resistance (most likely due to repulsion phase distribution of resistance genes in parents) has been found to be most common, parental relationship with hybrids for lodging resistance is not well understood.

R-line breeding

Germplasm utilization

Some of the most outstanding and widely used pollinators with the private sector have their likely origin from Gujarat Agricultural University (GAU), Jamnagar and from ICRISAT, but their identity is not yet established. ICMP 451 (now highly susceptible to DM) and ICMR 356 (still highly resistant to DM) are the two restorers with good GCA that have been pollen parents of the two ICRISAT-bred hybrids. These provide a good base for their use in pedigree breeding of restorers. Several high-yielding OPVs (and some composites) have been produced at ICRISAT-Patancheru and in the SADC region, which would provide excellent materials for restorer line development.

With a view to develop a diverse range of productive restorers, inbreeding and selection in 23 OPVs and populations (15 from ICRISAT-Patancheru, 5 from WCA and 3 from the SADC region) have produced more than 800 S_1/S_8 progenies (Table 2.19).

Majority of these is in 46–55 days flowering group, which is now receiving increasing importance in India for breeding dual-purpose hybrids. Several of these progenies have now been grouped into trait-specific nurseries (Fig. 2.15), following the same philosophy as for seed parent progenies. While these materials will be adequate to serve the medium-term objective,

Table 2.19. Flowering classes of progenies derived from diverse populations of pearl millet during rainy season 2004 at ICRISAT, Patancheru, India.

Region (No. of populations/OPVs)[1]	Total number	Percentage of progenies in flowering class (days)					
		41–45	46–50	51–55	56–60	61–65	>65
Asia (15)	728	5	39	40	14	2	0
WCA (5)	42	5	14	57	17	2	5
SADC (3)	32	16	47	28	9	0	0

1. OPVs = Open-pollinated varieties; WCA = Western and Central Africa; SADC = Southern African Development Community.

a long-term perspective must include continued trait-based exploitation of germplasm from the genebank until more efficient approaches for the identification of the target traits have been devised and validated.

Figure 2.15. High-tillering restorer progeny (S4) derived from pearl millet Mandor Restorer Composite.

Line breeding/GCA testing

The same trait-based selection approach combined with high yield potential and DM resistance has also been followed for restorer line breeding as for the A-line breeding. One major difference is that in restorer breeding, there is very negligible effort on breeding dwarf R-lines. For DM resistance, the same procedure is applied as in seed parent breeding. Thus, in restorer line breeding also, it was observed that among progenies that had 0–10% DM incidence against Durgapura pathotype, 60% had 0–10% DM incidence against Jalna pathotype as well (Table 2.20). In comparison, of those progenies that had 20–30% DM incidence against Durgapura pathotype, 48% had 0–10% DM incidence against Jalna pathotype. Thus, these results showed that selection for high levels of resistance against one pathotype could be effective in rejecting a large proportion of susceptible progenies against another pathotype. The potential of restorer progenies is confirmed for their fertility restoration ability, which requires testing their hybrids. This test provides preliminary information about the hybrid yield potential of these R-lines.

Table 2.20. Dual-purpose elite A_4-restorer progenies of pearl millet with resistance to two diverse pathotypes of downy mildew (DM) pathogen under glasshouse condition.

DM incidence (%) class (Durgapura pathotype)	No. of progenies tested	Percentage of progenies in DM incidence (%) class against Jalna pathotype			
		0–10	11–20	21–30	>30
0–10	37	60	21	11	9
11–20	29	34	28	14	24
21–30	23	48	35	13	4
>30	91	36	19	18	27

Dual- and multiple-restorers

Inbred lines that restore male fertility of two CMS systems (dual-restorers) and those that restore male fertility of several CMS systems (multiple-restorers) are useful for genetic studies. Genetic backgrounds of the segregating populations developed from crosses between these restorers and isonuclear A-lines will be similar, and hence will allow to discount for the genetic background effects on gene action. Some of the most outstanding inbred lines in terms of their performance per se (including DM resistance) and GCA will be converted into dual-restorers of the two most useful CMS systems (A_4 and A_5).

R-lines designation/characterization/documentation

Restorer lines have been variously designated in the past as ICPs, ICMPs and ICMRs. Henceforth, they will be designated as ICMRs, following the same five-digit system as for the A-/B-lines. The lines will be eligible for designation once they have been advanced to F_8/S_6 levels and beyond, have high grain yield potential in the respective maturity groups (and also high biomass yield in the dual-purpose group) and high levels of DM resistance, have achieved acceptable uniformity for agronomic traits, and have been reconfirmed for their male fertility restoration ability in hybrids. It will be ensured each year that the set of R-lines to be designated are morphologically diverse. The designated R-lines will then be finally characterized for yield potential and agronomic traits (including DUS traits) in replicated yield trials conducted at least at Patancheru for two seasons. This will be followed by the documentation of R-lines.

Hybrid development

The way all the high-yielding hybrids have been developed and released in India, there seems to be no specific guideline as to which plant type of R-line will combine well with which plant type of A-line. However, a few important considerations such as flowering time, plant height and panicle types do merit rational judgment. There should be as less difference between the flowering time of an A-line and R-line as possible though synchronous flowering of A- and R-lines is highly preferred. The height of an R-line should be no less than that of an A-line. Having these basic requirements met, hybrid development in pearl millet basically remains a game of numbers. However, identification of heterotic groups in the elite breeding materials can enhance the hybrid breeding efficiency. Going further down to landraces to group them in heterotic groups could also be useful in the long term, but use of such materials can drag the hybrid program back by a decade or two. In WCA, a breeding strategy is being developed that will identify heterotic groups of landraces originating all the way from Senegal to Sudan, and use this genetic pattern to breed both OPVs and hybrids.

New research frontiers

Exceptional germplasm identification and use

Trait-based evaluation and utilization of pearl millet germplasm identified in acceptable range of variability will continue to be the major focus of hybrid parents research. However, germplasm with exceptional traits have been available or have been developed. The first example of this is thick panicle populations (both tall and dwarf versions) developed at ICRISAT-Patancheru that have >50 mm panicle diameter compared to 20–30 mm diameter of the normal breeding materials. These populations mature in 85–90 days and have large seed size (11–14 g 1000-seed mass). These are currently being used for seed parents development. Germplasm accessions having up to 150 cm panicle length compared to 25–30 cm panicle length in the normal breeding materials of India have been available from WCA collections. These have been evaluated and are being used to introgress this trait in adapted genetic backgrounds for restorer line development. Similarly, germplasm with 20 g 1000-seed mass as compared to 8–12 g in the general breeding materials have been identified, evaluated and are now being used for introgression of this trait into adapted genetic backgrounds for seed parents development.

Biotech integration

Molecular MAS has been applied as a tool to enhance the efficiency of breeding for DM resistance, drought tolerance and stover quality in pearl millet. The MAS for drought tolerance and stover quality remains in the strategic research phase, and its effectiveness (in terms of both cost and the extent of improvement) is yet to be confirmed. The MAS for DM resistance has been found quite effective and can be selectively integrated with the mainstream breeding. More than 56 quantitative trait loci (QTLs) for DM resistance against 13 diverse pathotypes have been identified (Table 2.21). Of these, 34 QTLs belong to 7 Indian pathotypes (Patancheru, Jaipur, Jodhpur, Jamnagar, Jalna, New Delhi and Mysore) and 22 QTLs belong to 7 African pathotypes. Utilization of these QTLs has been under way in breeding DM resistant versions of the parental lines of several commercial hybrids.

The greatest progress made so far is the development of HHB 67-2, the DM resistant version of the earliest-maturing (65 days to mature) commercial hybrid HHB 67, which has now been showing signs of breakdown of its DM resistance. HHB 67-2 (Fig. 2.16) has basic plant morphology similar to HHB 67. In 11 AICPMIP tests it took 42 days to flower (2 days more than HHB 67), had 2115 kg ha^{-1} grain yield (6% more than HHB 67) and 4560 kg ha^{-1} dry fodder yield (8% more than HHB 67), and had 0–2% DM incidence against the Jodhpur and New Delhi pathotypes compared to 60–91% in HHB 67 in the greenhouse seedling inoculation test (Table 2.22). Based on this superior performance, HHB 67-2, as 'HHB 67 Improved' has now been recommended by the Central Seed Committee and notified for cultivation for the whole of India, especially in parts of Haryana and Rajasthan where the original HHB

Table 2.21. Major quantitative trait loci (QTLs) in pearl millet for downy mildew resistance against various pathotypes of *Sclerospora graminicola*[1].

Pathotype	Minimum no. of major QTLs[2]	Linkage group	Most important resistance gene donor parents
India			
Patancheru	8	1,2,4,6,7	863B, ICMB 90111, ICMP 451, P 310-17, P 1449-2, P 7-3, PT 732B, W 504, IP 18293
Jaipur	4	1,2,4	863B, ICMB 90111
Jalna	4	1,2,3,4	863B, ICMB 90111, ICMP 451
Jamnagar	7	1,2,3,4,7	863B, ICMB 90111, IP 18293
Jodhpur	6	1,2,3,4	863B, ICMB 90111, P 1449-2
New Delhi	4	2,3,4,7	ICMB 90111
Mali			
Bamako	4	1,2,4,7	ICMB 90111, P 1449-2, P 310-17
Bengou	5	1,4,6,7	ICMP 451, W 504, IP 18293
Maiduguri	3	1,2,4	ICMB 90111, P 1449-2
Others[3]	11	1,2,3,4	–
Total	56	–	

1. Source: Data of CT Hash, ICRISAT.
2. QTLs accounting for at least 20% of the variability in downy mildew resistance.
3. Includes Mysore (India), Sosane (Eritrea), Kebiamid Nguru (Nigeria), Doffane and Dimetaba (Senegal) and Kordofan (Sudan).

Table 2.22. Performance of pearl millet HHB 67-2, a downy mildew (DM) resistant version of HHB 67 developed by marker-assisted selection[1].

Character	HHB 67-2	HHB 67
Yield and flowering[2]		
Grain yield (kg ha^{-1})	2115	1986
Fodder yield (kg ha^{-1})	4560	4240
Time to 50% flower (days)	42	40
DM incidence (%) in glasshouse		
Jodhpur	2	60
Delhi	0	91
DM incidence (%) in disease nursery		
Hisar	2	14
Anand	3	18

1. Source: Data of CT Hash, ICRISAT.
2. Mean of 11 environments from AICPMIP trials.

Figure 2.16. HHB 67-2 (HHB 67 Improved), an early-maturing downy mildew resistant pearl millet hybrid developed using marker-assisted selection (MAS).

67 was cultivated. HHB 67-2 is a unique hybrid with its yield potential and extra-early maturity, and it will be quite some time when another hybrid with similar maturity but greater yield will be bred. Till that time HHB 67-2 will have served its best purpose of increasing the longevity of HHB 67.

Development of HHB 67-2 is basically maintenance breeding. The challenge is to transfer DM resistance by MAS in the prospective parental lines that have higher yield potential (both per se and in hybrids) and farmer-preferred traits. This strategy clearly integrates yield enhancement with DM resistance breeding using MAS as a tool. Also, development of such lines provides much better materials for use in the further round of hybridization and pedigree breeding for grain yield and DM resistance improvement. This strategy would make hybrid parents development program in Asia much more effective. Such strategy would be truly vital in the context of hybrid parents development in the African regions because of the limited ability of the breeding programs for parental lines turnover in those regions.

Allele-specific molecular markers for appropriate photoperiod sensitivity in different ecological zones, and for restorers of the A_1, A_4 and A_5 CMS systems could enhance hybrid breeding efficiency in the WCA region. Exploitation of sorghum/pearl millet synteny relations to identify *Striga* resistance in pearl millet could also help in efficient genetic management of this devastating parasitic weed.

Quality

In hybrid parents breeding, routine attention to evident grain quality traits such as size, shape and color is a rather straightforward exercise. The HarvestPlus Challenge Program project has now added another dimension to grain quality that relates to higher levels of Fe, Zn and β-carotene. Identification of golden millet with about 1.37 ppm of β-carotene, which is comparable to β-carotene in golden rice (*Oryza sativa*), and 3–5 times more than in the traditional pearl millet grown in India was encouraging. This grain quality trait, however, is in a photosensitive background. Using yellow endosperm as a proxy to β-carotene, this trait is currently being transferred into elite genetic backgrounds, using conventional backcross method.

Evaluation of a diverse range of materials (40 hybrid parents, 30 each of population progenies and OPVs and 20 germplasm accessions) has led to identification of parental lines and population progenies that have up to 120 ppm Fe and up to 68 ppm Zn. Highly significant positive correlation between the National Institute of Nutrition (NIN), Hyderabad, India and ICRISAT values both for Fe and Zn ($r = 0.77^{**}$ to 0.97^{**}) show that the use of in-house facility for Fe and Zn analysis may speed up the process of screening larger number of parental lines, OPVs and germplasm accessions to identify new sources with still higher levels of Fe and Zn density, preferably in released parental lines and OPVs. The high positive correlation ($r = 0.84^{**}$) between Fe and Zn density (Fig. 2.17) shows that simultaneous selection for high Fe and Zn levels is likely to be effective.

Soil salinity tolerance

Salinity tolerance research has grown out of an inter-institutional collaborative effort to support International Center for Biosaline Agriculture (ICBA) for identification of germplasm, OPVs and improved breeding lines (including hybrid parents) that have high levels of salinity tolerance both for biomass and grain yields. Screening results under 15 dS m^{-1} of salinity level both at ICRISAT and ICBA have identified some of the agronomically elite and high-yielding parental lines (ICMP 451 and ICMA 02111), OPVs (ICMS 7704, Raj 171 and GB 8735) and a composite (HHVBC Tall), and some of the germplasm accessions as highly tolerant to soil salinity. Salinity tolerance of these identified salt-tolerant materials is being confirmed and new sources of salt tolerance are being identified. Initial results of a mass selection experiment designed to

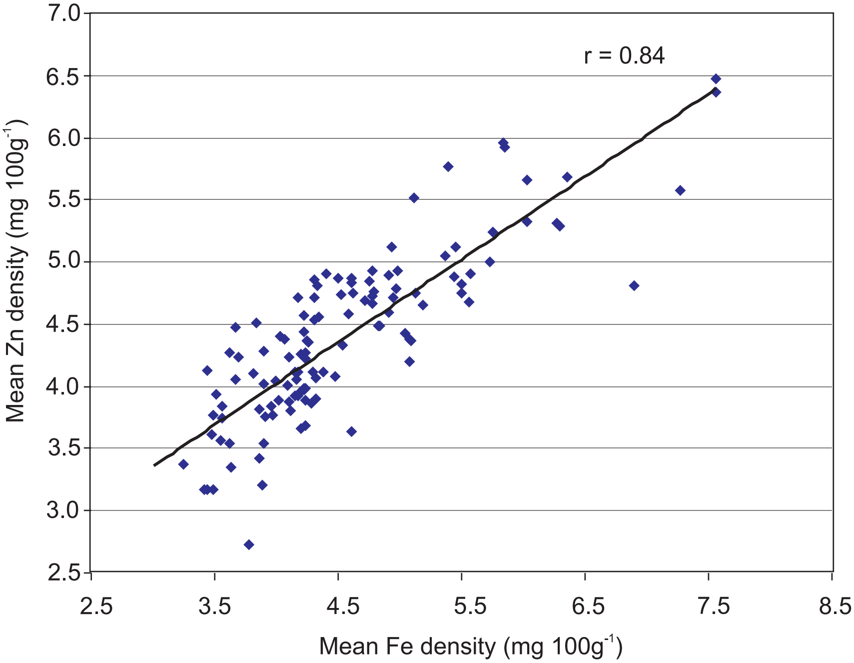

Figure 2.17. Relationship between grain Fe and Zn density in pearl millet.

improve the salinity tolerance of HHVBC Tall and Raj 171 have shown no significant variability for this trait in these populations. Lines with varying salinity tolerance are being used to develop hybrids to assess the relationship of hybrids with their parental lines for salinity tolerance. Interestingly, highly significant positive correlation (r = 0.65**) between biomass yield under saline pot condition and salinity tolerance index have been observed, indicating that biomass yield itself can be used as an effective selection criterion to select for salinity tolerance and biomass productivity under saline conditions.

Heat tolerance

Large genetic variability for heat tolerance, both at the seedling and reproductive stages, has been demonstrated in pearl millet. For instance, some of the pearl millet populations (including ICRISAT-bred population NCD_2) were shown to have good seedling emergence and survival at soil surface temperatures exceeding 62°C (Peacock et al. 1993). There is a large pearl millet area under summer cultivation, especially in Gujarat. While several high-yielding hybrids have failed to set seed under high air temperatures exceeding 46°C during flowering, some private sector hybrids have been found to set excellent seed under such situation. Some of the private seed companies (eg, Proagro and Mahyco) have shown willingness to offer limited field facilities at their test sites to evaluate ICRISAT breeding lines for heat tolerance under these conditions.

Research and development partnerships

Development of parental lines, evaluation of their hybrid yield potential, actual hybrid development and release, and seed production and technology exchange are all interlinked and vital components of impact-oriented research and development strategy. The key to the success lies in harnessing comparative and complementary skills and advantages in an institutional alliance framework (formal or informal) to integrate all the components for efficient delivery of the cultivar. Pearl millet hybrid research in India has formal collaboration with NARS under the umbrella of the Indian Council of Agricultural Research (ICAR)-ICRISAT Partnership projects, and informal collaboration with the private sector through the Hybrid Parents Research Consortium. The NARS are basically the recipients of ICRISAT trials and nurseries based on the mutual agreement worked through the AICPMIP meetings under the umbrella of ICAR-ICRISAT Research Partnership project. The private sector, like the NARS, are largely the recipients of improved breeding lines and parental lines based on their selections made during the Scientists' Field Days. Both sectors are involved at varying degrees in the impact assessment of ICRISAT-bred materials. The partnership with the private sector has been fruitful in terms of accelerating the impact of ICRISAT-bred materials and more recently in terms of resource mobilization with 25 seed companies having joined the Pearl Millet Hybrid Parents Research Consortium. Their involvement in impact assessment and research priority assessment is also increasing and this will substantially benefit hybrid parents research at ICRISAT. ICRISAT-NARS partnerships in the ESA and WCA regions should be further strengthened with a view to include those NARS in the hybrid program who have inclination to work on and adopt this technology during the seed production and dissemination phase.

Impact

Considering the research and development-oriented aspects of pearl millet hybrid parents research at ICRISAT, the impact has to be viewed both in medium and long terms; and also at various levels, from on-farm to those that relate to the strengthening of NARS and the private sector research programs.

On-farm impact

Hybrid cultivar adoption

The first and the greatest on-farm impact from ICRISAT's hybrid parents research occurred with the release and adoption of a high-yielding and DM resistant hybrid ICMH 451 that was bred using ICRISAT-bred A-line (81A) and ICRISAT-bred R-line (ICMP 451). ICMH 451 was released in 1986 at a time when the most widely cultivated hybrid BJ 104 had suffered from a DM epidemic. At the peak of its adoption in early 1990s, ICMH 451 was adopted on more than 1.2 million ha (about 10% of the total pearl millet area in India), and it continued to be grown on about 0.3 million ha till 2002, when it became susceptible to DM and was subsequently withdrawn from cultivation. Prior to the release of this hybrid, there was utter reluctance on the part of breeders in NARS to use 81A in their hybrid programs, mostly on the account of its late maturity (52–55 days to flower) and its typical dense plant canopy. The release of this hybrid, publication of mean hybrid potential of 81A as compared to the most popular A-line of that time (5141A) (Rai et al. 1986), and an aggressive breeder seed production program generated so much interest in 81A that 12 hybrids based on 81A were released during 1986–99.

During the past 2−3 years, more than 70 hybrids (mostly from the private sector) have been reportedly grown on 5 million ha (>50% of the pearl millet area) in India. At least 60 of these are based on ICRISAT-bred A-lines, or on proprietary A-lines developed from the use of improved breeding lines bred at ICRISAT. This has made remarkable contributions to biodiversity (largest number of hybrids on-farm in pearl millet as compared to any other coarse grain crop), enhanced yield stability, and increased productivity (3-year mean grain yield increasing from 450 kg ha^{-1} during 1970−75 to 750 kg ha^{-1} during the past five years, ie, 66% yield gain) for this hardy crop cultivated largely under most marginal environments with negligible external inputs.

Seed production benefits

Andhra Pradesh State Seed Development Corporation and a large number of private seed companies in Hyderabad (now a nerve center of hybrid seed industry for field crops in India) have been the greatest beneficiaries from pearl millet hybrid seed production. Farmers in just two districts of Andhra Pradesh who produce >80% of the country's pearl millet hybrid seed requirements have benefited from this research as the availability of a large number of hybrids and the ensuing competition among seed companies for seed production gave opportunities to seed-producing farmers in these areas for negotiating competitive seed procurement price. This seed production activity gives farmers an estimated additional income of at least US$2.5 million every summer crop season.

Impact on genetic base of hybrid breeding programs

Since 1986 (when the first ICRISAT-bred hybrid was released) till 2004, 72 hybrids have been released in India, of which 43 hybrids (ie, 60%) are based on ICRISAT-bred A-lines (Table 2.23). Of the 58 hybrids evaluated in AICPMIP's Initial Hybrid Trial in 2003, 45 hybrids (ie, 77%) were based on ICRISAT-bred A-lines (Table 2.24). Of the 144 hybrids evaluated in AICPMIP's hybrid trials in 2004, 119 hybrids (ie, 83%) were based on ICRISAT-bred A-lines. Development and dissemination of a diverse range of trait-specific materials (maturity range, seed size range, tillering ability, long panicle and thick panicles, large seed size) combined with high yield potential and resistance to diverse pathotypes of the DM pathogen, have made substantial contributions to diversify the genetic base of hybrid parents breeding programs in the country. This is reflected in 98 A-lines of diverse morphological characteristics and in diverse genetic and cytoplasmic backgrounds developed and disseminated to hybrid breeding programs in India. In a single Scientists' Field Day event in 2000, more than 50 scientists from the public and private sectors selected material and were supplied with a total of 2106 breeding lines and potential hybrid parents. In the 2004 Field Day, more than 40 scientists selected 1312 breeding lines and potential hybrid parents (Table 2.25).

Impact on institutional alliances

The ICRISAT-private sector consortium has dramatically enhanced the institute's scale of research operations and also enabled to provide partial funding support for off-season nursery to some NARS collaborators. Besides,

Table 2.23. Pearl millet hybrids based on ICRISAT-bred A-lines released in India during 1986–2004.

Research sector	No. of released hybrids	Hybrids based on ICRISAT-bred A-lines	
		Number	Percentage
Public sector	43	26	60
Private sector	29	17	59
Total	72	43	60

Table 2.24. Pearl millet hybrids based on ICRISAT-bred male-sterile lines in AICPMIP's Initial Hybrid Trial 2003.

Research sector	No. of hybrids in trial	Hybrids based on ICRISAT-bred A-lines	
		Number	Percentage
Public sector	38	28	76
Private sector	20	17	85
Total	58	45	77

Table 2.25. Number of pearl millet breeding lines selected by public and private sectors during Scientists' Field Days at ICRISAT, Patancheru, India, and seed samples supplied.

Field day (year)	No. of lines			No. of seed samples		
	Public	Private	Total	Public	Private	Total
2000	1014	1969	2106	2010	9999	12009
2004	883	831	1312	1756	1562	3318

this institutional alliance has gone far beyond the resource mobilization into such areas as: (i) private sector participation in joint evaluation of ICRISAT-bred advanced breeding materials in specific and diverse climatic regions; (ii) private sector feedback on the utility of a wide range of breeding lines (based on evaluation in their own programs); (iii) continuing feedback from private sector on the prevailing and changing farmers' perceptions of cultivar traits and emerging new niches, which helps in periodic updating of research directions; (iv) on-farm impact assessment; and (v) joint efforts in seed-related disaster management. This partnership with a non-traditional sector stands out as the first example of its kind in the entire Consultative Group on International Agricultural Research (CGIAR) system.

IPR and research product documentation

Documentation of both the scientific information and designated parental lines of hybrids has been lagging behind in the pearl millet hybrid parents research at ICRISAT. This has been largely due to greater attention paid to actual breeding than to documentation of the research results. In view of the IPR matter becoming increasingly more critical, documentation of at least the potential hybrid parents has lately emerged as an important activity. The first level of the documentation for DUS traits of the parental lines will be published in the International Sorghum and Millets Newsletter to make these lines a prior art and place them in the public domain to prevent anyone else claiming IPR on these lines. Considering the resource implications in DUS characterization, a clear pragmatic approach has to be adopted in the documentation of genetic stocks and advanced breeding lines with specific traits such as high levels of DM resistance and salinity tolerance, and high grain Fe, Zn and β-carotene content. The second level of documentation may be for the measured yield potential per se, DM resistance and combining ability, and any other adaptation and quality traits.

In case of parental lines of released hybrids, there is yet another level of documentation, which involves ICRISAT and NARS (and in future may involve ICRISAT and private seed companies) and these need to be sorted out carefully in the IPR age. In case of public sector hybrids, a beginning has been made by publishing a booklet on released pearl millet cultivars (Khairwal et al. 2004) in which ICRISAT has been listed along with the NARS in release of some of the recent hybrids. This has been further modified to include ICRISAT scientists as co-developers or collaborators of the released hybrids. While such documentation is of little relevance to our IPR protection, it is important from the viewpoint of impact assessment.

Alternative hybrid options

Hybrid breeding research in India continues to focus on single-cross hybrids except for feasibility research on alternative hybrid options done by ICRISAT. The three major alternative hybrids include three-way hybrids, topcross hybrids and inter-population hybrids. Considering the stage of hybrid industry development in India, with private sector increasingly playing a dominant role in hybrid breeding and marketing, it is unlikely that these alternative hybrid forms will become commercial in India. However, they may be relevant for

African regions, at least in the initial phase of hybrid development, for the following reasons.

- All three alternative hybrid forms allow for more economical seed production, either because of the higher yield potential of seed parents (F_1 male-steriles in three-way hybrids and male-sterile population in inter-population hybrids) or because of the higher female:male ratio in seed production plots (OPVs with more vigor and productivity used as male parents of topcross and inter-population hybrids, requiring fewer rows than inbred lines).
- In case where some degree of synchrony between the two parents can be achieved by selection within the populations parents (pollen parents in case of topcross hybrids, and both parents in case of inter-population hybrids).
- All the three hybrid forms are more heterogeneous and hence may be less vulnerable to DM as well as ergot and smut. This would then save resources from resistance breeding that could be diverted to yield improvement. Considering the limited scientific manpower in African regions, replacement hybrids cannot be produced as rapidly as in India, in case the breakdown of a popular hybrid to diseases warrants such a replacement.
- The notion of 'uniform hybrids' is not yet as deep rooted in Africa as it is in India. Therefore, morphological variability in hybrids may not be a farmer-acceptance problem in Africa. As far as the seed certification is concerned, OPVs have been successfully certified in India. Therefore, certification of population parents of hybrids may not be a problem in Africa as well.
- Identification of heterotic and promising topcross hybrids and inter-population hybrids may be useful in identifying heterotic groups and thus provide a platform for eventual transformation to single-cross hybrid program.

Research shows that top-cross hybrids with yield levels comparable to some of the highest-yielding single-cross hybrids can be produced. For instance, ICRISAT did develop a high-yielding topcross hybrid (ICMH 312), which gave as much grain yield as the highest-yielding commercial check hybrid (ICMH 451) with comparable height and maturity over three years of coordinated trials (Talukdar et al. 1999). It is a different matter that ICMH 312 remained no more than three years in the market and its adoption did not exceed more than 5,000 ha despite the dedicated efforts of ICRISAT partnership with a private seed company in Maharashtra, primarily on account of its variability. Research shows topcross hybrids as the best way to exploit agronomic eliteness and yield potential of seed parents and local adaptation of landraces or landrace-based improved populations (Mahalakshmi et al. 1992). Research in the African regions has largely concentrated on topcross hybrids, using A-lines developed outside the specific target regions.

ICRISAT research also shows that F_1 male-sterile approach to producing three-way hybrids provides a mechanism to more effective DM disease management and manipulation of flowering time of parental lines of three-way hybrids (Rai et al. 2000b). For the exploitation of inter-population hybrids, development of male-sterile populations with complete and stable male sterility, and restorer populations with high frequency of restorers are some of the basic requirements. ICRISAT research using the A_4 CMS system and NCD_2 population as a test case has shown that it is possible to develop male-sterile populations with as high and stable male sterility as the commercial A_1-system inbred male-sterile lines (Rai et al. 2000a). Recently, it has also been shown that 1–2 cycles of recurrent selection can effectively convert any population into a nearly complete restorer or maintainer version.

Research conducted in African regions has shown that topcross and inter-population hybrids can outyield their higher-yielding parental populations generally by 25–50% (Table 2.26). Validation of results of some of the highest-yielding topcross and inter-population hybrids through multilocational on-farm and on-station trials would put hybrid programs in these regions on a solid footing. In case, this testing succeeds in identifying high-yielding hybrids, such combinations will not only provide materials for commercialization

Table 2.26. Grain yield advantage of topcross and inter-population hybrids over open-pollinated varieties (OPVs) in various trials of pearl millet.

Hybrid/Location	No. of hybrids in trial	Best OPV	Yield advantage over best OPV[1] (%)
Topcross hybrid			
Cinzana, Kolo, Sadore, Tara	4	CIVT	14–38
Lucydale, Makoholi	100	ICMVF 86415	38–52
Inter-population hybrid			
Bambey (2 years)	35	Souna II	27–59
Sadore, Bengou	10	P_3 Kolo	32–45

1. Range for four top ranking hybrids in the trial.
Source: Rai et al. (1997).

after addressing the related requirements of commercial hybrids, but will also provide the base for initiating a long-term breeding strategy for single-cross hybrids and three-way hybrids. Such studies may also lead to confirmed identification of high-yielding inter-population hybrids. Parental populations of such hybrids can be subjected to reciprocal recurrent selection for which regionally coordinated strategy is being developed in the WCA region.

Implications for African region hybrid research and development

Pearl millet hybrid research in Africa today is in a much better position than what it was in India about 40 years ago, due to the scientific knowledge and breeding materials generated in pearl millet program worldwide, especially in India (including ICRISAT). It is because of the IT-empowered rapid access to this knowledge (scientific information, approaches and consequences) and materials that pearl millet hybrid programs in Africa stand to make rapid strides in breeding high-yielding and farmer-acceptable hybrids in the near future. Some of the most significant aspects requiring attention are as follows:

- Access potentially useful breeding lines and potential hybrid parents developed in-house in various regions and test for their utility in the target regions. For instance, based on the adaptation of ICRISAT-bred OPVs in the ESA region, it can be assumed that much of the useful material developed at ICRISAT-Patancheru could be of direct as well as indirect use for hybrid breeding programs in ESA region, and vice-versa to some extent. The breeding materials and parental lines developed at Patancheru will be of no direct use in the WCA region. However, use of breeding lines with agronomic eliteness in the hybridization program may be useful to develop hybrid parents adapted to the WCA region. Some of the elite breeding lines developed in the WCA region could be of significant direct use in hybrid programs in ESA region, and of indirect use in genetic diversification of hybrid parents in Asia region.
- The initial thrust in African regions should be placed in addressing relatively better-endowed environments with fewer high priority traits, taking into account all the factors that increase the probability of success in the medium term. Those of the complex nature, highly uncertain outcome, and requiring protracted involvement should remain in experimental domain.
- Hybrid development, testing and release should target broad agro-ecological regions across the countries. It is important to be selective, considering the

resources and need for making impact, rather than getting thinly stretched. The guiding principle should be to make an impact somewhere, which should then catalyze a chain reaction, including interest of the private seed companies.

- Farmer-preferred traits, based on their current knowledge of various traits, should be considered in developing hybrids. Farmers, however, need to be explained in their language as well as in scientific terms the utility of new traits in relation to productivity and nutrition.
- Productive institutional alliances, based on comparative and complementary skills and resources of the partners, should be formed to address the entire spectrum of activities, right from parental lines development to seed production, and perhaps catalyzing the marketing channels. This will include research, seed production and processing.

Recommendations

Based on the successes and failures of various approaches in pearl millet hybrids and hybrid parents development in India and at ICRISAT-Patancheru, considering the reduced resource base and multiplicity of demands on ICRISAT's scientific manpower, and the increasingly stronger roles of NARS and the private sector, the following recommendations are made, largely in the context of Asia region.

CMS utilization. With the A_1, A_4 and A_5 CMS resources well characterized for their commercial potential, investment in search for additional CMS sources is not a priority. Seed parents development in pearl millet is well positioned to enhance the utilization of A_4 and A_5 as the two most stable and more useful CMS systems than the A_1 CMS system. The pace of shift to these two new CMS sources would depend on the pace of their restorer development, for which various approaches (pedigree breeding, backcross breeding and population approaches) have been shown to be effective, and are being followed.

Hybrid options. Considering the increasingly dominant role of the private sector and ever diminishing role of seed corporations in hybrid development and seed production, single-cross hybrids will remain the only commercial option in India. For the African regions, initially better options may be topcross hybrids (and inter-population hybrids?), but laying the foundation in terms of inbred seed parent development with high yield potential, DM resistance and adaptation to the regions concerned may have to start sooner than later.

Geographical focus. Hybrid parents research should continue for the relatively better-endowment environments as in the past because of greater probability of success, strong presence of NARS and the private sector in these regions, and the continuing yield gains. Research attention to more droughty environments typical of western Rajasthan should move parallel to NARS program and their field testing facilities for reliable data returns. The private sector, however, has reservations on venturing into these marginal environments due to lack of significantly superior hybrids, unpredictable demands (rising from uncertain rainfall) for hybrid seeds from the farmers, and poor economics of seed business.

Trait focus. Grain yield and DM resistance will continue to be the most important traits in hybrid parents research. For an effective hybrid development program in the African region, it is essential to develop greenhouse screening facilities in the region. ICRISAT is well positioned to address the issue of increasingly important dual-purpose hybrids for northern India, and medium-maturing grain hybrids for central and southern India. A small research component to breed for earliness will also continue. There is interest in and opportunity for breeding forage hybrids, but it will remain a secondary activity for the near future. In case of both stover and forages, there should be emphasis on yield, with the quality aspects (other than those visually assessed leaf and stem traits) being simply a monitoring level activity. Other traits related to farmers' acceptance (panicle compactness, panicle size, lodging resistance, grain size and color) remain an integral part of the program and their relative importance should be continually assessed in consultation with NARS and the private sector. Other traits are of relatively minor importance, and the research attention would depend on funding sources and research partnerships (eg, salinity tolerance and micronutrients). *Striga* is a serious problem in WCA. Stem borer and head miner are also significant production constraints in this region. However, the genetic progress with these traits made over protracted period and with relatively high investment has been slow in sorghum. The situation in pearl millet is even less promising than in sorghum due to the complexity of the traits (polygenic inheritance), fewer sources with low resistance levels, and relatively less effective screening protocols. Thus, there is a need to resort to non-genetic management approaches that should be integrated with yield and DM resistance improvement. This prioritization is essential to ensure that the main thrust on yield and DM resistance as the two primary traits is not diluted.

Exploitation of germplasm and breeding lines. Recent research has introgressed enough variability for large seed size, panicle length and girth, and tillering ability. Search for new germplasm sources for these traits may not be a priority for a long time to come. However, search should continue for new germplasm sources for high biomass yield, and panicle compactness combined with good panicle size. New germplasm sources with high Fe and Zn content may also be identified. Use of diverse breeding lines with complementary traits in generating more productive lines may be increased.

Thematic integration for genetic improvement. Molecular marker-assisted backcross breeding in hybrid parents development may be selectively applied to more promising and prospective hybrid parents for DM resistance gene deployment. Integration of this tool with the mainstream breeding for drought tolerance and stover quality will be done when it is cost-effective. New initiatives, contingent to special project funding, need to be undertaken to identify molecular markers for tolerance to drought, soil salinity and high air temperature (during flowering), and those providing diversity information for heterotic grouping of elite breeding lines and germplasm.

Linkage among ICRISAT regional programs. The ESA region may directly benefit, to some extent, from the seed parents developed at ICRISAT-Patancheru in hybrid development and testing. The WCA region may benefit from the use of advanced plant types developed at ICRISAT-Patancheru. Marker-assisted selection research for DM resistance at Patancheru may enhance the hybrid parents breeding efficiency for the African regions. Considering the Asia center's comparative advantage in strategic research, the African regions should selectively collaborate with Asia center in developing strategic research information. Also, the centers in Africa should take advantage of using the strategic information generated at the Asia center.

Addressing non-traditional agro-ecologies. Considering the adaptation range and productivity potential of pearl millet, there may be a need to look beyond the semi-arid tropics of Asia and Africa to position this crop in the global agriculture, which is likely to be faced with increasing water shortages, rising temperatures, need for increased cropping intensity, need for increasing the productivity in degraded lands, increasing awareness of the need to move to degraded lands and in the non-traditional environments, and health food and environmental sustainability. This, of course, can be effectively done in a partnership mode with the local/national/regional programs in these non-traditional areas undertaking research and ICRISAT playing purely a support role in terms of technology exchange.

Research partnerships. The research partnerships with NARS in India will be further strengthened to include further research expansion for the A1 zone, and salinity and micronutrient research. Private sector will be encouraged to provide limited field test facilities for testing the breeding materials for specific adaptation. ICRISAT-Patancheru will provide limited charge-based services for DM screening of the private sector materials. Private sector will also be increasingly involved in impact assessment studies. Similar partnerships will be required to make hybrid development programs a success in the African regions. Partnerships with advanced research institutions will be developed in the strategic research areas, and with other international agricultural research centers in both strategic and applied research areas.

Summary

Pearl millet being a highly cross-pollinated crop provides two cultivar options: OPVs and hybrids. Outbreeding system of the crop, high degree of heterosis for grain yield, and the availability of stable CMS and fertility restorer were the key biological factors that led to the commercialization of hybrids. During the initial phase of the research, ICRISAT emphasized breeding improved populations and OPVs to complement the efforts of the NARS. However, with the conclusive evidence of hybrid superiority over OPVs across environments, NARS thrust on hybrids increased, including participation of the private sector in the hybrid development, seed production and seed sale. ICRISAT-Patancheru gradually reoriented its research in line with NARS research priority.

Commercialization of pearl millet hybrid cultivars has benefited relatively better-endowed environments in India. Development of hybrids adapted to more marginal environments still remains a great challenge and a matter of strategic research. Hybrid programs in India and ICRISAT-Patancheru accorded highest priority to grain and stover yield, and DM resistance in various maturity groups (mostly in the range of 75–85 days) as per the agro-ecological requirements, in addition to the grain quality traits (shape, size and color). Although drought is a major abiotic constraint in pearl millet production, breeding for tolerance to this trait has been treated as a strategic research issue due to the complexities involved in screening and breeding, and the limited successes attained through conventional breeding.

Widespread cultivation of a few single-cross hybrids during the initial phases of hybrid development program in India resulted in frequent DM epidemics. During the past 15 years, however, no such epidemics have occurred, largely due to hybrid cultivar diversity, DM resistant hybrid parents, effective field monitoring of DM, and use of fungicide for seed treatment. ICRISAT-Patancheru is focusing on breeding genetically diversified hybrid parents with resistance to different DM pathotypes, leaving actual hybrid development, testing and release to NARS and the private sector who have distinct comparative advantage in these areas.

Extensive use of the A_1 CMS system in production of pearl millet hybrids raised concern about its potential vulnerability to diseases and insect pests, and thus need for CMS diversification. Although seven CMS systems are reported, the A_5 system is most stable followed by A_4 and A_1. Also, the frequency of maintainers is highest on A_5, followed by A_4 and A_1 systems in that order. Multi-environment evaluation of isonuclear hybrids showed that hybrids with A_4 cytoplasm produced about 5% less grain yield than the A_1-hybrids, which though statistically significant, is not of much practical consequence, considering the above two advantages with this alternative CMS system. There was no significant difference between the mean grain yield of hybrids with the A_1 and A_5 cytoplasm. Considering these positive attributes of A_4 and A_5 CMS systems, greater efforts are now being made at ICRISAT in breeding A-lines with these alternative cytoplasm.

After a gap of 10 years, restorer breeding at ICRISAT-Patancheru was reactivated in 2000. Excellent A_1 system restorers are available in the public and private sector hybrid programs in India. The utility of A_4 and A_5 CMS system has been constrained by the lack of their restorers. Genetic stocks of A_4 and A_5 restorers were developed at ICRISAT-Patancheru, which are being used for backcross breeding of restorer lines.

Seed parents with potential to produce high-yielding hybrids should also produce high grain yield per se that makes seed production more remunerative. Hence, while developing seed parents, selection for high yield has been accorded a high priority as there is no correlation between per se performance and GCA. Trait-specific breeding approach is used in breeding seed parents for traits that are needed by the seed industry and farmers (eg, long and compact panicle, lodging resistance, good exsertion, tillering ability, large seed, etc). Periodic DM screening of breeding lines against target pathotypes during the course of inbreeding is done to ensure the selection of DM resistant progenies. Potential B-lines identified based on multiple criteria of yield potential, agronomic traits and DM resistance are converted into A-lines using backcross method of conversion.

Utilization of the germplasm in the hybrid parents development has been quite substantial at ICRISAT- Patancheru. Of the 95 A/B pairs designated, 17 have been directly derived from the germplasm and 65 involved germplasm or composites in their parentage. Similarly diverse populations (23) developed in Asia and Africa have been utilized in restorer parent development.

Molecular MAS as a tool has been applied to enhance the efficiency of breeding for DM resistance, with its application in the areas of drought tolerance and stover quality. Development and release of HHB 67-2, the DM resistant version of the earliest-maturing commercial hybrid HHB 67 (65 days to mature) that is currently cultivated on more than 0.4 million ha, has demonstrated the usefulness of MAS technology for DM resistance breeding.

The identification and introgression of exceptional germplasm, especially for long and thick panicles, and large-seed size into the locally adapted genetic background is in progress in addition to introgression of the white seed color. Four new research areas have emerged in the recent year that will receive increasingly greater hybrid parents development focus in the years ahead. One deals with respect to high grain Fe, Zn and β-carotene content and the second one deals with salinity tolerance. Wide genetic variability was observed in diverse range of materials for Fe and Zn density, and micronutrient dense lines were identified in elite genetic background. The positive significant correlation ($r = 0.84^{**}$) between Fe and Zn indicates the possibility of simultaneous improvement for high grain Fe and Zn. Agronomically elite and high-yielding parental lines have been identified as salinity tolerant in addition to some of the germplasm accessions. The significant positive correlation between biomass yield under saline conditions and salinity tolerance index indicates that biomass yield in saline condition itself can be used as an effective selection criterion to select for salinity tolerance and biomass yield under saline conditions. The large pearl millet area under summer cultivation requires hybrids to set seeds under air temperatures exceeding 46°C during flowering. Although few private sector hybrids do set seeds and have found market in that area, the necessity to identify heat-tolerant hybrid parents has emerged as a new research area to enhance the hybrid cultivar diversity in summer conditions. Increasing attention will also be paid to breeding parental lines of forage hybrids.

ICRISAT-Patancheru in partnership with NARS and the private sector has been successful in forming institutional alliances for harnessing comparative and complementary skills and advantages. The collaboration with ICAR and the private sector (through Hybrid Parents Research Consortium) has accelerated hybrid research in India, wherein ICRISAT-Patancheru plays a catalytic role of breeding hybrid parents leaving the development and release of hybrids to its partners.

ICRISAT-Patancheru hybrid research program has made significant contributions in terms of biodiversity (about 70 hybrids under cultivation in 50% pearl millet area in India of which at least 60 have ICRISAT-bred hybrid parents or improved germplasm). This has enhanced yield stability, and increased productivity (from 450 kg ha^{-1} during 1975 to 750 kg ha^{-1} during 2000–04). In view of IPR becoming increasingly important, the documentation of hybrid parents for DUS traits has been initiated and it will be an integral part of hybrid parents development in the future.

Pearl millet hybrid parents research at ICRISAT-Patancheru has great implications for hybrid breeding programs in Africa, in terms of geographical and trait focus and institutional alliances. In India, single-cross hybrid development continues to receive highest priority. Other hybrid options such as three-way, topcross and inter-population hybrids remain strategic in nature, but these are initially most relevant to African regions as the notion of 'uniform hybrids' is not yet deep-rooted in Africa. Hybrid development in Africa will initially benefit and most likely will have quicker impacts in relatively better-endowed environments. Grain and stover yield along with DM resistance should receive high priorities. Concomitant development of seed production system and organized seed industry might put hybrid research in Africa in the forefront. Hybrid research demands a stronger ICRISAT-NARS partnership in WCA and ESA, especially with those NARS who have interest in hybrid program, and envisage sustainable yield gains and stability from adoption of such technologies.

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3. Sorghum Hybrid Parents Research: Strategies and Impacts

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Considering the importance of sorghum (*Sorghum bicolor*) as food/feed/fodder crop, considerable efforts have been made to improve its productivity through genetic enhancement and crop production and protection management research all over the globe. Initially, pure lines were the target products although phenomenon of heterosis was demonstrated in sorghum as early as 1927 (Conner and Karper 1927). The predominant self-pollinating nature with limited outcrossing of 2 to 15% (House 1985), depending on the cultivar, nature of panicle (loose or compact) and climatic conditions coupled with tiny florets with single seed per emasculation and pollination prevented commercial exploitation of heterosis in sorghum. However, with the discovery of a stable and heritable cytoplasmic-nuclear male sterility (CMS) mechanism (Stephens and Holland 1954), enabling large-scale, economic hybrid seed production, it has become a matter of routine commercial application since early 1960s. Using CMS mechanism, numerous hybrids have been developed and released/marketed for commercial cultivation in all sorghum growing regions with strong national agricultural research systems (NARS).

Considering the success story of CMS-based hybrid technology in sorghum, greater investments have been made in hybrid parents and hybrid development research in several NARS and at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). The objective of this document is to review the present status and future prospects of hybrid parents research in general and at ICRISAT, in particular.

Why hybrids?

Hybrids are the means of maximizing best complementary combination of desired genes from two deliberately selected parents. It was the superiority of F_1 hybrid for harvestable product that attracted the plant breeders to exploit

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heterosis for improvement of crop productivity. Early vigor and early flowering are commonly observed in hybrids, besides higher grain and fodder yield potential (Quinby 1974). Hybrids, as a cultivar option, are determined more by their yield advantage over improved varieties than by yield advantage over the inbred parents. Several studies have shown the superiority of single-cross hybrids over the highest-yielding pure line varieties of comparable maturity for grain and fodder yields in all production environments including biotic and abiotic stresses, in all regions/countries, where sorghum is cultivated as detailed below.

Hybrid advantage under rainfed conditions

Grain yield

The greater contribution of hybrids to grain yield, compared to improved and landrace varieties has been demonstrated in almost every situation. In Sudan, three elite sorghum hybrids had 50% higher mean yield over the best open-pollinated local varieties in 27 yield trials across four seasons (Ejeta 1983). The hybrids not only have yield advantage over varieties but also are adapted to different environments. Grain yields of top ranking hybrids in the West African Sorghum Hybrid Adaptation Trial (WASHAT)-1986 were 30% higher than the improved control varieties (Murthy 1986). The best hybrids bred at ICRISAT, Patancheru, India were superior to the best varieties at least by 8% in different regions in International Sorghum Varietal and Hybrids Adaptation Trials (ISVHAT) over the years (Table 3.1). International testing of newly developed *guinea*-based hybrids during 2004 has indicated similar range of hybrid superiority of top 20% best hybrids over well-adapted local varieties.

Green fodder/sweet-stalk yield

Hybrids are also known to produce higher green fodder yields compared to the best varieties. Several private sector and a few public sector research and development organizations have exploited heterosis for green fodder yield, and developed and marketed/released sorghum-sudan grass hybrids primarily based on the available grain sorghum CMS lines and sudan grass pollinators. The hybrids outyielded the varieties for stover and fresh fodder yields; nitrogen (N), phosphorus (P), and potassium (K) contents in grain and stover; total uptake of N, P and K; as well as crude protein content (Pal et al. 1996).

Table 3.1. Range of standard heterosis of the best hybrids over the best varieties in different regions in International Sorghum Varietal and Hybrids Adaptation Trials (ISVHATs).

Region	Estimates of standard heterosis (%) range of best hybrids over best varieties over the years					
	1989	1990	1991	1992	1993	1994
Asia	10.2−207.5	10.6−26.2	22.9−69.0	16.2−59.9	15.7−27.3	16.3−150.0
Southern and Eastern Africa	10.2−37.7	7.7[1]	3.9−100	12.3[1]	11.2−24.4	NA[2]
Western and Central Africa	7.2−10.9	9.6−19.3	9.6−30.4	18.1−28.3	29.2−52.5	NA
Northern Africa (Egypt)	12.0[1]	NA	17.31	10.6[1]	19.5[1]	NA
Americas	10.4–36.2	6.8[1]	10.9−22.0	NA	NA	NA

1. Data from a single location.
2. NA = Data not available.

Substantial heterosis for green fodder yield and millable cane yield and juice yield in forage and sweet sorghum hybrids, respectively has been reported (Table 3.2) by scientists in India.

Table 3.2. Range of heterosis estimates of hybrids over the best check varieties for green fodder yield (in forage sorghum) and millable cane yield and juice yields (in sweet sorghum).

Cultivar type	Trait	Heterosis (%) range over standard check in desirable direction
Forage sorghum[1]	Green fodder yield (t ha^{-1})	8.8 to 17.1 (over the best variety SSG 59-3)
Sweet sorghum	Millable cane yield (t ha^{-1})	0.4 to 15.85 (over the best variety SSV 84)
	Juice yield (kl ha^{-1})	0.3 to 52.9 (over the best variety SSV 84)

1. Source: AICSIP (1998).

Hybrid advantage under abiotic stresses

Comparative evaluation of hybrids vs varieties under low-input production conditions in the Southern African Development Community (SADC) region indicated an average superiority of hybrids by 36% over the varieties (Osmanzai 1994a). As growing conditions become stressed, the yields of both decline, but the yield difference between hybrids and varieties become larger (by about 30%), favoring the hybrids (House et al. 1997). Blum et al. (1992) and Osmanzai (1994b) have shown that hybrids performed better than varieties under moisture stress conditions and recover faster when moisture stress was released. Across drought environments, hybrids outyielded two local varieties by 12%. Mean hybrid superiority over male parent values was 42% for grain yield (Haussmann et al. 1998). The single-cross hybrids were consistently superior to their parents with an average heterosis of 54% across eight frequently drought-prone environments in semi-arid Makueni district of Kenya (Haussmann et al. 2000). The hybrids are known to perform better than the varieties under other abiotic stresses also. For example, seedling germination and emergence was higher in sorghum × sudan grass hybrids (Blum 1969) and sorghum grain hybrids (Pinthus and Rosenblum 1961) than in varieties and parents under sub-optimal temperatures. Kannan (1981) found that two sorghum hybrids showed fewer iron (Fe)-deficiency symptoms than their parents when grown in an Fe-deficient nutrient culture and recovered better than the parental lines when stress was released. Hybrids have also been proved to be better than varieties in problematic soils. For example, of the nearly 200 sorghum hybrids evaluated at Matazul, Colombia (60% Al^{3+} and 4.6% organic dry matter), the hybrids ICSA 38 × Real 60, ICSA 73 × ICSR 110, ICSA 89002 × Real 60 and SPMDA 94045 × A 2267-2 were superior by 25% for grain yield to the acid soil-tolerant control variety, Real 60 (Reddy et al. 2004b). These hybrids were also less susceptible to foliar diseases, greener at the time of maturity, and taller than Real 60. Similarly, hybrids had better tolerance to salinity than the parental lines/varieties (Jiqing Peng et al. 1994, Ramesh et al. 2005).

Hybrid advantage under biotic stresses

Grain mold in rainy season and shoot fly in both rainy and postrainy seasons are economically important biotic yield constraints in sorghum in Asia. Hybrids have been found to be superior to the best pure line resistant control variety

Table 2.3. Range of heterosis estimates of sorghum hybrids over the best resistant **check varieties for shoot fly and grain mold resistance at ICRISAT, Patancheru,** India.

Resistant trait	Range of heterosis (%) in desirable direction
Shoot fly resistance (as measured by deadheart %)	0.3 to 67.82 (over best check M 35-1)
Grain mold (as measured by PGMR[1])	1.0 to 68.75 (over best check PVK 801)

1. PGMR = Panicle grain mold rating; scored on a 1−9 scale, where 1 = no mold and 9 = more than 50% panicles affected by mold.

for resistance to shoot fly and grain mold at ICRISAT-Patancheru (Table 2.3). A number of heterozygous populations (F_2) were superior to the local cultivars for lower *Striga* infestation across two locations each in Kenya and Mali. For *Striga* emergence traits, F_2 heterosis ranged from 5.4% to –36.2% (Haussmann et al. 2001).

Hybrids contribution to productivity

The hybrids have contributed to increased grain/forage yield in several countries with strong NARS and well-developed seed industry. In the pre-hybrid era of early 1960s, the average sorghum productivity was 0.49 t ha^{-1} in India, 0.66 t ha^{-1} in China, 0.76 t ha^{-1} in sub-Saharan Africa, 1.48 t ha^{-1} in Australia, and 2.8 t ha^{-1} in USA. In USA, Northern and Central America, where commercial hybrids were exploited, there was 40% increase in productivity from early 1960s to early 1990s. A similar trend was noticed globally. The productivity increased by 47% in China and 50% in India from early 1960s to early 1990s. However, it remained static at 0.79 t ha^{-1} in Africa from 1960s to early 1990s (FAO 1960–96), and this may be attributed to non-exploitation of hybrids for commercial cultivation in Africa. The adoption of the first commercial hybrid (CSH 1) in India over much of the rainy season sorghum area, while local varieties confining to fairly narrow specific environmental niches is a testimony to the wide adaptability of hybrids over the varieties (House et al. 1997). Such is the power of hybrid technology that over 95% of sorghum area is planted to hybrids in countries like USA, Australia and China. In India, entire summer and over 85% rainy season sorghum area is planted to hybrids.

These results suggest that wider adoption of hybrids is due to heterosis for adaptation traits such as resistance to biotic and abiotic stresses. Therefore, development of sorghum hybrids should be given a strategic importance in favorable production environments as well as those with biotic and abiotic stresses.

CMS systems

The commercial hybrids produced so far all over the globe are based on the single cytoplasm designated as *milo* or A_1 (Reddy and Stenhouse 1994, Moran and Rooney 2003). However, based on the experience in other crops, the chances of these A_1 cytoplasm-based hybrids becoming vulnerable to an unforeseen insect pest and/or disease outbreak cannot be ruled out. For instance, outbreak of corn leaf blight disease in 1970 devastated maize (*Zea mays*) hybrids possessing Texas (T) cytoplasm (Tatum 1971). In addition to the risk associated with cytoplasmic uniformity in the hybrids, the use of single cytoplasm restricts nuclear genetic diversity of male-sterile lines (A-lines) as well as restorer lines (R-lines). Therefore, as a contingency plan to prevent such eventualities and to broaden the genetic base, the need for diversification of CMS-base of sorghum hybrids was felt long ago and as a result, several non-*milo* CMS systems designated as A_2, A_3, A_4 (VZM), A_4 (Maldandi) and A_4 (Guntur), were identified and developed (Schertz 1994) for use in hybrid breeding programs.

In higher plants, CMS is a maternally inherited defect in pollen production that perhaps results from the expression of unusual or aberrant mt-genes (mitochondrial genes) interacting with the nuclear genome leading to production of degenerated or non-viable pollen grains or non-dehiscent anthers with or without functional pollen grains (Kaul 1988, Ducos et al. 2001). Several nuclear genes are known to control the expression of CMS and thus, different CMS types can be distinguished through classical methods (restoration pattern in testcrosses and anther morphology) and through biotechnological tools (molecular markers). Differentiation of cytoplasmic types is a prerequisite for needed diversification of CMS-base of the hybrids.

Classical method

Schertz and Pring (1982) reviewed and provided a summary of various cytoplasm sources (42 from India, 24 from USA, and one from Africa) distinguished, based on male fertility restoration pattern. Some of the cytoplasms were reported to be similar based on their restoration pattern. For example, Schertz and Pring (1982) indicated that cytoplasms of G_1 (G_1-S, ms G_1, G_1-G, G_1A) are analogous to IS 1112C (A_3) of USA. Over the years, many of these cytoplasm sources were either lost or not widely available. The most commonly available ones include: A_1 (milo source), A_2 (IS 12662C or TAM 428), and A_3 (IS 1112C) of USA origin, A_4 (Guntur, VZM and Maldandi) of Indian origin, and 9E (a selection made in 9E) from Ghana. These cytoplasms (excluding 9E) were categorized based on the pattern of fertility restoration. Reddy and Stenhouse (1994) have identified minimum differential testers for differentiating A_1 to A_4 cytoplasms based on fertility restoration. These are:

- TAM 428B (A_2) gives fertile F_1s only on A_1 cytoplasm,
- IS 84B (A_4-Maldandi) gives fertile F_1s on A_1 and A_2 cytoplasms,
- IS 5767R (A_4-Maldandi) gives fertile F_1s on all cytoplasms, except A_3, and
- CK 60B (A_1) gives male-sterile F_1s on all cytoplasms.

A_1 to A_4 CMS cytoplasms are being maintained at ICRISAT-Patancheru. The lack of differential restoration patterns, however, does not provide conclusive evidence that the CMS sources involved are necessarily similar as it is possible that the pollinator parents used in the testcrosses were inadequate in number and have sufficient diversity to elicit CMS differences. It is also important that testcrosses are made on isonuclear alloplasmic A-lines to ensure that nuclear genetic differences of the female parents are not confounded with their cytoplasmic differences while assessing fertility restoration.

Molecular markers

Cytoplasmic factors associated with male sterility have been shown to be encoded by mitochondrial DNA (mtDNA) (Hanson and Conde 1985). The various cytoplasms could be differentiated through restriction fragment length polymorphism (RFLP) of mitochondrial genome (Schertz et al. 1997). A_4 and 9E have been distinguished by RFLP analysis (Xu et al. 1995). Using maize and pearl millet (*Pennisetum glaucum*) mtDNA specific probes, Sivaramakrishnan et al. (1997) showed the differences among A_1 to A_6 cytoplasms with the help of RFLP banding pattern of mtDNA.

Fertile plants from *S. versicolor*, *S. almum*, *S. halepense* and *Sorghastrum nutans* (yellow Indian grass) were identical in 3.8 kb DNA fragment, and differed from CMS lines containing A_1, A_2 and A_3 cytoplasms with a 3.7 kb DNA fragment. A 165 bp deletion, located in the middle of the RNA polymerase β-subunit, encoded by the gene *rpo*C2 was identified in the CMS lines (Chen et al. 1995). A_1 and A_2 cytoplasms produced similar patterns with Hind III restriction enzyme, while *EcoRI* and *Pst I* expressed identical patterns in A_1, A_2, A_3 and A_4 cytoplasms (Thin et al. 1993). A total of 276 out of 326 patterns of RFLP bands was common to both R-lines and maintainer lines (B-lines), whereas 32 and 18 bands were unique to R-lines and B-lines, respectively. RFLPs and expression pattern of *mt*-genes indicated that the cytoplasms classified tentatively as Indian A_4 types were distinct from the American A_4 and A_1 types. Although the geographical origin of cytoplasms was identical to each other, they are distinguished from each other based on RFLP induced by *atp 6*, *atp 9* and *rrn 18*. The three A_4 cytoplasms also differed from their maintainers in the location of *nad 3*, *rps 12* and *atp A*, and the differences in the pattern of expression of *atp A* between all the CMS cytoplasms and their respective maintainers was also observed (Sane et al. 1996). The molecular differences observed within the A_4 cytoplasmic group also provide an explanation for the inconsistency in fertility restoration behavior with a definite set of testers (Sivaramakrishnan et al. 1997).

Factors influencing CMS utilization

Although six workable CMS sources have been identified in sorghum, all have not been found commercially useful. Several factors such as stability of male sterility, maintainer/restorer gene frequency, effect of nuclear genetic background on male sterility and CMS effects on economic traits influence CMS utilization.

Stability of male sterility

Instability of male sterility in A-lines increases the problem of roguing pollen shedders from seed production plots leading to low hybrid seed yield and hence higher seed production cost. Further, if pollen shedders are not rogued out due to human errors (as it happens in several instances), hybrid seed quality decreases and thereby grain yield decreases in commercial hybrid crop. Such an unstable CMS system also reduces breeding efficiency as the backcross progenies found fully sterile may not be necessarily so during the subsequent generations, leading to their rejection. Thus, stability of male sterility has a direct bearing on the cost and quality of hybrid seed production. Ideally, a commercial male-sterile line should neither shed pollen nor set seed when selfed, regardless of the location and the season. This, however, is seldom observed in practice. For instance, several A-lines based on the A_1 CMS system in sorghum have been extensively used to develop hybrids, which are planted on millions of hectares in India alone. Most of these A-lines produce, albeit low frequency (<1%) of pollen shedders, depending on the environments. Several researchers reported the role of temperature on the expression of male sterility and male fertility restoration in sorghum (Downes and Marshall 1971, Li et al. 1981). It affects some cytoplasms more than others (Schertz et al. 1997).

The work at ICRISAT-Patancheru showed that restoration is poor when night temperature falls below 10°C, just before flowering, during postrainy season and that the male sterility in CMS lines breaks down when the day temperature rises above 42°C, before flowering (Reddy and Stenhouse 1994). This evidently increases the need to screen the CMS lines in areas where the temperature rises above 42°C before flowering for the absence of seed set under bagging to ensure stability of male sterility. An evaluation of hybrids obtained by crossing A_1 and A_2 cytoplasms-based A-lines in *durra* and *zerazera* background with landrace pollinators for seed set at low temperatures (10°C for several days) indicated better seed set in *zerazera* than in *durra* background in both A_1 and A_2 cytoplasms-based A-lines (Reddy and Stenhouse 1994). When A_1, A_2, A_3 and A_4 male-sterile lines were compared for seed setting under selfing during summer at Bhavanisagar (where temperature reaches beyond 42°C), India, it was found that A_1 is more stable for male sterility than A_2, A_3 and A_4 (Maldandi); A_2 than A_3 and A_4; and A_4 than A_3 (Reddy and Stenhouse 1994). Devi and Murthy (1993) showed intactness of tapetum and sterile pollen in A_2 A-lines during postrainy season (low temperature) but partial or complete degeneration of tapetum and fertile pollen during summer (high temperature), in a few nuclear genetic backgrounds, indicating the unstable nature of male sterility in A_2 CMS system.

Maintainer/restorer frequency

Frequency of maintainer genes in a diverse range of improved populations and breeding lines has a direct bearing on the success of nuclear genetic diversification of A-lines. Conversely, the frequency of restorers influences directly the use of such diversified male-sterile lines in hybrid development. In sorghum, Scheuring and Miller (1978) found a frequency of 0.62 restorers and 0.23 maintainers on *milo* (A_1) cytoplasm in the world collection of 3,507 sorghum accessions. The work carried out at ICRISAT-Patancheru showed a restoration frequency of 0.9 on A_1, 0.5 on A_2, 0.01 on A_3 and 0.03 on A_4, when 48 germplasm lines were testcrossed onto A_1, A_2, A_3 and A_4 CMS systems (Reddy et al. 2005b). Senthil et al. (1998) found that the frequency of restoration was 0.15 on A_1, 0.04 on A_2, 0.01 on A_3 and 0.03 on A_4 CMS systems. Of late, several restorers on A_1 and dual-restorers (on A_1 and A_2) have been identified at ICRISAT-Patancheru. This suggests that the restorer frequency is high on A_1 and least on A_3 system. Considering the adequate restoration frequency, A_1 and A_2 CMS systems provide sufficient choice in selecting restorers. Therefore, A_1 and A_2 CMS systems could be deployed readily for developing grain sorghum hybrids. On the other hand, A_3 and A_4 CMS systems may be readily used in cases where grain is not the economic product (eg, for forage/sweet-stalk purpose).

Testcrossing of a sub-sample of 62 accessions with appropriate maturity for the Sudanian zone sampled from *guinea*-core collection (of 293 accessions) of Western, Eastern and Southern Africa and Asia origin onto the A_1 CMS system indicated relatively higher frequency of lines with restorer reaction among the African accessions, while all Asian accessions showed restorer reaction (Table 3.4). Further examination within the accessions of Western, Eastern and Southern Africa origin, indicated higher frequency of maintainer reaction among the lines of West Africa origin, while all the lines of eastern humid-zone origin showed restorer reaction (Table 3.5).

Table 3.4. Percentage of *guinea*-core accessions exhibiting the maintainer, restorer and partial-fertility reaction at ICRISAT, Sotuba, Mali.

Region	No. of accessions	Maintainer reaction (%)	Restorer reaction (%)	Partial restorers (%)
Western and Central Africa	36	22	53	25
Eastern and Southern Africa	18	28	61	11
Asia	8	0	100	0

Table 3.5. Percentage of *guinea*-core accessions showing the maintainer, restorer and partial-fertility reaction within lines of Western and Central Africa origin at ICRISAT, Sotuba, Mali.

Region	No. of accessions	Maintainer reaction (%)	Restorer reaction (%)	Partial restorers (%)
West Africa	22	36	23	41
East Africa	14	0	100	0

Season specificity of maintainer/restorer frequency

In maintainer lines development program at ICRISAT-Patancheru, the frequency of B-lines observed in A_1 (Table 3.6), and A_2 (Table 3.7) CMS systems was higher during postrainy season (cooler temperature) than during rainy season (warmer temperature) (Reddy et al. 2005b). However, researchers of Indian national programs have reported that restoration frequency in A_2 CMS system is higher during postrainy season than during rainy season (UR Murthy, Ganga Kaveri Seeds Private Limited, Hyderabad, India, personal communication). Research involving A-lines in same nuclear background might provide a better understanding of the stability of different CMS systems for maintainer/restoration reaction in different seasons.

Table 3.6. Maintainer and restoration frequency in sorghum A_1 cytoplasm in rainy and postrainy seasons at ICRISAT, Patancheru, India.

A_1 cytoplasm	Total plants tested	Frequency	
		Maintainers	Restorers
Rainy season 2000			
ICSA 56	75	0.71	0.29
ICSA 84	66	0.83	0.17
ICSA 101	87	0.84	0.16
CK 60 A	49	0.55	0.45
Total	277	0.75	0.25
Postrainy 2000			
ICSA 1	39	0.62	0.38
ICSA 9	39	0.87	0.13
ICSA 101	200	0.95	0.05
ICSA 88005	21	0.90	0.10
Total	299	0.89	0.11

Source: Reddy et al. (2005b).

Effects of genetic background on male sterility

The effectiveness of genetic diversification of A-lines is determined by whether or not the genetic background of B-lines influence the stability of male sterility of A-lines produced from them. Similarly in sorghum, the *kafir*-based crosses with CK 60B produce higher frequency of maintainers on A_1 CMS system than with *caudatum*-based B-lines. At ICRISAT-Patancheru, the maintainer gene

Table 3.7. Maintainer and restoration frequency in sorghum A_1 cytoplasm in rainy and postrainy seasons at ICRISAT, Patancheru, India.

A_2 cytoplasm	Total plants tested	Frequency	
		Maintainers	Restorers
Rainy season 1999			
MR 750	130	0.62	0.38
ICSA 94003	140	0.63	0.37
Total	270	0.62	0.38
Postrainy season 1999			
MR 750	19	0.47	0.53
ICSA 88004	110	0.45	0.55
ICSA 94001	20	0.85	0.15
Postrainy season 2000			
ICSA 38	133	0.97	0.03
ICSA 743	72	1.00	0.00
ICSA 88001	34	0.85	0.15
Total[1]	388	0.79	0.21

1. Postrainy season 1999 and 2000.
Source: Reddy et al. (2005b).

frequency ranged from 0.3 to 1.0 in the derivatives of various sets of crosses with A_1 CMS system (Table 3.8) although both the parents involved in such crosses are maintainers (Reddy et al. 2005b). Higher number of testcrosses would indicate more realistic range of maintainer frequency.

CMS effects on economic traits

In pursuit of exploitation of alternate CMS systems for accomplishing the required diversification of A-lines and hence hybrids, agronomic performance of CMS-based hybrids cannot be compromised. Therefore, before large-scale exploitation of any alternative CMS system for hybrid cultivar development, they should be confirmed to be free of any undesirable effects on economic traits of interest. Several attempts (Kishan and Borikar 1988, Maves and Atkins 1988, Secrist and Atkins 1989) have been made to assess the effects of different CMS systems on grain yield and other traits of importance in sorghum. However, the results reported in these studies are not only inconsistent, but also the test hybrids based on alternative CMS systems were not in common nuclear genetic background. It is possible that the variable cytoplasmic effects

Table 3.8. Maintainers and restoration frequency in various sorghum A_1 CMS maintainer lines' crosses (B × B) at ICRISAT, Patancheru, India.

B-lines used as females	No. of B-lines used as males	No. of progenies testcrossed	Frequency	
			Maintainers	Restorers
ICSB 11	4	6	0.5	0.5
ICSB 73	5	31	0.9	0.1
ICSB 89	5	18	0.9	0.1
ICSB 101	5	21	1.0	0.0
ICSB 443	3	18	0.6	0.4
ICSB 463	4	4	0.5	0.5
ICSB 568	1	4	0.5	0.5
ICSB 203	2	9	0.3	0.7
Total		111	0.8	0.2

observed in such studies might be confounded with nuclear genetic differences. It is therefore, essential that the hybrids must be developed using isonuclear A-lines (of different CMS systems) and common restorers to preclude the influence of nuclear genetic background of A- and R-lines for assessing the effect of different CMS systems on the expression of economic traits.

A_1 and A_2 CMS effects on grain yield and other traits

An investigation was carried out to assess the efficiency of A_2 CMS system in comparison to the widely used A_1 CMS system in terms of mean performance, combining ability and better parent heterosis during rainy season 2001 and 2002 and postrainy season 2002/03 and 2003/04 at ICRISAT-Patancheru, utilizing two sets, each of six pairs of isonuclear alloplasmic (A_1 and A_2) A-lines and dual-restorers developed in a program on CMS diversification of hybrid parents. The results revealed that A_2 CMS system is as efficient as A_1 CMS system in terms of general combining ability (GCA) effects of A-lines in set I (Table 3.9) and in set II (Table 3.10) and mean performance in sets I and II (Table 3.11), and frequency of hybrids with significant specific combining ability (SCA) effects and better parent heterosis in desirable direction in both rainy and postrainy seasons in sets I and II (Table 3.12).

Evaluation of five pairs of sorghum isonuclear A_1 and A_2 CMS lines in four locations of Tamaulipas, Mexico, viz., Rio Bravo (irrigated), El Tapo

Table 3.9. Estimates of general combining ability (GCA) effects of A_1- and A_2-based sorghum A-lines in set I during rainy season 2001 and 2002 at ICRISAT, Patancheru, India[1].

	Time to 50% flower (days)		Plant height (m)		Plant agronomic score[2]		Grain yield (t ha^{-1})	
A-line	A_1	A_2	A_1	A_2	A_1	A_2	A_1	A_2
ICSA 17	−0.40	−0.1	−0.10	−0.12**	−0.1	–0.2	−0.1	−0.2
ICSA 37	1.66**	2.38**	0.00	0.03	–0.1	0.11	0.2	−0.2
ICSA 38	1.77**	0.99**	0.00	0.03	–0.2	0.11	0.36	0.2
ICSA 42	−0.50	1.38**a	0.04	0.00	0.17	0.17	−0.2	−0.3
ICSA 88001	−1.06**	−1.17**	0.07*	0.04	0.11	0.56	0.0	0.26
ICSA 88005	−2.62**	−2.62**	0.00	0.03	−0.1	−0.1	−0.2	0.11
SE± (gi)	0.34		0.03		0.12		0.22	
CD (A_1-A_2) (P = 0.05)	0.95		0.09		0.35		0.62	

1. * Significant at P = 0.05 level; ** Significant at P = 0.01 level; a = Significant cytoplasmic differences.
2. Scored on a 1–5 scale, where 1 = good and 5 = poor.

Table 3.10. Estimates of general combining ability (GCA) effects of isonuclear sorghum **male-sterile lines in set II as influenced by their cytoplasm during postrainy season** 2002 and 2003 at ICRISAT, Patancheru, India[1].

	Time to 50% flower (days)		Plant height (m)		Plant agronomic score[2]		Grain yield (t ha^{-1})		100-seed mass (g)	
A-line	A_1	A_2	A_1	A_2	A_1	A_2	A_1	A_2	A_1	A_2
ICSA 11	−2.38**	−2.15**	2.41	3.24	−0.05	0.01	−0.02a	−0.51**	0.35**	0.29**
ICSA 26	0.51	0.62	−5.09	−3.15	0.34**	0.23	0.03	−0.17	−0.02	−0.1
ICSA 88004	0.84*	0.84*	8.79**	10.74**	0.18	0.18	0.23	0.73**a	0.07	0.04
IS 18757	−0.38	0.29	10.74**	2.41	−0.1	0.06	−0.95**a	−1.42**	0.16**	0.06
PM 17467	1.34**	1.01**	7.69*a	−1.76	–0.05a	0.29*	0.44**	0.24	−0.44**	−0.52**
PM 7061	−0.27	−0.27	−19.82**	−16.2**	−0.49**	−0.60**	0.77**	0.64**	0.05	0.04
SE± (gi)	0.39		3.13		0.12		0.14		0.05	
CD (A_1-A_2)	1.08		8.68		0.33		0.38		0.13	

1. * Significant at P = 0.05 level; ** Significant at P = 0.01 level; a = Significant cytoplasmic differences.
2. Scored on a 1–5 scale, where 1 = good and 5 = poor.

Table 3.11. Mean performance of isonuclear alloplasmic sorghum hybrids evaluated during rainy season 2001 and 2002 (set I) and postrainy season 2002 and 2003 (set II) at ICRISAT, Patancheru, India[1].

	Time to 50% flower (days)		Plant height (m)		Plant agronomic score[2]		Grain yield (t ha^{-1})	
Cytoplasm	R	PR	R	PR	R	PR	R	PR
A_1	67	74	2.5	1.9	1.9	2.0	5.55	3.9
A2	68	74	2.5	1.9	2.1	2.1	5.55	3.8
CD (*P* = 0.05)	2.34	2.7	0.21	0.20	0.85	0.80	1.51	0.9

1. R = Rainy season 2001 and 2002; PR = Postrainy season 2002 and 2003.
2. Scored on a 1–5 scale, where 1 = good and 5 = poor.

Table 3.12. Number of isonuclear sorghum hybrids with significant specific combining ability (SCA) effects and heterosis during rainy season 2001 and 2002 (set I) and postrainy season 2002 and 2003 (set II) at ICRISAT, Patancheru, India.

		No. of hybrids with significant SCA effects and heterosis in desirable direction							
		Time to 50% flower (days)		Plant height (m)		Plant agronomic score[1]		Grain yield (t ha^{-1})	
Cytoplasm	No. of hybrids	SCA effects	Heterosis	SCA effects	Heterosis	SCA effects	Heterosis	SCA effects	Heterosis
Rainy season 2001 and 2002 (set I)									
A_1	18	2	11	1	0	1	0	0	9
A_2	18	4	12	1	0	1	0	2	10
Postrainy season 2002 and 2003 (set II)									
A_1	18	0	1	0	15	0	0	3	6
A_2	18	0	1	0	15	2	1	2	3

(drought), El Canelo (drought) and Guelatao (drought), during fall-summer season of 1992 indicated significant differences between A_1 and A_2 CMS lines for grain yield only in drought conditions (Rodriguez-Herrera et al. 1993). While A_2-based CMS lines (1.5 t ha^{-1}) yielded better than those based on A_1 CMS system (1.3 t ha^{-1}) at El Canelo, A_1-based CMS lines (0.34 t ha^{-1}) yielded better than those based on A_2 CMS system (0.25 t ha^{-1}) at Guelatao, suggesting there is no specific and consistent advantage of A_2 CMS system in comparison with A_1. However, no significant differences were found between A_1 and A_2 CMS lines for plant height, panicle length and panicle exertion.

A_1 and A_2 CMS effects on responses to shoot fly and grain mold

Two sets each of six isonuclear, alloplasmic A-lines with A_1 and A_2 cytoplasms in six different nuclear genetic backgrounds and their hybrids (refer previous section) were evaluated for their responses to shoot fly infestation and grain mold infection at ICRISAT-Patancheru during rainy season 2004.

Responses to shoot fly infestation. Cytoplasmic background of A-lines did not appear to have any influence either on GCA effects or on SCA effects in hybrid combinations for percentage of deadhearts (DH%) in both the sets. However, significant differences between A_1 and A_2 cytoplasm-based hybrids were observed for DH% per se in both the sets. Although the magnitude of cytoplasmic differences varied with the nuclear genetic backgrounds of the hybrids, no definite pattern of association of DH% with a particular cytoplasm was observed. However, when mean DH% was considered, there were no differences between A_1 and A_2 cytoplasm-based hybrids. Further, the frequency of A_2 cytoplasm-based hybrids with significant better parent heterosis in desirable direction for DH% was comparable to that based on A_1 cytoplasm. Thus, the results suggested that A_2 cytoplasm-based seed parents and hybrids are comparable to those based on A_1 cytoplasm.

Responses to grain mold infection. As observed in case of shoot fly responses, cytoplasm background of A-lines did not appear to have any influence either on GCA effects or on SCA effects in hybrid combinations for panicle grain mold (PGM) and threshed grain mold (TGM) severity scores in both the sets. However, significant differences between individual A_1 and A_2 cytoplasm-based hybrids were observed for mean PGM and TGM severity scores. Although the magnitude of cytoplasmic differences varied with the nuclear genetic backgrounds of the hybrids, no definite pattern of association of PGM and TGM severity scores with a particular cytoplasm was observed. However, when mean of PGM and TGM severity scores over all the hybrids were considered, there were no differences between A_1 and A_2 cytoplasm-based hybrids. Further, the frequency of A_2 cytoplasm-based hybrids with significant mid parent and better parent heterosis in desirable direction for PGM and TGM severity scores was comparable to that based on A_1 cytoplasm. Thus, the results suggested that A_2 cytoplasm was as efficient as A_1 cytoplasm for commercial exploitation.

Differences between different CMS systems for responses to shoot fly infestation

An evaluation of isonuclear A-lines in six different CMS backgrounds and their B-line for responses to shoot fly infestation in three seasons at ICRISAT-Patancheru indicated that A_4 (Maldandi) cytoplasm is relatively less susceptible to shoot fly than the other CMS systems. Recovery from shoot fly damage is better in A_4 (Maldandi), A_3 and A_2 cytoplasms than the A_1 cytoplasm. The shoot fly survival and development is poor on A_4 (Maldandi) and A_4 (VZM) CMS systems. A_4 (Maldandi) supported relatively fewer deadhearts than the other CMS systems (Fig 3.1) (Sharma et al. 2005).

Differences between A- and B-lines (A_1) for time to 50% flower

Considerable variation between A_1 CMS system-based A- and B-lines for time to 50% flower was observed at ICRISAT-Patancheru. In the early group, a few A-lines tend to be late by a day or two that was not significant. But in the medium and late maturity groups, A-lines tend to be significantly late in

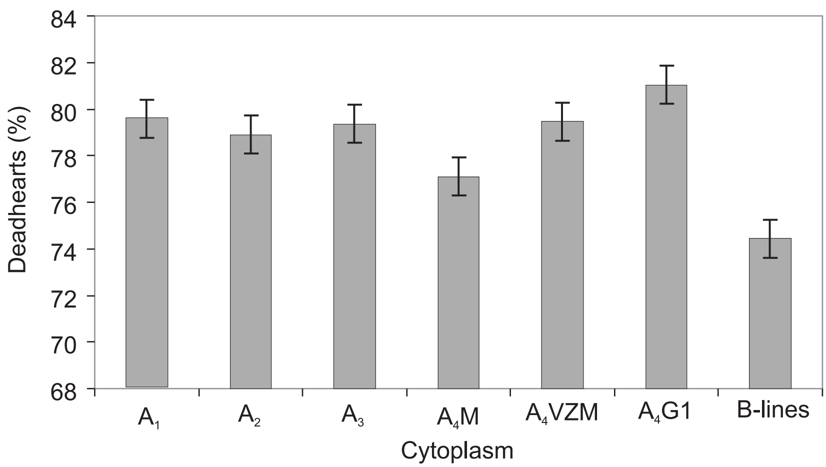

Figure 3.1. Relative susceptibility of different CMS systems to sorghum shoot fly Atherigona soccata. *[Note: $A_4M = A_4$ (Maldandi); $A_4G1 = A_4$ (Guntur).]*

Table 3.13. Frequency of sorghum male-sterile and maintainer lines differing in time to 50% flower at ICRISAT, Patancheru, India.

Differences in time to 50% flower between A- and B-lines (days)	Early maturity group (<67 days)	Medium maturity group (67–74 days)	Late maturity group (>74 days)
−2	0.00	0.02	0.04
−1	0.00	0.08	0.08
0	0.74	0.41	0.31
1	0.24	0.40	0.34
2	0.02	0.09	0.19
3	0.00	0.00	0.04
Total number tested	34	108	26

Source: Reddy et al. (2005b).

flowering and there is a tendency of increased delay in flowering in A-lines with increased maturity period (Table 3.13). However, the differences in time to 50% flower are minimal to have any practical significance. Rodriguez-Herrera et al. (1993) also showed delay in flowering of A-lines (A_2) than their maintainer (B) counterparts.

Differences between A- and B-lines (A_1) for defensive responses to biotic stresses

The spikelet damage and adult emergence of sorghum midge was significantly lower on midge resistant B-lines (PM 7061 and PM 7068) than their corresponding A-lines, and vice-versa in the midge susceptible parental lines (296A and ICSA 42) (Sharma et al. 1996). Further, A_1 cytoplasm was more susceptible to shoot fly than the maintainer line cytoplasm, while the reverse was true for stem borer resistance (Reddy et al. 2005b). Studies on resistance/susceptibility of A-lines and their B-lines (seven shoot fly resistant and five susceptible A- and B-lines) indicated that CMS lines (A-lines) were preferred for oviposition and suffered more deadheart formation than the B-lines. The larval period was shorter and fecundity was greater on A-lines than on the respective B-lines. In general, larval survival, adult emergence, pupal weights, fecundity and overall antibiosis index were greater on A-lines than on the B-lines. The differences in susceptibility and antibiosis between A-lines and B-lines were greater in shoot fly resistant genotypes than the susceptible genotypes. The expression of leaf glossiness and trichomes was better in the

B-lines as compared to the respective CMS lines. However, the reverse was true in case of seedling vigor, leaf surface wetness and chlorophyll content.

Utilization of CMS systems

For reasons already explained, the diversification of CMS-base of hybrids is the need of the hour as a contingency plan to counter any eventual diseases and insect pests in future. Considering the stability of male sterility, maintainer/restorer gene frequency, comparable agronomic performance, and the extent of heterosis and frequency of heterotic hybrids, at present, A_2 offers the best CMS option after A_1 for immediate exploitation for hybrid development and promotion. At present, only China has developed and released one A_2-based grain sorghum hybrid, Zinza No. 12 for commercial cultivation, which currently occupies 200,000 ha accounting for one-sixth of total sorghum area in China (Liu Qing Shan et al. 2000). The possible reasons for limited exploitation of A_2 CMS system is that, the anthers in A_2 male-sterile lines, unlike the A_1 male-sterile lines mimic the fertile or maintainer lines (ie, B-lines) and lead to difficulties in monitoring the purity of hybrid seed production. However, such difficulties could be overcome by experience and by appropriate training of the personnel involved in hybrid seed production.

As two (A_1 and A_2) of the six available CMS systems meet all the requirements for commercial exploitation, the diversification of seed parents for CMS-base with A_1 and A_2 and hence nuclear genetic-base of both the parents would be adequate as a contingency plan to tackle any unforeseen outbreak of pests and diseases. Further, since some beginning has been already made in identification of restorers, utilization of A_4 CMS system, especially for hybrid development for postrainy season adaptation would soon become a reality in the near future once adequate number of restorers are identified/developed. Given these options, it is wise to intensify research and development efforts for utilization of A_4 (Maldandi), considering its higher level of resistance to shoot fly infestation compared to other CMS systems (Sharma et al. 2005), rather than investing on identifying new CMS sources, which is highly resource-demanding.

Hybrid parents research

Hybrid parents improvement leads to hybrids improvement. Therefore, hybrid cultivar development requires additional research investment over that needed for non-hybrid cultivars. ICRISAT, established at Patancheru (Andhra Pradesh, India) with a global mandate of improving productivity of sorghum as one of the crops for food use in the semi-arid tropics (SAT) of Asia, sub-Saharan Africa and Latin America initiated hybrid parents research during 1978. The major objective was to develop hybrid parents and hybrids with an assumption that hybrids developed at ICRISAT-Patancheru would be useful for developing hybrids with wide adaptation in Asia, Africa and Americas. Since then, the hybrid parents research and hybrid development strategies at ICRISAT have undergone significant changes. External environment, donors' and NARS perceptions of changing crop requirements and opportunities, and NARS capacity are the most important factors that influenced these changes.

Seed parents research

Sorghum seed parents research at ICRISAT can be traced in three phases: Phase I (1978–88), Phase II (1989–98) and Phase III (1999 onwards).

Phase I (1978–88)

During this phase, seed parents research was carried out at ICRISAT-Patancheru. Grain yield and grain food quality-evident traits along with geographic adaptation trait such as maturity duration received greater emphasis to match the crop season and geographical region-specific requirements. The breeding strategy involved conversion of F_6 homozygous lines with male sterility maintainer reaction (B-lines) derived from pedigree selection from planned crosses involving parents with desired traits. Only those lines with good GCA for grain yield, grain quality, desired maturity and plant height (dwarf) were converted into A-lines with repeated backcrosses to a known A-line with A_1 (*milo*) cytoplasm. Often, three to five testers were used to estimate GCA effects of the lines intended for conversion normally in one season and rarely in two seasons. Normally, five to six backcrosses were made to recover nuclear genetic background of B-lines. A total of 92 high-yielding A-/B-lines, including 17 early-maturity (less than 66 days to 50% flowering) lines, and 75 medium-maturity (66 to 75 days to 50% flowering) lines were developed during this period (Table 3.14). These A-/B-lines were sent to NARS programs in Asia and Eastern and Southern Africa (ESA) for hybrid development and testing for their grain yield potential and other traits of interest.

Table 3.14. Grain yield potential of best five high-yielding sorghum seed parents developed at ICRISAT, Patancheru, India during Phase I.

Trait	Rainy season		Postrainy season	
	Time to 50% flower (days)	Grain yield (t ha^{-1})	Time to 50% flower (days)	Grain yield (t ha^{-1})
Early maturity	53–57	2.9–3.6	52–57	3.4–4.4
Control (2219B)	58–60	3.0–3.5	NA[1]	NA
Medium maturity	66–75	3.1–5.4	63–68	4.5–5.6
Control (2077B)	70–73	3.0–3.8	NA	NA

1. NA = Data not available.

Phase II (1989–98)

Diversification of hybrid parents for resistance to biotic and abiotic constraints into hybrid parents to stabilize the yield was given major emphasis during this phase.

Trait-based seed parents. Trait-based breeding approach was followed to develop hybrid parents during this phase. Considering the high correlation between per se performance of parental lines and hybrids (Rao 1972), an efficient method of A-line development (Fig. 3.2) was conceptualized and adopted. The method involved simultaneous selection for resistance to a specific biotic stress (shoot fly, stem borer, midge, head bug, grain mold, downy mildew, leaf blight, anthracnose, rust and *Striga*) and abiotic stress (terminal drought and stay-green trait) based on families, and for grain yield based on individual plants within the selected resistant families from F_4 generation onwards. The selected lines with maintainer reaction were converted into A-lines resistant to biotic and abiotic stresses in the shortest possible period of seven years (Reddy et al. 2005b). A total of 567 trait-based A-/B-lines (487 A_1, 51 A_2, 17 A_3 and 12 A_4 CMS systems-based) were developed at ICRISAT-Patancheru. Besides these, 57 high-yielding A-/B-lines were developed during Phase II.

The trait-based method ensured retaining greater genetic diversity in the A-lines. The defensive responses to different insect pests infestation and diseases along with grain yield potential of five best A-/B-lines in each trait have been provided in Tables 3.15 and 3.16.

The grain yield of photoperiod-insensitive best B-lines bred for stay-green trait (a proven defensive trait against terminal drought stress) ranged from 2.8

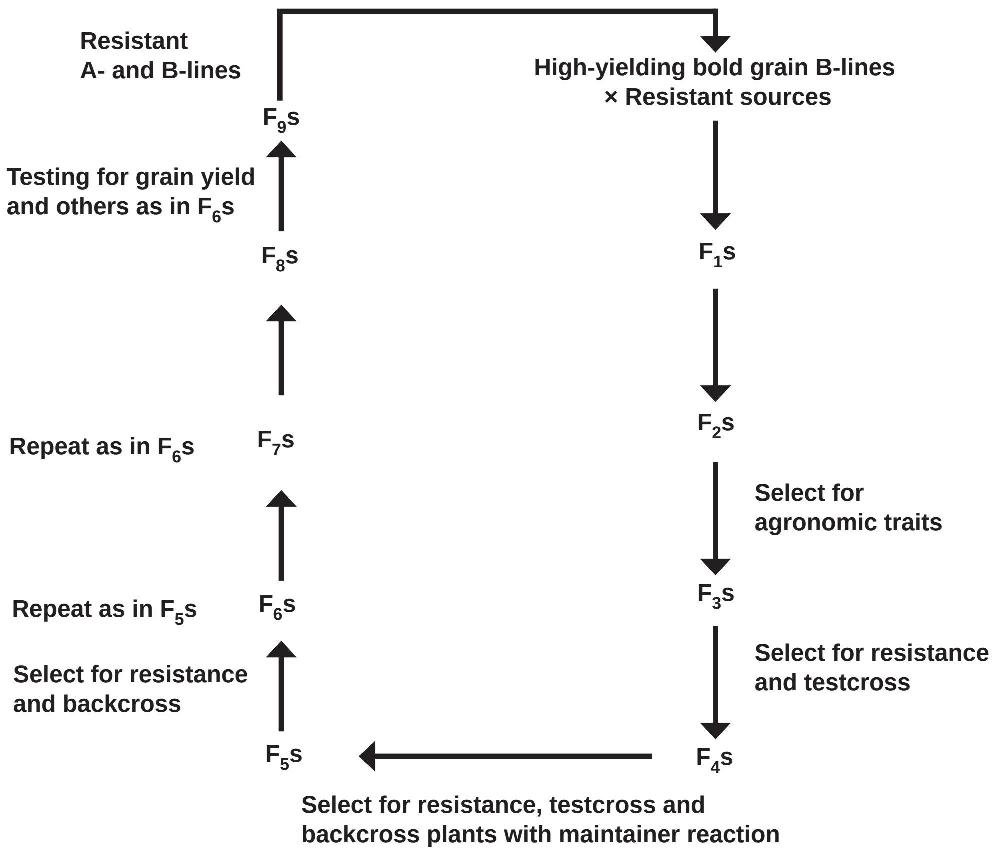

Figure 3.2. Method of breeding of sorghum male-sterile lines resistant to yield constraints.

to 3.4 t ha^{-1} and was comparable to that of the best check 296B (3 t ha^{-1}). The stay-green levels in these lines were similar to E 36-1, a photoperiod-sensitive stay-green source.

Soil acidity tolerance. Latin America is considered to be the future "food-basket" considering vast tracts of uncultivated areas. However, these areas (Llanos of Colombia, Venezuela, Bolivia and Cerrados in Brazil) have high levels of soil acidity toxicity due to Al^{3+} concentration (65%), besides being low in organic content. Identification/development of high-yielding soil acidity tolerant sorghums is the best option to increase the productivity in such soils. Extension of cultivation of sorghum in these soil acidity-affected soils would not only help increase production, but also ensure sustainable and eco-friendly management of such problematic soils. Large number of A-/B-lines

Table 3.15. Response of five best sorghum seed parents to each of four insect pests and their grain yield potential.

	Response score		Grain yield (t ha^{-1})	
Resistant trait	Best B-lines	Susceptible control (296B)	Best B-lines	High-yielding control (296B)
Shoot fly[1] (postrainy season)	14.2–31.1	50.5	2.7–5.3	3.0
Shoot fly[1] (rainy season)	36.7–52.6	77.5	2.3–3.5	3.3
Stem borer[1] (postrainy season)	31.7–37.0	56.2	2.6–4.2	3.3
Stem borer[1] (rainy season)	36.7–48.7	71.1	2.1–4.5	3.3
Head bug[2]	4.7–5.1	6.3	2.5–4.7	3.2
Midge[3]	1.1–2.2	5.8	2.9–5.8	3.1

1. Response scored as percentage of deadhearts.
2. Response scored on a 1–9 scale, where 1 = few grains with bug feeding punctures and 9 = most of the grains shriveled due to head bug damage.
3. Response scored in caged heads on a 1–9 scale, where 1 = <10% chaffy florets and 9 = >80% chaffy florets.

Table 3.16. Response of five best sorghum seed parents to each of the five diseases and *Striga* and their grain yield potential.

	Response score		Grain yield (t ha^{-1})	
Resistant trait	Best B-lines	Susceptible control (296B)	Best B-lines	High-yielding control (296B)
Anthracnose[1]	2.2–2.7	5.2	3.7–5.1	3.0
Downy mildew[2]	0.0–2.0	100	3.7–6.3	3.0
Leaf blight[3]	3.4–6.3	7.7	3.0–4.2	3.3
Rust[3]	2.5–4.7	4.7	1.8–5.0	3.3
Grain mold (PGMR)[4]	4.7–5.8	8.2	2.6–4.7	2.8
Striga[5]	1–1	3	3.4–5.9	3.3

1. Response scored for leaves and panicles on a 1–9 scale, where 1 = no anthracnose lesions and 9 = >75% leaf area covered with anthracnose lesions.
2. Response scored as percentage of plants infected.
3. Response scored on a 1–9 scale, where 1 = leaf lamina free from disease and 9 = >80% of leaf lamina affected with disease.
4. PGMR = Panicle grain mold rating; scored on a 1–9 scale, where 1 = <5% mold infected grain and 9 = >80% mold infected grain.
5. Average number of *Striga* plants m^{-2} counted at flowering and harvesting.

developed in Phases I and II were introduced and empirically screened for grain yield under acid soil conditions during July 1996 to December 1999 in a research project funded by Inter-American Development Bank (IADB) jointly implemented by ICRISAT-Patancheru, Centro Internacional de Agricultura Tropical (CIAT) and Latin American NARS. Fifteen grain sorghum A-/B-lines were selected for high yield, resistance to leaf diseases and tolerance to soil acidity (Reddy et al. 2004b). Some of these A-/B-lines were comparable to the resistant check Real 60 for grain yield potential (Table 3.17).

Table 3.17. Performance of male-sterile lines evaluated under six different acid soil conditions in Zamorano, Honduras (1997 and 1999, II season), Matazul (1997 and 1998, II season) and La Libertad (1998 and 1999, II season), Colombia.

A-/B-lines	Time to 50% flower (days)	Leaf disease score[1]	Grain mold score[2]	Grain yield (t ha^{-1})
ICSB 604	73	2.5	2.4	2.8
ICSB 605	77	2.4	1.9	2.8
ICSB 607	73	2.8	2.4	2.7
ICSB 608 (A_2)	74	2.1	1.6	2.7
ICSB 609 (A_2)	72	2.9	1.6	2.6
Real 60 (resistant check)	72	4.2	1.7	3.1
ICSB 338 (susceptible check)	66	3.3	2.7	0.9
Mean	72.8	3.2	2.1	2.2
CD	1.75	0.42	0.28	0.36
CV (%)	4.6	15.8	27.8	35.2

1. Measured on a 1–9 scale, where 1 = free of leaf diseases, 2 = 1–5% of leaf area affected, 3 = 6–10%, 4 = 11–20%, 5 = 21–30%, 6 = 31–40%, 7 = 40–50%, 8 = 51–75% and 9 = >75% of leaf area affected.
2. Measured on a 1–9 scale, where 1 = no mold and 9 = >80% surface of grain with mold.

Genetic materials for strategic research. Development of appropriate genetic material for conducting strategic research was also given emphasis during this phase at ICRISAT-Patancheru. These include isogenic lines for dwarf vs tall plant types, photoperiod sensitiveness vs photoperiod insensitiveness, tan vs non-tan, glossy vs non-glossy and trichomed vs non-trichomed 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 and plant defensive traits on grain yield and other traits of interest, the isonuclear alloplasmic A-lines are useful for assessing the effects of different

CMS systems on the expression of economic traits and understanding the inheritance of male fertility restoration on all the available diverse CMS systems. Also, during this phase, 18 A_2, seven A_3 and two A_4 CMS systems (non-*milo*)-based A-lines were developed at ICRISAT-Patancheru by converting some of the high-yielding medium maturity breeding lines into A-lines.

Phase III (1999 onwards)

This phase marked the beginning of race-specific and alternative (non-*milo*) CMS systems-specific diversification of A-lines. To capture the advantages of different races, race-specific diversification of A-/B-lines was initiated involving landraces in crossing programs at ICRISAT-Patancheru. 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. At present, all these are in advanced stages of conversion into A-lines. Also, diversification of A-lines for farmer-preferred grain quality-evident traits such as white, bold and lustrous grains for postrainy season adaptation is receiving greater emphasis. Diversification of seed parents for resistance to biotic stresses was scaled down to only two major stresses, namely shoot fly (for both rainy and postrainy seasons) and grain mold (for rainy season), while maintaining reasonably higher yield potential considering NARS priorities and donor perceptions.

The initial grain yield and grain quality traits-based breeding in Phase I and subsequent yield stabilizing defensive traits-based breeding (in Phases II and III) and race-specific breeding (in Phase III) at ICRISAT-Patancheru led to the development of 732 A-/B-lines, which include A_1 CMS system-based 165 (160 old + 5 new) high-yielding lines and 487 biotic and abiotic stresses 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 in ICRISAT website: http:/www.icrisat.org/grep/homepage/sorghum/breeding/pedigreemain.htm.

Identification/development of A-/B-lines for multicut trait, sweet-stalk trait, salinity tolerance, and grain micronutrients [Fe and zinc (Zn)] and β-carotene density are some of the programs initiated during Phase III, besides race-specific and trait-specific diversification of A-/B-lines.

Multicut trait. The A-/B-lines with good ratooning ability are required for the development of multicut hybrids with higher green fodder yield. Taking this cue, a total of 160 A-/B-lines (developed in Phases I and II) consisting of 133 A_1-based A-/B-lines, 18 A_2-based A-/B-lines, seven A_3-based A-/B-lines and two A_4-based A-/B-lines of different maturity groups developed earlier for various traits were evaluated along with the checks for green fodder yield and ratoonability (scored on a 1–5 scale, where 1 = >90% of the stubbles regrowth and 5 = no regrowth) during 2001/02 postrainy season. Significant differences were observed between A- and B-lines for ratoonability. A-lines had higher ratoonability than their B-line counterparts, which could be attributed to higher stalk sugar content because of non-partitioning of photosynthates to grains and to the possible cytoplasmic-nuclear interaction. Past experience at ICRISAT-Patancheru has shown that the lines with high stalk sugar content have good ratoonability. Based on green fodder yield and ratoonability, selected 27 A-/B-lines were evaluated for green fodder yield in main crop during 2002 rainy season and in ratoon crop during 2002/03 postrainy season. The results indicated that 12 B-lines had good ratoonability, of which four lines, viz., ICSB 472 (17.9), ICSB 401 (16.3%), ICSB 405 (16.1%) and ICSB 731 (15.9%) with high stalk sugar content showed ratoonability ranging from 36% to 81%. These 12 B-lines along with other 16 B-lines earlier identified having high stalk sugar content were evaluated during 2003 rainy season for green fodder yield and stalk sugar content. Based on the results, eight B-lines [ICSB 74, ICSB 264, ICSB 293, ICSB 297, ICSB 474, ICSB 664, ICSB 731 (A_2) and SP 20656B] were identified as promising with green fodder yield ranging from 30 t ha^{-1} to 47 t ha^{-1}. The stalk sugar content of these B-lines ranged from 14% to 20%.

Sweet-stalk trait. Sweet sorghum research (mainly for forage purpose) at ICRISAT-Patancheru was initiated way back in 1980. Due to changed focus driven by donor perceptions and NARS needs, sweet sorghum research at ICRISAT was discontinued in late 1990s. Research was renewed again in 2000 at ICRISAT-Patancheru to contribute its share to meet the possible increased demand created for ethanol following the Indian Government's policy to blend petrol with 5% ethanol. Distilleries and sugar industries in India are showing increasing interest to use sweet sorghum as raw material for ethanol production. The selected grain/forage A-/B-lines were screened for sweet-stalk trait. Several promising sweet-stalk A-/B-lines have been identified (ICSB 371, ICSB 401, ICSB 405 and ICSB 472). In rainy season 2004, a total of 238 elite bold grain B-lines, consisting of 198 A_1-based B-lines (old set), 21 A_2-based B-lines, 8 A_3-based B-lines, 6 A_4-based B-lines and 5 A_1-based new B-lines was evaluated for stalk sugar content. During postrainy season 2004, selected A-/B-lines were screened again for sweet-stalk trait. Information on some of the promising A-/B-lines is provided in Table 3.18. One of these A-lines, ICSB 38 (not shown in Table 3.18) is a parent of the sweet sorghum hybrid, NSSH 104, released in 2004 as a special purpose (sweet-stalk sorghum) hybrid by the National Research Centre for Sorghum (NRCS), Rajendranagar, India.

Table 3.18. High-yielding trait-based B-lines selected for stalk sugar content during postrainy season 2004 at ICRISAT, Patancheru, India.

A-/B-line	Trait	Average Brix (%)	Time to 50% flower (days)	Plant height (m)
ICSB 68	High yielding	15	68	1.4
ICSB 71	High yielding	14	68	1.4
ICSB 435	Shoot fly resistant (rainy season adaptation)	14	74	1.0
ICSB 479	Stem borer resistant (postrainy season adaptation)	13	68	1.9
ICSB 592	*Striga* resistant	13	67	1.9
296B (control)	High yielding	7.8	74	1.2

Soil salinity tolerance. The demand for sorghum to meet the food and fodder requirement of the ever growing population necessitates sorghum production in marginal and problematic soils such as saline and acidic soils. There are vast areas in India, Yemen, Saudi Arabia and Iran with salinity-affected soils. Extension of cultivation of sorghum to these salinity-affected soils would not only help meet increased demand for sorghum, but also ensure sustainable and eco-friendly management of such problematic soils. The development of high-yielding salinity tolerant sorghums is the best option to increase the productivity in such soils. As a short-term strategy, the available grain/forage sorghum A-/B-lines bred at ICRISAT-Patancheru were screened for salinity tolerance at pre-anthesis biomass production under induced soil salinity (at 23.4 dS m^{-1}) in pot culture experiments during summer and rainy season in 2003 at ICRISAT-Patancheru. The studies revealed significant genetic variability for salinity tolerance among the B-lines as measured by the pre-anthesis biomass yield in relation to biomass yield under stress-free conditions (Krishnamurthy et al. 2003). The same lines were further tested for salinity tolerance for grain and fodder yields at maturity. Some of the B-lines such as ICSB 709, ICSB 657, ICSB 676 and ICSB 678 produced better grain and stover yields in relation to their performance under stress-free conditions. The same set of B-lines was field-tested under natural soil salinity (8 dS m^{-1}) at the Agricultural Research Station (ARS), Gangavathi, University of Agricultural Sciences (UAS), Dharwad, India. The grain yield of these B-lines ranged from 2.0 to 3.3 t ha^{-1} as against the susceptible check 296B, which yielded only 0.9 t ha^{-1} (Ramesh et al. 2005).

Micronutrient density. Deficiency of Fe, Zn and β-carotene is highest in the diets of poor people in South and Southeast Asia and sub-Saharan Africa. Considering that the development and dissemination of Fe, Zn and β-carotene dense cultivars through plant breeding approach is the best and sustainable option to minimize the micronutrient deficiency by taking advantage of the consistent daily consumption of large quantities of sorghum-based diets, a program was initiated in 2004 under HarvestPlus Project – Challenge Program of the Consultative Group on International Agricultural Research (CGIAR). As a part of the pre-breeding activity, 21 B-lines along with a diverse set of other lines (a total of 86 entries) were evaluated in replicated trial during 2003/04 postrainy season to identify lines with high grain Fe, Zn and β-carotene contents. Several *milo* (A_1) cytoplasm-based B-lines such as ICSB 37, ICSB 38, ICSB 39, ICSB 52, ICSB 74 (all high-yielding lines), ICSB 418 (shoot fly resistant-rainy season adaptation), ICSB 472 (stem borer resistant-rainy season adaptation) and ICSB 484 (stem borer resistant-postrainy season adaptation) had grain Fe and Zn contents more than trial mean (Table 3.19). All these are white-grain types with only traces of β-carotene content (Ramesh et al. 2005).

New high-yielding bold grain A-/B-lines. Considering that *caudatum* race has been exploited extensively for diversification of hybrid parents at ICRISAT-Patancheru and elsewhere, greater emphasis was given for the use of other races for hybrid parents development since 2000 at ICRISAT-Patancheru. As a result of concerted efforts, a total of 85 new race-specific A-/B-lines (39 A_1 and 46 A_2 CMS systems-based) have been developed (Table 3.20). The grain yield potential of some of the best *durra* bold grain B-lines (A_1) are significantly better than the control 296B with a comparable grain size (Table 3.21).

On the behest of private seed companies and NARS, strategic research in areas such as relationship between parental per se performance and hybrid performance for resistance to shoot fly and grain mold and green fodder yield,

Table 3.19. Estimates of grain iron and zinc contents in promising A-/B-lines (A_1).

A-/B-line	Iron (ppm)	Zinc (ppm)
ICSB 418	31.2	20.4
ICSB 74	32.8	19.8
ICSB 472	36.8	25.5
ICSB 484	28.9	23.6
ICSB 38	30.0	19.7
ICSB 37	34.3	20.8
ICSB 39	32.1	21.2
Trial mean	28.0	19.0
SE±	0.76	0.63
CD (5%)	2.57	2.15
CV (%)	4.67	5.75

Table 3.20. The number of race-specific A-/B-lines developed in Phase III (1999 onwards) at ICRISAT, Patancheru, India.

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

Table 3.21. Grain yield potential of best *durra* bold grain B-lines (A_1) during rainy season 2003 at ICRISAT, Patancheru, India.

B-line	Time to 50% flower (days)	Plant height (m)	Grain yield (t ha^{-1})	100-seed mass (g)
SP 58441	67	1.9	3.3	2.2
SP 58427	67	1.6	2.7	2.1
SP 58415	73	1.9	2.3	2.7
SP 58435	70	1.7	2.2	2.2
SP 58429	68	1.6	2.2	2.2
SP 58437	67	2.0	2.2	2.3
Control 296B	73	1.3	1.0	2.1
Trial mean	72	1.6	1.4	2.0
SE±	0.97	0.04	0.14	0.13
CD (0.05)	2.75	0.12	0.39	0 .38

sweet-stalk and juice yields was also given due emphasis during this phase. The strategic research issues are dealt in detail in a separate section.

Shoot fly resistance program. The success of breeding for shoot fly resistance, a difficult trait for genetic manipulation, is largely dependent on the availability of resistant sources coupled with cost-effective, reliable large-scale field screening techniques. At ICRISAT-Patancheru, interlard-fishmeal technique (Nwanze 1997) has been used to develop shoot fly resistant seed parents. While breeding for shoot fly resistance, resistant sources in desirable agronomic background (ICSV 702, ICSV 705, ICSV 708, PS 21318, PS 30715-1 and PS 35805) as well as sources in not-so-good agronomic background (IS 18551) were used. Though several other shoot fly resistant sources were used in the past, the derivatives resulting from crosses between the resistant germplasm sources (PS 19349, IS 1054, IS 1082, IS 2312, IS 2313, IS 2134, IS 2146, IS 2195, IS 2205, IS 5604, IS 18417 and IS 18551) and high-yielding lines had poor agronomic background. Following trait-based pedigree breeding approach as described earlier, a large number of shoot fly resistant seed parents for both rainy season (ICSA-/B-409 to ICSA-/B-436) and postrainy season (ICSA-/B-437 to ICSA-/B-463) were developed (Reddy et al. 2005b). All these B-lines have been designated and their characteristics are available in ICRISAT website: http:/www.icrisat.org/text/research/grep/homepage/sorghum/breeding/main.htm. Percentage of deadhearts (DH%) was used as the major criterion to select for shoot fly resistance following Resistance Index (RI) = [X − (C1 + C2)/2]/1 + (C1 + C2)/2, where X = DH% in testplots; C1 and C2 = DH% in adjacent resistant control plots (Reddy et al. 1997). The RI takes care of variability in shoot fly incidence in different test blocks. The lines with low RI values were considered resistant. Besides shoot fly resistance, other traits such as desired maturity, plant height and good grain quality and size were considered. However, breeding for shoot fly resistance is rather slow and the progress is rather limited owing to the complexity of inheritance and insect load-dependent resistance responses coupled with low level resistance in the sources.

Currently, 31 shoot fly resistant B-lines for rainy season adaptation are under advanced stages of conversion (BC_3) into A-lines (22 on A_1 and 9 on A_2). For postrainy season adaptation, 30 shoot fly resistant B-lines (25 on A_1 and 5 on A_2) are in early stages (BC_1) of development. To address serious concerns on the extensive use of a single shoot fly resistant source (IS 18551), sources not used in earlier programs 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 were involved in crosses to generate new variability for selection. The material is now under different stages from F_1 to F_3 generations.

Grain mold resistance program. All the A-lines (seed parents) developed at ICRISAT prior to 1989 were not bred with any emphasis on resistance to diseases and insect pests. Specific program to develop grain mold resistant seed parents was initiated through trait-based breeding approach during Phase II of seed parents development. Major emphasis was laid on white grain background while breeding for grain mold resistance (GMR) as the white grain sorghums were largely preferred for human consumption. Breeding seed parents for GMR in red grain background was carried out only for a brief period in late 1980s and received reduced emphasis after 1980s (Reddy et al. 2000). Several putative grain mold resistant germplasm lines such as IS 2501, IS 2815, IS 3436, IS 10288B, IS 10475B, IS 10646, IS 21599 and IS 23585 were identified during 1980 to 1990. These were tall, poor yielders in rainy season and mostly photoperiod sensitive besides possessing colored (non-white) grains and therefore were not suitable for conversion into seed parents. So, these resistant lines were crossed with high-yielding B-lines (A_1 cytoplasm) such as ICSBs 11, 17, 37, 42, 51 and 70, which are susceptible to grain mold. Selection for highly heritable traits such as time to flower, plant height and grain color was practiced in F_2 generation and the resulting F_3s and advanced generations were screened following the modified screening technique as outlined by Bandyopadhyay et al. (1998). Family-based selection for GMR and individual plant-based selection for grain yield within the resistant families were followed (as practiced for shoot fly resistance) to develop grain mold resistant lines and those with maintainer reaction were converted into A-lines (Reddy et al. 2000). The A-/B-lines obtained were evaluated for other characters.

Fifty-eight A-lines with A_1 cytoplasm were thus produced at ICRISAT-Patancheru (Reddy et al. 2005b). Of these, 35 were white-grained, 20 red-grained, and three were brown-grained. Several resistant sources (IS 2815, IS 21599, IS 10288, IS 3436, IS 10646, IS 10475 and IS 23585) contributed to these 58 A-lines. Of these, IS 2815 contributed to nearly more than 50% of the derivatives. For detailed data on various agronomic characters and pedigree of these grain mold resistant seed parents, visit website: http//www.icrisat.org/text/research/grep/homepage/sorghum/breeding/main.htm. Also, the grain mold resistant sources, IS 9470 with A_1 (*milo*), A_2, A_3 and A_4 (Maldandi), and IS 15119 with A_3 and A_4 (Maldandi) cytoplasms were converted into A-lines.

Since 2000, efforts were further intensified to develop grain mold resistant seed parents considering limited success in improving GMR in bold white grain and elite agronomic background at ICRISAT-Patancheru. Pedigree selection among segregating progenies derived from 17 crosses between grain mold resistant lines (ICSB 383, ICSB 392, ICSB 403, IS 8614, IS 13817, IS 10646, IS 25060, IS 21599 and IS 23585) and high-yielding bold grain B-lines (ICSB 11, ICSB 37, ICSB 42, ICSB 70 and ICSB 101) for GMR and conversion of resistant lines with maintainer reaction into A-lines led to the development of 43 promising grain mold resistant B-lines, with desirable agronomic and grain traits and moderate grain yield potential. These were tested through a collaborative Sorghum Grain Mold Resistance Stability Nursery (SGMRSN) between ICRISAT and All India Coordinated Sorghum Improvement Project (AICSIP). The SGMRSN was established at Akola, Parbhani, Palem and Patancheru in 2002. Results indicated that of the 43 lines, five (SGMRs 14, 19, 20, 21 and 23) showed resistance to grain mold with 1 to 2.5 mold severity scores (grain mold score taken on a 1–5 scale, where 1 = no mold and 5 = >50% grains molded on panicle) across the four locations compared with 4.4 on the susceptible check Bulk Y and 1.6 on the resistant check IS 14384 (Thakur et al. 2003).

Evaluation of the 28 single-plant selections from these 43 promising B-lines during rainy season 2003 for GMR [a 1–9 scale, where 1 = no mold and 9 = >75% mold was used to assess GMR at physiological maturity (ie, PGM) and on threshed grain (ie, TGM)] resulted in identification of three lines, SGMR 3-2 (PGM 4.0 and TGM 4.3), SGMR 7-1 (PGM 4.4 and TGM 5.2) and SGMR 7-2 (PGM 4.9 and TGM 5.4) in white grain background with moderate GMR levels, although they had pigmented (red) glumes. All those white grain B-lines with white glume color were susceptible to grain mold (Reddy et al. 2005c). Nevertheless, several high-yielding mold resistant B-lines in white grain background developed earlier at ICRISAT-Patancheru such as ICSB 353, ICSB 358, ICSB 362, ICSB 368, ICSB 379 and ICSB 402 and a variety, PVK 801, in white glume background are the best examples to show that it is possible to deploy GMR in white glume (and white grain) background. The significant positive correlation between PGM and early flowering and significant negative correlation between PGM and TGM scores with grain yield implied that it is necessary to maintain a balance between maturity, GMR levels and grain yield. Further, it was interesting to note poor correlation between GMR levels and grain mass and grain hardness contrary to earlier reports of significant negative correlation between GMR and grain mass (Reddy et al. 2000) and positive correlation between GMR and grain hardness (Audilakshmi et al. 1999). These results indicate better prospects for developing grain mold resistant seed parents without compromising for grain size (one of the important farmer-preferred traits). Concerted breeding efforts involving diverse sources of grain mold resistant germplasm lines with different mechanism of resistance and high-yielding bold grain lines are essential for the development of B-lines with enhanced GMR levels in desirable agronomic background.

Currently, 12 grain mold resistant lines with maintainer reaction are in advanced stages of conversion into A-lines (4 BC_4s on A_1 and 8 BC_3s on A_2). To address concerns on the use of limited sources of GMR, several grain mold resistant sources such as IS 18758, IS 30469, IS 40657, IS 41397, IS 41618, IS 41675 and IS 41720, along with grain mold resistant B-lines, are being used in the crossing program to generate variability for the development of grain mold resistant seed parents.

Seed parents for postrainy season adaptation. At ICRISAT, with a global mandate of developing improved breeding products, sorghum improvement for postrainy season adaptation, which is unique to India, received less emphasis. The strong program for postrainy season sorghum improvement in Indian NARS is another major reason for limited emphasis on postrainy season sorghum improvement at ICRISAT-Patancheru. The Indian NARS has developed several hybrids for postrainy season cultivation. However, most of them could not impress farmers as they lacked terminal drought and shoot fly tolerance and grain quality traits that match with those in M 35-1, the most popular postrainy season adapted variety. On the behest of private sector seed companies and Indian NARS, the program for postrainy season sorghum improvement has received new impetus since 2000 at ICRISAT-Patancheru. Consequently, seed parents development for postrainy season adaptation was intensified at ICRISAT-Patancheru. Considering that low temperature and terminal drought tolerance and grain quality traits such as pearly white, bold and lustrous grains are critical for postrainy season adaptation, variability was generated by involving several postrainy season adapted landraces (M 35-1, Gidda Maldandi, DSH 128, E 36-1, Barsizoot, Dagadi Sholapur, Dagadi local, Amaravathi local, M 35-1 selection bulks, etc.) and elite varieties and B-lines with good grain quality traits. Several elite selections (44 from F_5 and 92 from F_4 generations) are made based on grain size and luster and agronomic desirability.

These selections will be further evaluated for agronomic performance and simultaneously screened for shoot fly resistance in postrainy season 2005. Those selections with desirable agronomic and grain quality traits that match with those in M 35-1 will be converted into A-lines (A_1). In addition, Gidda Maldandi, which is restorer on A_1, is being converted into A_2, A_3 and A_4-based A-lines.

The hybrid seed parents research in southern Africa is being carried out under Sorghum and Millets Improvement Program (SMIP) and was initially dependent on the selections from the A-/B-lines received from USA and ICRISAT-Patancheru and exploited 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 location, 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 made for maturity duration (early to medium), grain yield and grain quality traits, and stay-green. These A-/B-lines are slightly taller than the controls, slightly earlier (2%), superior in grain yield (8%) and 5–110% superior in milling quality. These new A-lines are grouped into three categories: (1) dwarf (<1.0 m) with broad drooping leaves, tan plants and resistant to leaf blight and sooty stripe; (2) 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 (3) semi-tall (1.7–1.9 m) with broad leaves, and tan plants but susceptible to leaf blight and sooty stripe.

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

Seed parent research at ICRISAT, Sotuba, Mali for western and central Africa (WCA) adaptation was initiated in 1982 with the assessment of 227 Malian landraces (consisting of 74% *guinea* landrace accessions) for fertility reaction on A_1 CMS system. Although 36% of these *guinea*-based landraces showed maintainer reaction, no attempts were made to convert them into A-lines. Seed parent research (based on only A_1 CMS system) was revived at ICRISAT, Sotuba, Mali in late 1990s in collaboration with the Institut d'Economie Rurale (IER) and INERA. High grain yield with acceptable grain quality and *guinea* glume and panicle characteristics to assure value and acceptance of the product (free threshing, good milling recovery and good grain storage capability) were major traits targeted while developing seed parents.

As a result of concerted efforts, three *guinea* landrace-based A-lines (Fambe, IPS001 and CSM 219) were developed at ICRISAT, Sotuba, Mali, and seven inter-races cross [*guinea* landrace (Bimbiri Soumale) × *caudatum* varieties] derivatives-based A-lines were developed at IER in 2000–01. 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 typical of *guinea* race.

Several B-lines (on A_1 CMS system) from the *guinea*-core collection have been identified at ICRISAT, Sotuba, Mali. These are currently in advanced stages of conversion (in BC_3 generation) into A-lines. They are expected to provide large diversity for most agronomic traits, spanning the range of grain size (100-seed mass 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 under conversion represent a wide range of maturity that is intended to address the needs of the Northern Sudanian zone (600–800 mm), the Southern Sudanian zone (800–1000 mm) and the Northern Guinean zone (1000–1200 mm). The lines (Table 3.22) with heading before 15 September (along with earlier developed CSM 219A and inter-racial A-lines) are most promising for the Northern Sudanian zone, whereas those with heading between 15 and 25 September and thereafter are most promising for the Southern Sudanian and the Northern Guinean zones, respectively.

Table 3.22. Seed mass and heading dates of sorghum maintainer lines from the *guinea*-core collection in advanced stages of conversion (in BC_3 generation) into male-sterile lines at ICRISAT, Sotuba, Mali.

Maintainer lines under conversion	Origin	Snowden classification	100-seed mass (g)	Heading (days after 10 Sep)
IS 20064	Senegal	*Margaritiferum*	1.0	21
IS 9220	Uganda	*Margaritiferum*	1.3	35
IS 19970	Senegal	*Guiniense*	1.9	29
IS 20114	Senegal	*Gambicum*	2.0	29
IS 22677	Mali	*Guiniense*	2.1	2
IS 6781	Burkina Faso	*Guiniense*	2.2	25
IS 27494	Burkina Faso	*Gambicum*	2.3	13
IS 27580	Burkina Faso	*Guiniense*	2.3	28
IS 23645	Gambia	*Guiniense*	2.4	20
IS 6749	Burkina Faso	*Guiniense*	2.4	25
IS 3534	Sudan	*Conspicuum*	2.5	30
IS 14414	Malawi	*Conspicuum*	3.0	18

Restorers research

Utilization of CMS system for hybrid development would require complementary efforts in developing restorers. Identification of promising restorer lines with respect to agronomic and adaptation traits and high GCA for grain yield is an important component in hybrid breeding research. Equally important is genetic improvement of existing R-lines for these traits. A situation may arise where a high-yielding inbred line might produce completely or partially male-sterile hybrids. This is likely to occur more with respect to those CMS systems for which there is low frequency of restorers in the working collection of breeding materials, the extreme case as indicated earlier being that of A_3 CMS system in sorghum. In such cases, the most effective approach is to identify best restorer source(s) and undertake backcross transfer of restorer gene(s) in these lines.

Specific efforts were not made to develop restorers at ICRISAT-Patancheru nor at other centers in Africa. This is because, several of the improved varieties bred in various projects at ICRISAT-Patancheru were found to be restorers on A_1 CMS system and were added to the restorer gene pool. The selections with restorer reaction in seed parent development programs were added to the restorer gene pool, though their contribution to the restorer gene pool is limited. Restorer program therefore, rested mainly on varietal development program, wherein grain quality traits and yield potential were given major emphasis during 1972 to 1978, and resistance to biotic and abiotic stresses during 1979 to 1988 at ICRISAT-Patancheru. Varietal improvement program was de-emphasized at ICRISAT-Patancheru, while it was strengthened at ICRISAT centers in Africa from 1989 onwards. The program on varietal/restorer improvement has been renewed in the last three years at ICRISAT-Patancheru, though at a low pace with the availability of private sector funds.

Varietal/restorer improvement programs led to the identification/ development of large number of restorers for A_1 and A_2, dual-restorers for A_1 and A_2 and common restorers on all the available CMS systems at ICRISAT-Patancheru. So far, 1015 restorers on A_1, 182 on A_2, two on A_3 and four on A_4 CMS systems have been identified at ICRISAT-Patancheru (Table 3.23). All these R-lines have been designated and their characteristics are available in ICRISAT website: http:/www.icrisat.org/grep/homepage/sorghum/breeding/pedigreemain.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, A_4 (Maldandi), A_4 (VZM) and A_4 (Guntur) CMS systems have been identified. Further, during 2005, 14 high-yielding restorers have been identified. These 14 along with 36 new R-lines are yet to be designated. Considering the paucity of restorers on A_3 and A_4 CMS systems, a backcross-breeding scheme of these two CMS systems could be followed.

Table 3.23. Number of sorghum restorers developed at ICRISAT, Patancheru, India.

	Restorers	
CMS system	Old	New[1]
A_1	873	142
A_2	146	36
A_3	–	2[a]
A_4	–	2+2[b]
A_1 and A_2 (isonuclear)	3	32
A_1, A_2 and A_3 (isonuclear)	–	2[a]
A_1, A_2, A_3 and A_4 (isonucleaar)	–	2[b]

1. Values followed by same letter indicate same lines; restorer frequency: $A_1>A_2>A_4>A_3$.

As in the case of A-/B-lines, the available varieties/restorers were screened for acid soil tolerance, multicut trait, sweet-stalk trait, salinity tolerance and grain Fe, Zn and β-carotene contents in various programs as discussed in the section on seed parents development and several promising lines have been identified at ICRISAT-Patancheru.

Acid soil tolerance

Large number of R-lines developed in Phases I and II were introduced and empirically screened for grain yield and other traits under acid soil conditions during July 1996 to December 1999 in a research project funded by IADB and jointly implemented by ICRISAT-Patancheru, CIAT and Latin American NARS. Fifteen grain sorghum R-lines were selected for high yield, resistance to leaf diseases and tolerance to acid soil (Reddy et al. 2000). Some of these R-lines were comparable to resistant check Real 60 for grain yield potential and grain mold response scores (Table 3.24).

Table 3.24. Performance of sorghum R-lines (A_1) evaluated under six different acid soil conditions in Zamorano, Honduras (1997 and 1999, II season), Matazul (1997 and 1998, II season) and La Libertad (1998 and 1999, II season), Colombia.

Variety/R-lines (A_1)	Time to 50% flower (days)	Leaf disease score[1]	Grain mold score[2]	Grain yield (t ha^{-1})
ICSR 91012	74	2.8	1.6	2.8
ICSR 93033	74	3.2	1.8	2.7
ICSR 110	68	3.1	1.8	2.7
ICSV 93042	77	3.0	1.7	2.6
ICSR 91020-1	67	2.5	1.4	2.6
ICSR 143	75	3.1	1.6	2.5
ICSR 194	66	3.3	1.7	2.5
Real 60 (resistant check)	70	3.9	1.7	2.9
SPRU 94008 (susceptible check)	64	3.5	3.0	1.1
Mean	70	3.09	1.77	2.34
SE±	1.02	0.09	0.10	0.12
CV (%)	7.8	15.4	19.5	37.7

1. Measured on a 1–9 scale, where 1 = free of leaf diseases, 2 = 1–5% of leaf area affected, 3 = 6–10%, 4 = 11–20%, 5 = 21–30%, 6 = 31–40%, 7 = 41–50%, 8 = 51–75% and 9 = >75% of leaf area affected.
2. Measured on a 1–9 scale, where 1 = no mold and 9 = 50% surface of grain with mold.

Multicut trait

For the reasons explained in earlier section on multicut seed parents identification, the R-lines/varieties developed in various programs were evaluated along with the checks for green fodder yield and ratoonability (scored on a 1–5 scale, where 1 = >90% of the stubbles regrowth and 5 = no regrowth) during rainy season 2002. Significant variability was observed for all these traits. Several promising R-lines with higher green fodder yield and good ratoonability have been identified. Some of the best R-lines were comparable to the control SSG 59-3 (Table 3.25).

Table 3.25. Performance of promising sorghum R-lines selected for green fodder yield in main and ratoon crops during rainy season 2002 at ICRISAT, Patancheru, India.

	Time to 50% flower (days)		Brix reading (%)		Green fodder yield (t ha^{-1})		
Variety/R-lines (A_1)	Main crop	Ratoon crop	Main crop	Ratoon crop	Main crop[1]	Ratoon crop	Ratoon-ability score[2]
ICSR 93024-1	87	70	17.8	12.0	29.2	21.2	2.5
GD 65239	90	61	20.5	14.6	24.8	19.9	2.0
ICSR 93025-1	87	73	18.1	15.8	22.7	18.1	1.5
GD 65174-2	77	55	10.4	19.6	22.6	17.7	1.5
SSG 59-3 (control)	81	54	15.9	12.9	19.2	14.3	1.0
Mean	79	57	16.58	13.83	18.27	10.87	2.38
SE±	2.17	3.83	1.49	2.44	3.39	2.93	0.55
CV (%)	3.86	9.58	12.72	24.92	26.24	38.09	32.43

1. At 45 days after sowing.
2. Measured on a 1–5 scale, where 1 = highly ratoonable and 5 = least ratoonable.

Sweet-stalk trait

In an effort to identify promising sweet-stalk R-lines as a short-term strategy for immediate utilization in hybrid cultivar development, existing diverse set of R-lines developed/identified in restorer/varietal improvement programs were evaluated at ICRISAT-Patancheru during rainy season 2002 and postrainy season 2002/03. Some of the lines such as GD 65003, GD 65080, ICSV 96143, ICSR 93034, ICSV 93046 and Entry# 64 DTN were found promising. Besides these, several other promising R-lines (Table 3.26) have been identified based on the evaluation at ICRISAT-Patancheru during rainy season 2004.

Table 3.26. Performance of sorghum R-lines for sweet-stalk and related traits during rainy season 2004 at ICRISAT, Patancheru, India.

Variety/R-line (A_1)	Time to 50% flower (days)	Brix reading at maturity (%)	Millable cane yield (t ha^{-1})	Juice yield (kl ha^{-1})	Sugar yield (on juice yield) (t ha^{-1})
ICSV 574	85	21.7	34.6	11.2	2.2
ICSR 93034	86	19.3	35.0	10.7	1.8
S 35	70	19.3	30.0	9.8	1.7
ICSV 700	75	19.0	30.2	12.3	2.1
ICSR 93019-2	68	17.7	29.4	10.2	1.6
ICSV 93046	76	16.3	33.1	14.8	2.2
SSV 84 (control)	88	22.7	41.0	12.1	2.4
Mean	69	15.70	32.92	10.82	1.53
SE±	0.68	0.74	2.84	1.35	0.21
CV (%)	1.72	8.12	14.96	21.56	24.26
CD (5%)	1.90	2.05	7.91	3.75	0.60

Salinity tolerance

A total of 16 selected R-lines were evaluated for salinity tolerance during summer and rainy season in 2002 at ICRISAT-Patancheru under induced salinity at 23.4 dS m^{-1} in pot culture experiment. Based on the pre-anthesis biomass production at 39 days after sowing relative to the biomass of the plants evaluated in the control-normal pot culture treatment, four R-lines (ICSR 196, ICSR 89010, ICSR 91005 and ICSR 93046) were identified as salinity tolerant (Krishnamurthy et al. 2003). These selected R-lines along with others were evaluated for grain yield and agronomic traits under naturally salinity-affected (8.0 dS m^{-1}) soils at ARS, Gangavathi, UAS, Dharwad. The results revealed that grain yield of some R-lines such as ICSR 89010 (2.8 t ha^{-1}), ICSR 900I7 (2.0 t ha^{-1}), ICSR 196 (2.0 t ha^{-1}) and ICSR 160 (1.9 t ha^{-1}) were comparable to the trial mean (1.9 t ha^{-1}) (Ramesh et al. 2005).

Micronutrient density

As a part of the pre-breeding activity under HarvestPlus Project – Challenge Program, selected 24 R-lines were evaluated in a replicated trial consisting of a diverse set of 86 entries during postrainy season 2003/04 to identify lines with high grain Fe, Zn and β-carotene contents. The results revealed that the grain Fe and Zn contents of some of the R-lines such as ICSR 37, ICSR 98, ICSR 196 and ICSR 90017 were similar to the trial mean values (Table 3.27) (Reddy et al. 2005b). Interestingly, all these four R-lines are used as male parents in the hybrids marketed by private sector seed companies.

Table 3.27. Promising sorghum R-lines (A_1) rich in iron and zinc contents.

R-line	Iron (ppm)	Zinc (ppm)
ICSR 37	29.1	19.0
ICSR 98	28.0	20.8
ICSR 196	28.6	21.2
ICSR 90017	29.3	2.36
Trial mean	28.0	19.0
SE±	0.76	0.63
CD (5%)	2.57	2.15
CV (%)	4.67	5.75

New high-yielding bold grain R-lines

The R-line development program led to the identification of 142 R-lines on A_1 CMS system since 2000. A preliminary evaluation of selected (based on agronomic score) 100 R-lines indicated significantly higher grain yield (ranging from 6.0 t ha^{-1} to 6.5 t ha^{-1}) of 10 R-lines compared to the control CSV 4 (5.0 t ha^{-1}) (a prominent restorer line of many commercial hybrids). These were re-evaluated along with three controls (CSV 15, CSV 4 and RS 29) in rainy season 2004. Two of these 10 R-lines (ICSR 24010 and ICSR 24006), each with grain yield of 5.6 t ha^{-1} significantly outyielded the control CSV 4 (4.4 t ha^{-1}) with similar maturity period and Brix value (Table 3.28). Besides grain yield, the two R-lines (with 100-seed mass 2.79 and 2.65 g) were superior to all the three control varieties/R-lines (100-seed mass 2.22 to 2.5 g) for grain size as well. Further, ICSR 24001 (5.4 t ha^{-1}) and ICSR 24009 (5.4 t ha^{-1}) were numerically superior to CSV 4 (4.4 t ha^{-1}) for grain yield, besides being significantly superior for grain size.

Table 3.28. Mean performance of sorghum R-lines for various traits in Advanced R-lines Trial (ART 2004K) during rainy season 2004 at ICRISAT, Patancheru, India.

R-line (A_1)	Time to 50% flower (days)	Plant height (m)	Plant agronomic score[1]	Brix reading (%)	100-seed mass (g)	Grain yield (t ha^{-1})
ICSR 24010	73	2.0	2.7	19.94	2.79	5.6
ICSR 24006	71	2.3	2.0	17.21	2.65	5.6
ICSR 24005	73	1.8	2.0	19.42	2.46	5.5
ICSR 24009	74	1.9	1.0	14.54	2.74	5.4
ICSR 24001	71	1.7	3.0	17.17	2.59	5.4
Controls						
CSV 15	69	2.5	2.3	18.58	2.50	5.9
RS 29	72	2.3	2.0	20.25	2.22	5.8
CSV 4	69	1.6	3.0	18.33	2.29	4.4
Mean	71	1.92	2.26	17.06	2.60	5.2
SE±	0.54	0.06	0.33	1.16	0.06	0.42
CV (%)	1.31	5.44	25.01	11.75	4.06	13.83
CD (5%)	1.58	0.18	0.95	3.38	0.18	1.21

1. Measured on a 1–5 scale, where 1 = very good, 2 = good, 3 = average, 4 = below average and 5 = poor.

Restorers program for postrainy season adaptation

The Indian NARS with strong sorghum improvement program for postrainy season adaptation has developed several varieties/restorer lines. However, many of these varieties could not attract farmers as they lacked grain quality traits and shoot fly resistance that match with those in M 35-1. At ICRISAT-Patancheru, restorer development for postrainy season adaptation was intensified in 2000. Several restorers (40) on A_1 CMS system were derived from 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. These restorers were evaluated for agronomic performance during 2005 postrainy season. Further, 32 selections with good agronomic desirability and good grain traits within postrainy season adapted varieties (M 35-1 and Swathi), germplasm lines (IS 4504, IS 4606, IS 5631, IS 8920 and IS 33844), breeding lines (such as SP 76942, SP 76942, SP 76946, SP 76947, SP 76948 and SP 76951) and derivatives from SPV 462 × 296B cross were found to be dual-restorers (on A_1 and A_2).

The segregating generations derived from crosses involving several 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 desirability and 24 each of breeder and farmer selections were evaluated in replicated trials at Regional Research Station, Bijapur and ICRISAT-Patancheru in 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 grain yield potential, grain size, grain luster and shape score, stay-green score, lodging score, time to 50% flower and plant height comparable to M 35-1 (Table 3.29).

Table 3.29. Performance of best sorghum farmer and breeder selections for various traits in postrainy season 2004 at ICRISAT, Patancheru and RARS, Bijapur, India.

Line	Plant color	Time to 50% flower (days)	Plant height (m)	Plant agro-nomic score[1]	Stay-green score[2]	Lodging score[3]	Grain luster and shape score[4]	100-seed mass (g)	Grain yield (t ha^{-1})
Farmer selections									
SP 71312	Non-tan	66	2.5	2.8	4.0	2.7	1.7	3.37	2.06
SP 71324	Non-tan	74	2.3	2.3	3.8	2.3	1.7	3.11	2.07
SP 71326	Non-tan	66	2.3	3.2	4.5	3.3	2.0	2.88	2.74
SP 71327	Non-tan	65	2.2	3.0	4.3	3.3	2.7	3.09	2.90
Breeder selections									
SP 71513	Non-tan	68	2.4	3.2	4.2	2.8	2.0	3.03	2.11
SP 71520	Tan	66	2.5	2.7	4.5	3.3	1.2	3.41	2.44
SP 71522	Tan	72	2.4	2.8	4.7	3.0	2.2	3.36	2.16
SP 71528	Tan	63	2.1	3.7	4.8	4.0	1.5	2.85	2.46
SP 71533	Non-tan	73	2.5	1.8	4.3	3.7	2.5	3.49	2.84
Controls									
M 35-1	Non-tan	67	2.4	2.4	4.3	2.9	1.4	3.59	2.52
SPV 1359	Non-tan	72	2.4	2.8	4.8	2.7	2.7	3.10	2.26
CV (%)	–	2.80	8.81	27.37	12.94	28.96	–	10.20	32.95
CD (5%)	–	2.24	0.23	0.92	0.64	1.00	–	0.36	0.77

1. Measured on a 1–5 scale, where 1 = very good, 2 = good, 3 = average, 4 = below average and 5 = poor.
2. Measured on a 1–5 scale at harvest, where 1 = >75% green, 2 = up to 75%, 3 = 26–50%, 4 = 10–25% and 5 = <10% green.
3. Measured on a 1–5 scale, where 1 = no lodging, 2 = up to 25% lodged, 3 = 26–50%, 4 = 51–75%, 5 = >75% plants lodged.
4. Measured on a 1–5 scale, where 1 = lustrous and globular like M 35-1, 2 = lustrous but not globular, 3 = less lustrous but globular, 4 = less lustrous and flat and 5 = less lustrous and flat with beak.

In southern Africa, as was done 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 ICRISAT sites 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).

In eastern and central Africa region, the 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.

At ICRISAT, Sotuba, Mali, several lines with restorer reaction with a range of panicle length (28–40 cm), 100-seed mass (1.0–2.9 g) and heading date (10–47 days after 10 September) have been identified from a sub-sample of *guinea*-core collections. The characterization of these lines for attributes important for R-lines such as plant height, pollen abundance, panicle architecture, etc was initiated in 2004.

Characterization of hybrid parents

Parallel to tremendous progress in the development and application of modern genetic improvement tools, there has been an increase in private sector investments in agricultural research, and increased demand for seeking intellectual property rights (IPR) over research products, which led to the introduction of legislations to protect new plant varieties in USA, some European countries and several countries in Asia including India.

The enactment of *sui generis* Protection of Plant Varieties and Farmers' Rights (PPV&FR) Act in India in 2001 and similar acts in several other developing countries under Trade Related Intellectual Property Rights (TRIPS) agreement will have significant implications on the International Public Goods (IPGs) nature of hybrid parents developed by ICRISAT at Patancheru and at its other centers in Africa. The Indian PPV&FR 2001 Act, which is yet to be implemented, stipulates the requirement of registration of the varieties/hybrids, for which protection is sought based on distinctiveness, uniformity and stability (DUS) and novelty criteria. ICRISAT has to protect its hybrid parents to enable it to disseminate them to all interested and also prevent others from limiting ICRISAT's role to make the products available. The revised ICRISAT Material Transfer Agreement (MTA) for breeding materials includes conditions that the recipient should not seek IPR/ownership of the materials received and should not transfer to third party. It, however, itself does not help ICRISAT to challenge the recipient from infringing MTA conditions under PPV&FR regime.

ICRISAT seeks to counter infringement by others on its sorghum hybrid parents by placing them in the public domain through establishing them a prior art. As an immediate strategy, ICRISAT intended to characterize all the available hybrid parents as per DUS test guidelines and make the information accessible to common public by placing it in public libraries and assigning the accession number(s) to the document(s). It is planned to document the characterization data of all the available hybrid parents in a phased manner.

In the first stage, a total of 277 designated A-/B-lines, which include 74 high-yielding lines (20 early maturing and 54 medium maturing), 75 diseases resistant lines (9 early maturing, 44 medium maturing and 22 late maturing), 62 insect pests resistant lines (47 medium maturing and 15 late maturing), 22 moisture stress (related) tolerant lines (11 *Striga* resistant, 5 acid soil tolerant and 6 stay-green), 2 tillering lines, 42 non-*milo* CMS-based lines (28 A_2, 8 A_3 and 6 A_4) and 160 R-lines, which include 56 early-maturing lines, 86 medium-maturing lines and 18 late-maturing lines were evaluated in 2004 during rainy season (in Alfisols and Vertisols) and postrainy season (in Vertisols) for the traits stipulated in DUS test guidelines of the Indian Council of Agricultural Research (ICAR). The data are processed and draft characterization document is under in-house review.

During rainy season 2005, 351 designated A-/B-lines which include 74 high-yielding lines (21 early maturing and 53 medium maturing), 123 diseases resistant lines (15 early maturing, 84 medium maturing and 24 late maturing), 81 insect pests resistant lines (8 early, 63 medium maturing and 10 late maturing), 38 moisture stress tolerant lines (23 *Striga* resistant, 10 acid soil tolerant and 5 stay-green), 1 tillering line, 34 non-*milo* CMS-based lines (21 A_2, 8 A_3 and 5 A_4) and 186 R-lines, which include 50 early-maturing lines, 111 medium-maturing lines and 25 late-maturing lines were evaluated in Vertisols at ICRISAT-Patancheru.

Inheritance of fertility restoration

The inheritance of fertility restoration is dependent on the specific interaction of cytoplasm and nuclear genes. Fertility restoration is controlled by a single gene in some combinations (eg, A_1) but is controlled by two or more polygenes when the same nuclear genotype interacts with a different cytoplasm (Schertz 1994). Segregating progenies with A_1 cytoplasm in F_2 generation showed that a single gene was responsible for fertility restoration of A_1 male-sterile cytoplasm (Murthy 1986, Murthy and Gangadhar 1990). Other studies on A_1 cytoplasm have concluded that one or two genes (Qian 1990) or even one to three genes (Lonkar and Borikar 1994) are involved in controlling fertility restoration of A_1 cytoplasm. However, at least three genes control the fertility restoration of A_2 cytoplasm (Murthy 1986). In another study, F_2 progenies with A_2 cytoplasm showed a 9:7 ratio indicating that two complementary genes (Msc_1 and Msc_2) are necessary for fertility restoration in A_2 (Murthy and Gangadhar 1990). Lonkar and Borikar (1994) indicated that two to four genes are necessary, but three genes were more optimal for the fertility restoration in A_2 cytoplasm in backcross generations. Research at ICRISAT-Patancheru showed that the frequency restorers are least on A_3 than A_4, A_2 and A_1 indicating the possible involvement of more number of genes in the inheritance of fertility restoration of A_3 than the other CMS systems (Reddy and Prasada Rao 1992). El'konin et al. (1996) concluded that the fertility restoration of 9E cytoplasm in sorghum is controlled by an interaction of two complementary dominant genes. In their study, the tester line, KVV 114 was a restorer for 9(ET) × 398 and a maintainer for 9E *milo* 10, indicating that one or more dominant inhibitor genes in *milo* 10 suppressed the action of restorer gene of KVV 114. Further, a novel and unusual phenomenon of gradual restoration of male fertility was observed in subsequent backcross generations of A_4 and 9E cytoplasms in sorghum (El'konin et al. 1998).

These studies suggest the involvement of at least two genes for fertility restoration on A_1 and three on A_2 cytoplasm. However, the results of these studies are not based on common nuclear genetic background and common R-lines. Therefore, the differences in the reported results on the number of genes involved in fertility restoration could be due to the effect of different nuclear genetic backgrounds of A-lines and R-lines and their interactions. With the availability of isonuclear alloplasmic A-lines and common restorers on all the available CMS systems at ICRISAT-Patancheru, the genetics of fertility restoration can now be established more clearly.

Genetic diversity in hybrid parents

In pursuit of diversifying breeding products (160 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 above. The tropical germplasm lines originating from Asia (165) have contributed most followed by tropical and temperate lines from Africa (162) and USA (105) (Table 3.30). These germplasm lines largely belonged to *durra* (80) (predominantly represented by Asia) and *caudatum* (48) (predominantly represented by Africa) among the basic sorghum races and *guinea-caudatum* (71) (predominantly represented by Africa) and *durra-caudatum* (45) (predominantly represented by Asia and Africa) among the hybrid races (Table 3.31).

Similarly, large genetic diversity has been captured in 85 new race-specific A-/B-lines (39 A_1 and 46 A_2 CMS system-based), which have been developed after 2000. More than 300 germplasm/breeding lines were utilized for generating variability, of which 72 lines have contributed to the development of these A-/B-lines (Table 3.32). The formation of core collection (Prasada

Table 3.30. Summary of origin of sorghum germplasm utilized to develop various categories of breeding products at ICRISAT, Patancheru, India.

	Seed parents		Improved parents		
Region/country	High-yielding A/B pairs	Trait-specific A/B pairs	Restorers	Varieties[1]	Total
Asia	16	31	54	64	165
USA	12	25	33	35	105
Western and Central Africa	1	17	24	45	87
Eastern and Southern Africa	2	8	18	30	58
ICRISAT[2]	–	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. Most of the varieties are restorers on A_1 cytoplasm.
2. Breeding materials.

Table 3.31. Race-wise distribution summary of the sorghum germplasm accessions that contributed to development of various sorghum materials at ICRISAT, Patancheru, India.

Race	Number of accessions				
	Seed parents		Improved		
	High-yielding A-/B-lines	Trait-specific A-/B-lines	Restorers	Varieties[1]	Total
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 cytoplasm.

Rao et al. 1995) helped enhanced utilization of these genetic resources. The proposed formation of 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 genetic resources.

Though several resistant germplasm sources were used to develop established grain mold and shoot fly resistant A-/B-lines, only a few germplasm lines have contributed to final products (Table 3.33). However, in the newly developed restorer and varieties and grain mold and shoot fly resistant B-lines that are in advanced stages of conversion into A-lines (on A_1 and A_2), higher proportion of the germplasm lines have contributed to the final products (Table 3.34).

Strategic research

Apart from diversification of hybrid parents for grain and forage yields and resistance to major biotic and abiotic yield constraints and of late, sweet-stalk

Table 3.32. Summary of the sorghum germplasm/breeding lines that contributed **to development of new 85 race-specific A-/B-lines at ICRISAT, Patancheru, India** since 2000.

	Number of A-/B-lines		Number of germplasm/breeding lines contributed to the products	
Category	A_1	A_2	A_1	A_2
New bold grain (*durra*)	23	28	8	18
Caudatum	6	4	5	5
Guinea	10	5	20	8
Feterita	0	9	0	8
Total	39	46	33	39

Table 3.33. Germplasm diversity captured in established and designated grain mold **and shoot fly resistant A-/B-lines developed at ICRISAT, Patancheru, India.**

Trait	Number of lines	Number of germplasm lines initially involved	Number 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 3.34. 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 at ICRISAT, Patancheru, India.

Trait	Number of lines	Number of germplasm lines initially involved	Number 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

trait, strategic issues such as 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 component trait (leaf trichomes), and relationship between parental and hybrid performances for resistance to shoot fly and grain mold and juice yield (in sweet-stalk sorghum) and forage yields were addressed at ICRISAT-Patancheru. The strategic research information would help enhance the efficiency and the pace of sorghum improvement programs.

Parental line criteria

The requirements of seed parents are different from those of restorer parents, especially when hybrids are based on CMS systems. Seed parents should have a number of particular per se requirements. The seed parents should have stable and perfect male sterility, even under high temperatures typical of SAT. Stable A-lines could be selected by evaluating the lines in environments where the day temperatures exceed 40°C during flowering. The other requirements of seed parents are desired maturity and plant height, high yield, non-tillering and good panicle exertion, seed set, grain size and seedling vigor. Restorer parents should perfectly restore the fertility in the hybrids even under low temperatures, typically experienced during postrainy season in India. Efficient and stable restorers could be selected by evaluating their testcrosses or hybrids under conditions where night temperatures are below 10°C during the flowering phase. In order to ensure enhanced outcrossing during hybrid seed production, restorer should be taller than seed parents with profuse and prolonged pollen grain production ability. Restorer parents must also possess many of the other traits required for seed parents that are heritable in hybrids (Reddy 1997). Restorers for the development of hybrids for postrainy season adaptation should completely restore male fertility in the hybrids in severe cold temperatures normally experienced during postrainy season.

Grain color criteria in hybrid parents vary with geographical location for which hybrids are targeted. While breeding hybrid parents for developing hybrids for India, white grains are preferred. On the other hand, both white and colored (red and/or brown) grain type hybrid parents are preferred in Africa. While white grain hybrid parents are used for developing hybrids for food use both in India and Africa, red/brown grain hybrid parents are used for developing hybrids (colored grain) for use in brewing industry in Africa. It is advantageous to incorporate stay-green trait in seed parents for developing hybrids for postrainy season adaptation in India to confer tolerance to terminal drought, typically experienced in postrainy season. Apart from these, they must have several other yield-stabilizing traits such as disease, insect pest and lodging resistance. Leaf blight resistance is important in ESA and anthracnose resistance is important in WCA and northern India (in forage sorghum). While stem borer resistance and *Striga* resistance are important throughout Africa, head bug resistance is important in WCA and eastern Africa and shoot fly resistance is important in India.

Germplasm base

High genetic variability for the specific traits characteristic of seed parents and restorer parents are the prerequisites for selection and development of elite hybrid parents. At ICRISAT-Patancheru, *caudatum* race has been extensively exploited to develop high-yielding A-lines as well as R-lines. The available heterotic seed parent, 296B, bred by the Indian national programs, though based on *durra* race has several seed production problems such as sensitivity to low temperature leading to poor seed set and chaffy ear heads, and susceptibility to most insect pests and diseases. While the use of the *durra* race directly introduces high sensitivity to low temperatures, the direct use of *guinea* race in developing hybrid parents, produces hybrids with small grains with clasped glumes, an undesirable trait. ICRISAT breeders have therefore introgressed *durra* (bold grain lines), *feterita* and *guinea* (grain mold resistant restorers) traits into high-yielding *caudatum* background to enhance the yield potential of elite sorghum B-lines. Using this strategy, several A-lines were developed following race-specific and trait-specific breeding approach. The germplasm lines selected for specific traits such as long panicles and large grains are also being introgressed to diversify the nuclear genetic base of A-lines.

The *caudatum*-based restorers developed earlier at ICRISAT-Patancheru were exploited fully by several seed companies and public sector institutions for over a decade, suggesting the need to diversify restorers to further enhance yield levels in the hybrids. An evaluation of hybrids developed by crossing five representative lines from each of the landraces (*caudatum*, *durra*, *guinea*, *bicolor* and *kafir*) as pollinators to six common A-lines (A_1) bred at ICRISAT-Patancheru in postrainy season 1991 and rainy season 1992, showed greater contribution of *guinea* and *caudatum* R-lines to grain yield and 1000-seed mass in hybrids across the seasons (Table 3.35). The *kafir* and *guinea* restorer-

Table 3.35. Heterosis[1] of hybrids developed from pollinators belonging to different races of sorghum evaluated during postrainy season (PR) 1991 and rainy season (R) 1992 at ICRSAT, Patancheru, India.

	Landrace restorers									
	Kafir		*Caudatum*		*Durra*		*Bicolor*		*Guinea*	
Character	PR	R	PR	R	PR	R	PR	R	PR	R
Time to 50% flower (days)	−6	−3	0	−3	0	11	4	−2	−6	−5
Grain yield (t ha^{-1})	−57	25	21	49	−100	15	6	40	37	22
1000-seed mass (g)	7	16	1	11	−7	19	16	24	21	21
Threshability score[3]	NA[2]	−12	NA	−24	NA	−29	NA	−7	NA	7

1. Average superiority of hybrids over restorer lines.
2. NA = Data not available.
3. Measured on a 1–5 scale, where 1 = grain free from glumes upon threshing and 5 = >50% of the grain with glumes.
Source: Reddy and Prasada Rao (1993).

based hybrids showed heterosis for earliness in both the seasons, while those based on *durra* race exhibited heterosis for earliness only in postrainy season. Hence, CMS-based seed parents and restorers need to be diversified by creating separate gene pools through crossing between *guinea*- and *durra*-based B-lines and between *caudatum*- and *guinea/durra*-based R-lines for various selected traits for both the seasons (in India). The race *bicolor* may also be introgressed with the available high-yielding B- and R-lines with *caudatum/durra* background, particularly for rainy season adaptation. However, banking on the limited variability by crossing among already developed B-lines leads to narrow genetic base of the resulting hybrids, although better parents could be quickly developed through this approach. However, for sustained and continuous improvement, fresh variability should be created by introgressing new sources of desired genes from landraces into elite agronomic background.

Mean performance, combining ability and heterosis

Grain yield

Literature is abundant to show that heterosis is greater in present-day hybrids than those developed earlier. From a trial to compare the yields of old and new sorghum hybrids in Texas, USA, Miller and Kebede (1981) found that at least 40% of the yield increase had been realized in 30 years. This is largely attributed to improvement of the parents for per se performance. Doggett (1988) claimed that about one-half of the yield increase could be ascribed to better parents. This is not surprising because improved hybrid performance comes primarily from additive gene action (Kambal and Webster 1965, Miller and Kebede 1981). Hence, early generation (in F_4 or F_5) testing for combining ability to capitalize additive gene action with a certain level of per se eliteness for yield and yield constraints together with desired grain qualities is the key to breeding hybrid parents. Early generation GCA tests are not intended to definitely identify the best general combiners (this cannot be done without extensive testing), but to increase the probability of retaining them for detection in later tests, as GCA is primarily a function of additive gene action, which can be fixed through selection and inbreeding. Opinion is divided about when to begin testing for combining ability in seed parent development; before, during or after seed parent development. Given an uncertainty of maintainer/restorer reaction on a given CMS system, it is better to test for combining ability after confirming maintainer reaction of the test plants.

Parental per se performance and GCA in sorghum is strongly correlated with hybrid performance (Quinby and Karper 1946, Murthy 1992, Bhavsar and Borikar 2002). This is also evident from the past experience of Indian NARS in hybrid cultivar development. For example, after the release of first four hybrids (CSH 1 to CSH 4), development of superior (in per se performance) restorer parents (CSV 4, CSV 5 and PD 3-1-11) and seed parents (2077A, 2219A, 36A and 296A) have brought significant yield improvement in the subsequently released hybrids (CSH 5, CSH 6 and CSH 9) for rainy season as well as hybrids (CSH 7 and CSH 8R) for postrainy season adaptation. The improvement in CSH 9 over CSH 5 or CSH 6 could be attributed mainly to the superiority of its seed parent 296A, since CS 3541 is a common restorer parent (Rana et al. 1985). New inbreds tend to be more vigorous than their predecessors. In particular, they are better equipped with defensive traits such as disease and insect resistance, and tolerance to abiotic stresses such as heat and drought or mineral deficiencies and toxicities (Doggett 1988). It seems likely, therefore that increased yield in grain sorghum hybrids gradually will depend less on heterosis for grain yield per se and more on complementation of defensive traits from parents that confer yield stability. Therefore, improving the parental GCA and/or per se performance for yield and yield components, together with desired grain quality traits are the keys to breeding hybrid parents and therefore hybrids.

Other traits

Grain mold in rainy season and shoot fly in both rainy and postrainy seasons are economically important biotic yield constraints in sorghum in Asia. Attempts to breed for resistance to these biotic yield constraints in the past have met with partial success owing to the low levels of resistance in the resistant sources coupled with disease and insect pressure-dependent resistance. Nevertheless, development of hybrids with at least moderate levels of resistance to these biotic constraints would be cost-effective and eco-friendly approach to manage them and adoption of resistant hybrids are expected to substantially increase the commercial yield levels considering lower grain mold infection and shoot fly infestation pressures in farmers' fields.

Responses to shoot fly infestation. To delineate method(s) of producing shoot fly resistant hybrids, 17 A-lines (female lines) (14 shoot fly resistant A-lines and 3 shoot fly susceptible A-lines) were crossed with 13 R-lines (male lines) (9 resistant and 4 susceptible R-lines) to obtain 221 hybrids in 2002/03 postrainy season. The deadhearts formation in the hybrids was taken as criterion to classify them as resistant/susceptible. The male and female parents with DH% ≤50 based on previous several evaluations were classified as resistant (R) and those with DH% >50 were classified as susceptible (S). All the 221 hybrids along with 17 female parents, 13 male parents, one resistant control (IS 18551) and one susceptible control (DJ 6514) were evaluated in replicated trial for shoot fly resistance at ICRISAT-Patancheru during rainy season 2004. The hybrids with DH% ≤50 were classified as resistant (R) and those with DH% >50 were classified as susceptible (S).

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. Based on the number of hybrids in different categories of the crosses and the number of hybrids with DH% ≤50, the probabilities of realizing shoot fly resistant hybrids were estimated. 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 3.36). Thus, it is clear from the results that the shoot fly resistance in either both parents or at least in seed parents is required to realize hybrids with reasonably higher levels of shoot fly resistance. Hence, it is essential to improve particularly seed parents for shoot fly resistance. It is worthwhile to improve both the hybrid parents for shoot fly resistance in separate programs, if resources and facilities are not limited.

Table 3.36. Distribution of shoot fly resistant (SFR) A_1 CMS system-based sorghum hybrids (in different categories of crosses) during rainy season 2004 at ICRISAT, Patancheru, India.

Category of the crosses[1]	No. of hybrids	Mean DH%	No. of hybrids with DH% ≤50	Probability that the SFR hybrids with DH% ≤50 belong 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% (percentage of deadhearts) ≤50 were classified as resistant (R); female and male parents with DH% >50 were classified as susceptible (S).

Responses to grain mold infection. In an attempt to delineate the method(s) of developing grain mold resistant hybrids, 168 hybrids were synthesized by crossing eight A-lines (female parents) with 21 R-lines (male parents) in postrainy season 2003/04. These 168 hybrids along with four grain mold resistant controls (IS 25017, IS 20, IS 14384 and PVK 801) and one grain mold susceptible control (Bulk Y) were screened during rainy season 2004 for GMR at ICRISAT-Patancheru. The hybrids, their parents and the controls were scored for PGM and TGM infection severity using 1–9 scale (1 = no mold, and 9 = >75% grain molded). Based on responses to grain mold infection, female and male parents with mean PGM and TGM scores ≤3 were classified as resistant (R) and those with TGM and PGM scores >3 were classified as susceptible (S). The hybrids were classified into R × R, R × S, S × R and S × S categories based on the grain mold infection response criterion of the parents. Though there were no significant differences between hybrids belonging to different categories of crosses (R × R, R × S, S × R and S × S) for mean TGM and PGM scores, hybrids involving at least one of the parents with GMR were slightly more resistant than those involving both the parents with susceptible reaction.

Based on the number of hybrids in different categories of the crosses and the number of hybrids with PGM and TGM scores ≤3, the probabilities of realizing grain mold resistant hybrids were estimated. The estimates indicated that the probability of producing grain mold resistant hybrids is higher from R × S category followed by S × R category of crosses compared to that from other categories (R × R and S × S) (Table 3.37). The diverse and complementary individual mechanisms, each with small effects, may be acting synergistically in hybrids leading to higher levels of resistance in S × R or R × S categories of hybrids compared to other categories.

It was shown in earlier work that different GMR mechanisms operating in hybrid parents complement resulting 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 females were crossed with hard white-grained males (Reddy et al. 2000) (Table 3.38). Thus, it may be worthwhile to breed both the hybrid parents for GMR in separate programs to realize hybrids with reasonably higher levels of GMR and with reasonable certainty.

Fodder yield. Considering the advantages of hybrids over the varieties with respect to biomass production potential and earliness, an experiment was planned to delineate the relationship between hybrid parents and the hybrids for green forage yield. As such, 144 forage hybrids produced by crossing nine A-lines (female parents) with 16 R-lines (male parents) with varying levels of stalk sweetness as measured by Brix value and green fodder yields were evaluated for green fodder yield at ICRISAT-Patancheru during rainy season 2004.

The mean green fodder yield of the female and male parents was set as a criterion for classifying them as high and low fodder yielders. Those female and male parents with green fodder yield of above and below the mean parental green fodder yields were classified as high (H) and low (L), respectively. Based on this classification criterion, the hybrid groups were classified as H × H, H × L, L × H and L × L and the performance of hybrids belonging to different categories were compared for green fodder yield. The results indicated that the hybrids belonging to H × H followed by L × H categories produced higher green fodder yield than those belonging to other two categories (H × L and L × L). Further, the probability that the hybrid belongs to L × H category is higher followed by H × H category of crosses compared to that from other

Table 3.37. Distribution of grain mold resistant A_1 CMS system-based sorghum hybrids in different categories of crosses during rainy season 2004 at ICRISAT, Patancheru, India.

Category of the crosses[1]	No. of hybrids	Mean PGM score[2]	Mean TGM score[2]	No. of hybrids with TGM and PGM scores ≤3.0	Probability that the resistant hybrids with TGM and PGM scores ≤3.0 belong to the category
R × R	9	3.89	3.00	3	0.33
R × S	54	3.40	3.27	28	0.52
S × R	15	3.32	3.17	7	0.47
S × S	90	3.93	5.75	7	0.08
Total	168	–	–	45	

1. Female and male parents with PGM (panicle grain mold) and TGM (threshed grain mold) severity scores ≤3.0 in the same trial were classified as resistant (R); female and male parents with PGM and TGM severity scores >3.0 in the same trial were classified as susceptible (S).
2. Measured on a 1–9 scale, where 1 = no mold and 9 = >75% grain molded.

Table 3.38. Selected red-grained A_1 CMS system-based sorghum hybrids and their parents for grain mold resistance and its components at ICRISAT, Patancheru, India.

Pedigree	Time to 50% flower (days)	Grain mold resistance[1]	Grain hardness[2] (kg)	Flavon-4-ols ($A550\ g^{-1}$)
Hybrids				
ICSH 91200	67	2.0	5.2	4.7
ICSH 91201	67	2.0	5.2	3.3
ICSH 91202	65	2.0	4.6	7.5
Parents				
BTx 2754	69	3.0	2.8	6.2
BTx 2755	68	4.0	2.7	5.2
ICSR 3	70	4.0	6.2	0.1
ICSR 41	72	3.0	4.8	0.2
ICSR 111	70	4.0	5.1	0.1
Control				
ICSH 153 (CSH 11)	66	4.0	3.4	0.2
SE±	0.6	0.002	0.28	0.46
Mean	67	3.3	4.1	3.5
CV (%)	3	12	12	13

1. Based on threshed grain mold score measured on a 1–5 scale, where 1 = no mold and 5 = >50% of the surface of the grain molded.
2. Pressure (kg) required to break the grain.
Source: Reddy et al. (2000).

Table 3.39. Relationship between A_1 CMS system-based sorghum hybrid parents and hybrids for forage production potential at ICRISAT, Patancheru, India.

Category[1]	No. of hybrids	Average green fodder yield (t ha^{-1})	No. of hybrids with green fodder yield above mean (45 t ha^{-1})	Conditional probability that the hybrids belong to the category
H × H	24	54.37	21	0.88
H × L	24	41.72	5	0.21
L × H	48	50.68	37	0.77
L × L	48	37.33	4	0.08
Total	144	–	67	–

1. Individual female parents with green fodder yield more than the mean green fodder yield (25 t ha^{-1}) of female parents were classified as high (H) and others as low (L); individual male parents with green fodder yield more than the mean green fodder yield (40 t ha^{-1}) of male parents were classified as high (H) and others as low (L).

categories (H × L and L × L) (Table 3.39). Thus, results suggested that it might be sufficient to breed male parents for high green fodder productivity potential to maximize the chances of developing productive forage hybrids.

Sweet-stalk yield. To meet the increased demand for ethanol, following Government of India's policy decision to blend 5% ethanol in petrol and diesel, distilleries in India have shown greater interest in using sweet-stalk sorghum as an alternative to sugarcane (*Saccharum officinarum*) molasses for ethanol production considering its lower water and inputs requirement besides short duration. Given the higher biomass production potential and photo-insensitiveness coupled with earliness of the hybrids over the varieties (Fig. 3.3), an experiment was planned to delineate the method(s) of producing hybrids with high biomass potential and sugar-rich stalks. As such, 144 sweet-stalk hybrids produced by crossing nine A-lines (female parents) with 16 R-lines (male parents) were evaluated at ICRISAT-Patancheru, and at Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri during rainy season 2004.

Based on the data recorded at ICRISAT-Patancheru, and at MPKV, Rahuri, the female parents with Brix value above 17% at ICRISAT-Patancheru and above 19% at Rahuri were classified as high (H) and those with below 17% Brix value at ICRISAT-Patancheru and below 19% at Rahuri were classified as low (L). Similarly, the male parents with Brix value above 19% and below 19% at ICRISAT-Patancheru and Rahuri were classified as high (H) and low (L), respectively. Based on these classification criteria, the hybrid groups were classified as H × H, H × L, L × H and L × L and the performance of hybrids

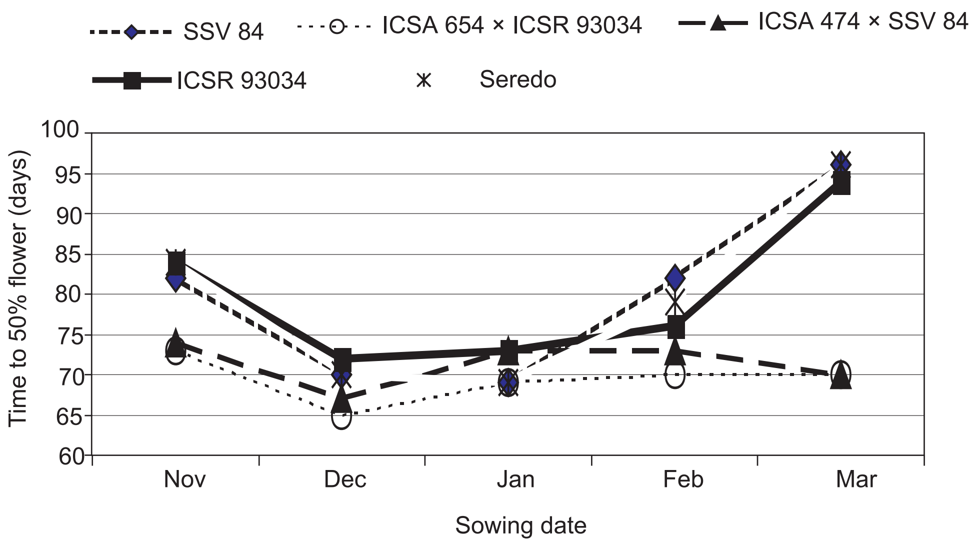

Figure 3.3. Time to flower of sweet sorghum hybrids vs varieties as influenced by different dates of sowing.

belonging to different categories were compared for Brix, millable cane yield, juice yields and other related traits.

The results from ICRISAT-Patancheru data revealed that the hybrids belonging to H × H followed by L × H categories produced higher millable cane yield and juice yield with higher Brix values than those belonging to other two categories (H × L and L × L). The results from MPKV, Rahuri data revealed that hybrids belonging to L × H followed by H × H categories produced higher juice yield with higher Brix values than those belonging to other categories of hybrids (H × L and L × L).

Based on the number of hybrids falling into different categories of the crosses and the number of hybrids with Brix value more than 17% at ICRISAT-Patancheru and 19% at MPKV, Rahuri, the probabilities of realizing hybrids with high Brix values in each category of crosses were estimated. The estimates indicated that the probability of producing hybrids with high Brix values is higher from H × H category followed by L × H category of crosses compared to that from other categories (H × L and L × L) (Table 3.40). Thus, results from the two locations suggested that it is advantageous to breed both the hybrid parents for sweet-stalk trait to develop sweet-stalk hybrids with high millable cane and juice yielding abilities.

Table 3.40. Distribution of sweet-stalk A_1 CMS system-based sorghum hybrids in different categories of crosses at ICRISAT, Patancheru and MPKV, Rahuri, India.

Category of the crosses[1]	No. of hybrids	ICRISAT, Patancheru: No. of hybrids with Brix ≥17%	ICRISAT, Patancheru: Probability that the hybrids with Brix ≥17% belong to the category	MPKV, Rahuri: No. of hybrids with Brix ≥19%	MPKV, Rahuri: Probability that the hybrids with Brix ≥19% belong to the category
H × H	40	23	0.58	13	0.33
H × L	40	2	0.05	10	0.25
L × H	32	7	0.22	10	0.31
L × L	32	0	0.00	9	0.28
Total	144	32	1.00	42	1.00

1. At ICRISAT-Patancheru, female parents with Brix value ≥17% and male parents with Brix value ≥19% at maturity in the same trial were classified as high (H) and female parents with Brix value <17% and male parents with Brix value <19% at maturity in the same trial were classified as low (L). At Rahuri, female and male parents with Brix value ≥19% at maturity in the same trial were classified as high (H) and female and male parents with Brix value <19% at maturity in the same trial were classified as low (L).

Parental diversity and heterosis

It has been established that divergent parents give rise to higher frequency of heterotic hybrids with higher heterosis and these heterotic hybrids generally throw a broad spectrum of variability in segregating generations in sorghum. Shinde et al. (1983) studied heterosis in postrainy season sorghum and reported that crosses between local parents exhibited maximum heterosis (41%) as compared to improved × improved varieties (13%) that might be due to greater genetic diversity present in the local strains by virtue of differential natural selection acting on them in different regions. Temperate × tropical crosses have played an important role in the past for the development of superior restorer parents (CSV 4, CSV 5 and PD 3-1-11) and seed parents (2077A, 2219A, 36A and 296A) of hybrids (CSH 5, CSH 6 and CSH 9) for rainy season as well as hybrids (CSH 7 and CSH 8R) for postrainy season adaptation. Greater yield heterosis was observed in derivative × tropical (African) varietal crosses due to diversity of genes (Rana et al. 1985). Rana and Murty (1978) have also reported that increase in number of seeds per panicle branch in short compact headed varieties (tropical) and increase in the panicle branches in the long panicle type (temperate) by introgression of genes from African germplasm result in yield heterosis. At ICRISAT-Patancheru, F_1s made on *caudatum*-based seed parents with *durra*-based pollinators resulted in high heterosis under postrainy season condition.

Season specificity of shoot fly resistance component

Damage due to shoot fly infestation is one of the major yield constraints both in rainy season and postrainy seasons. Breeding hybrid parents for shoot fly resistance is highly demanding in terms of financial and human resources requirement. Therefore, it was hypothesized that breeding hybrid parents for shoot fly resistance per se and/or its component traits for rainy season adaptation would be useful for postrainy season adaptation as well. However, the research data do not support this hypothesis. Shoot fly resistant A-/B-lines bred for season specific adaptation for shoot fly resistance were evaluated in replicated trials in rainy and postrainy seasons at ICRISAT-Patancheru for trichome density, one of the most important component traits of shoot fly resistance. The results revealed 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 41). Reverse trend was observed in case of shoot fly resistant B-lines bred for

Table 3.41. Season specificity for shoot fly resistance in maintainer lines (A_1) of sorghum in 1996 at ICRISAT, Patancheru, India.

	Trichome density mm^{-2}	
Line[1]	Rainy season	Postrainy season
SFR B-lines bred for rainy season adaptation		
SPSFR 94002B	51.7	16.5
SPSFR 94003B	46.3	43.0
SPSFR 94001B	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 adaptation		
SPSFPR 94001B	34.2	116.4
SPSFPR 94002B	43.8	78.7
SPSFPR 94005B	20.6	29.5
SPSFPR 94007B	20.0	0.0
Mean	32.9	74.9
CD (*P* = 0.05)	9.01	9.22

1. SFR = Shoot fly resistant.

Source: Jayanthi (1997).

postrainy season adaptation. Similar results were observed in hybrids based on the A-lines bred for a particular seasonal adaptation (Table 3.42). 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.

Table 3.42. Season specificity expression of A_1 CMS system-based sorghum hybrids for trichome density during 1996 at ICRISAT, Patancheru, India.

	Trichome density mm^{-2}	
Hybrids[1]	Rainy season	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. SFR = Shoot fly resistant.
Source: Jayanthi (1997).

Single-cross hybrids vs three-way-cross forage hybrids

Most of the forage sorghum hybrids marketed by private sector seed companies in India are three-way-cross hybrids on the premise that hybrid seed yield on single-cross male-sterile line would be higher than on inbred A-lines of single-cross hybrids during hybrid seed production. However, research at ICRISAT-Patancheru has shown that grain yield on inbred A-line would be as high as on male-sterile single-cross hybrid of three-way hybrid combination during hybrid seed production by improving per se performance of A-lines. The exploitation of single-cross hybrids by improving per se performance of seed parents would greatly economize hybrid seed production by avoiding one step in producing single-cross male-sterile for use as seed parent.

Postrainy season hybrids development approach

Landrace pollinators-based hybrids

The experience at ICRISAT-Patancheru and national programs prompted breeders at ICRISAT in late 1980s to conceptualize landrace pollinator-based approach to develop hybrids for postrainy season adaptation. The landrace pollinator-based hybrids referred to in this review are those derived by crossing landraces, or direct selections from landraces, or improved postrainy season adapted landrace varieties as pollinators with male-sterile lines, where many of the desirable attributes of landraces are inherited favorably in their hybrids. This can also be seen readily in the similarities between CSH 12R and its male parent, MR 148-138-1-1-2, which closely resembles the improved landrace M 35-1. Postrainy season adapted landraces or improved landraces (eg, M 35-1) have many of the desirable attributes for specific adaptation in addition to moderate levels of shoot fly resistance and desirable grain quality traits. However, they lack lodging resistance and have moderate yielding ability (Reddy et al. 1983). Since genes for resistance to shoot fly are additive and recessive, A-lines with resistance to shoot fly are needed to produce resistant landrace-based hybrids. Therefore, it is hypothesized and demonstrated that the landrace-based hybrid approach, particularly when hybrids are made with shoot fly resistant A-lines, may yield hybrids that are readily acceptable by farmers for almost all attributes. For this approach to work, high levels of fertility restoration in landrace sorghums and high heterosis for grain yield are essential. It was demonstrated that significant variability for restoration is available in all postrainy season adapted landraces and that heterosis is high (more than 20%) if there is diversity among parents like *caudatum*-based A-lines vs *durra*-based landrace restorers. This work gave impetus to the private sector to develop and market hybrids with postrainy season adaptation in India.

Single-cross male-sterile lines

Many of the Maldandi varieties are maintainers on A_4 (Maldandi)-based CMS, which could be readily converted to A-lines to widen the scope for exploitation of heterosis to enhance productivity. Unfortunately, such A-lines could not be exploited as A_4 (Maldandi)-based CMS lines support poor restoration. Therefore, it is hypothesized that single-cross male-sterile of such CMS system may support wider restoration which enhances the opportunities for exploitation of heterosis. Accordingly, 24 three-way-cross F_1s made at ICRISAT-Patancheru with single-crosses of A_4 (Maldandi) A-line in CSV 4 nuclear genetic background and 49 three-way-cross F_1s made with single-crosses of CSV 4 A_4 (VZM) A-lines were evaluated during rainy season 2003. Of the 73 hybrids, 13 (nearly 18%) were found to be completely fertile. The Maldandi cytoplasm with CSV 4 nuclear background supported higher (50%) restoration than VZM cytoplasm (2%) with same nuclear background. On the other hand, restoration frequency in single-crosses when A_4-Maldandi/VZM A-lines were directly used as parents is extremely low (<1.0%). These results indicate that restorer frequency on A_4 (Maldandi)-based CMS lines could be increased by extensive use of Maldandi sources for diversification of A_4 (Maldandi)-based A-lines for use in the development of hybrids for postrainy season adaptation. Simultaneously, popular postrainy season adapted landraces could be screened and selected for low temperature tolerance to enhance male fertility restoration on A_4 (Maldandi)-based CMS lines.

Role of nuclear genome on fertility restoration

Male fertility restoration by landraces is poorer on *durra*-derived A_1 CMS lines than on *caudatum*-derived A_2 CMS lines. When both A_1 and A_2 CMS lines were based on *caudatum*, fertility restoration was higher on A_1 than A_2. Evaluation of testcrosses at ICRISAT-Patancheru between a set of landraces and five *caudatum*- and four *durra*-derived A_1 CMS lines showed lower levels of fertility restoration on *durra*-derived A_1 CMS lines than *caudatum*-derived A_1 CMS lines in postrainy season, establishing the role of nuclear genetic base (for races) on male fertility restoration of a particular CMS system. This finding has a bearing on developing CMS lines involving *caudatum*-based germplasm lines adapted to postrainy season and testing for fertility restoration in hybrids.

Hybrids development

Ultimate worth of the hybrid parents would be known only after making hybrid combinations and testing them under target regions over the location and years for critical adaptation traits and resistance to major insect pests and diseases. The traits such as early maturity, grain yield, grain quality-evident traits (such as white, medium bold and 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 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. The development and dissemination of a method of producing heterotic landrace pollinator-based hybrids for postrainy season adaptation provided the impetus for the private sector to develop and market postrainy season adapted sorghum hybrids for the first time in India. Early maturity and grain quality-evident traits such as white, bold 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 are the important traits selection criteria, while developing and testing of hybrids for postrainy season adaptation in India.

All the hybrids developed and released/marketed so far in both 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, it is expected that there would be greater use of A_2 CMS system in future. A_4 (Maldandi) is the next priority CMS system for utilization (owing to its relatively higher levels of shoot fly resistance), once sufficient number of restorers is 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 1980–95. 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 (refer Table 3.1).

Considering increasing presence of private seed companies and their enhanced research and development capabilities, especially in large companies in India coupled with the emergence of 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 private sector to develop region-specific hybrids. As indicated earlier, several improved hybrid parents developed at ICRISAT-Patancheru were supplied to NARS in different regions (Table 3.43).

Table 3.43. Details of sorghum seed samples of A_1 CMS system-based hybrid parents and hybrids supplied from ICRISAT, Patancheru, India to various regions during 1986–2004.

	On request					For testing in trials/ nurseries	
Region	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 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 hybrids: Zimbabwe (ZWSH1), Zambia (MMSH413, MMSH375, MMSH1257 and WSH287) and Botswana (BSH1). Using materials from Texas A&M, USA and parents from ICRISAT-Patancheru, the national program in Zambia developed and released a forage sorghum hybrid, FSH22 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 3.44).

Table 3.44. Comparative performance of A_1 CMS system-based sorghum hybrids and varieties for grain yield (t ha^{-1}) in SADC region over the years 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 >9 t ha^{-1} (while the pioneer hybrids were the next best) in 2004. All these studies clearly showed that hybrids are the target materials for the farmers. In eastern and central Africa, during 1980s, several hybrids (A_1) were tested at Wad Medani, Sudan, and 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 WCA, ICRISAT program in Nigeria also developed A_1 CMS system-based hybrids based on hybrid parents bred at ICRISAT-Patancheru during 1989–96 and the selected hybrids were included in regional testing programs. In both southern and eastern and central Africa 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 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 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 West African collaborative regional hybrid trials in 2004 using the newly developed *guinea*-based A-lines. The best hybrids significantly outyielded all the well-adapted check varieties in each location environment. 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 3.45).

Table 3.45. Mean grain yield and mean grain yield superiority of the top 20% highest yielding sorghum hybrids relative to the mean yield of three well-adapted checks in four locations in Western and Central Africa in 2004.

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
Samanko-ICRISAT, Mali	12 June	22	3.1	2.3	38

1. Mean of best checks CSM335, CSM388 and Seguetana.

Table 3.46. Region-wise released A_1 CMS system-based sorghum hybrids using hybrid parents or their derivatives bred at ICRISAT, Patancheru, India.

Region	No. 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

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 3.46). 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 B-line bred at ICRISAT-Patancheru and R-lines bred by the Indian program and released by CVRC for commercial cultivation in India. The private sector seed companies are the major beneficiaries of ICRISAT-bred hybrid parents (especially A-lines) in India. Over 54 hybrids based on hybrid parents or their derivatives bred at ICRISAT-Patancheru have been developed and marketed in India. Apart from India, China has derived substantial benefits from hybrid parents bred at ICRISAT-Patancheru 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.

However, their widespread adoption depends on the farmer/producer acceptance and the availability of hybrid seed. Often it has been observed that lack of hybrid seed availability in 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 America, it is not so in African countries (barring Egypt and South Africa). Poor seed systems of NARS coupled with limited presence of private seed companies have been attributed to failure of hybrid technology in Africa.

New frontiers

Wide hybridization

Resistance to shoot fly needs to be transferred to both the hybrid parents in high-yielding background to develop resistant hybrids. However, the progress from conventional breeding is slow as the resistance level in the cultivated types (eg, IS 18551; 2n=20) is low and depends on insect density. The wild sorghums – *S. australiense* (2n=10), *S. dimidiatum* (2n=10), *S laxiflorum* (2n=10) and *S. angustum* (2n=10) – are known to have high levels of resistance, even under no-choice conditions. They are, however, not easily crossable with the cultivated types. The past experience with a rare success of crossing involving an accession belonging to *S. australiense* with a cultivated type was not encouraging as the resultant segregants were not only agronomically poor, but also lacked resistance, not even the levels observed in IS 18551, the most commonly used shoot fly resistant source at ICRISAT. However, it will be necessary to exploit the wild relatives of sorghum for shoot fly resistance again, perhaps involving a different set of cultivated genotypes in crosses with the newly identified wild accessions.

Genetic transformation

Stem borer is an important constraint in Africa. Resistance to stem borer is also important in sweet-stalk sorghum cultivars, as stalks are the economic product. Resistance levels in the cultivated types are not high. So, deployment of *Bt* genes through genetic transformation is expected to provide the desired outputs. The work is in progress and it should be taken to a logical conclusion including transfer of these genes in diverse hybrid parents by conventional breeding.

Molecular breeding

Grain mold is a major biotic yield constraint in rainy season, and many mechanisms are known to contribute to resistance. Source lines for various mechanisms are identified. Therefore, efforts should be made to identify suitable molecular markers to enable pyramiding the genes associated with various mechanisms in high-yielding hybrid parents. Head bug damage increases grain mold severity. It is a serious yield constraint in West Africa and in India in rainy season, and therefore, it might be useful to target selection for resistance to both grain mold and head bug to develop grain mold resistant cultivars.

Sweet sorghums

Sweet sorghums have potential to occupy important position in NARS economy. ICRISAT should embark on a crash program to improve hybrid parents, in particular seed parents and hybrids and develop a program of marketing the hybrids through an innovative system involving a limited number of distilleries and seed companies.

Resistance to abiotic stresses and micronutrients deficiency

Large sections of people in Africa and India (particularly, pregnant women and children), who depend on sorghum-based diets are affected by malnutrition due to micronutrients deficiency. Vast areas particularly irrigated soils in South Asia and West Asia and Northern Africa (WANA) are becoming increasingly saline. Similarly, there are vast stretches of grassland plains in Colombia, Venezuela and Brazil, which have high levels of soil acidity. Initial work on grain micronutrients (Zn and Fe) and β-carotene and tolerance to soil salinity and acidity showed significant genetic variability for all these traits in sorghum. Therefore, there is a need to initiate full-fledged genetic enhancement for these traits and develop proposals for the identification and application of molecular markers in developing improved hybrid parents.

Partnerships

Though ICRISAT's research centers are located at Patancheru in Asia and Bulawayo, Nairobi, Bamako and Niamey in Africa, and there are several special programs at El Baton, Mexico and Cali, Colombia in Central and South Americas, it is difficult to serve several diverse areas that need specific agro-ecological zonal adaptations with varying production and cropping systems. Research collaboration and partnerships among and with national, regional and international programs are the best means of meeting the diverse needs. Such research partnerships are also crucial for technology and information exchange, to avoid duplication of efforts and bring together comparative advantages to address and solve priority production constraints at relatively low cost. Recognizing the power of partnerships, ICRISAT has been proactive in developing partnership with public sector institutions, private sector organizations, non-governmental organizations (NGOs) and other stakeholders (Fig. 3.4). Partnerships could be formal and informal and involve scientists, extension staff and farmers in public institutions, private sector organizations and NGOs.

Figure 3.4. Partnerships in India: an ICRISAT-public sector grain sorghum hybrid (left)*; and an ICRISAT-private sector grain sorghum hybrid* (right).

Partnership with public sector

ICRISAT was able to develop and maintain stable, dynamic and broad-based partnerships among different stakeholders. The partnership mode followed at ICRISAT for research and technology exchange was a combination of both formal and informal links depending on the need and situation. ICRISAT has collaboration and partnership with:

- Nodal or apex agricultural research institutions or councils such as ICAR in India.
- Regional bodies or forums such as SADC.
- Regional networks such as Western and Central Africa Sorghum Research Network (WCASRN), Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA) and Cereals and Legumes Asia Network (CLAN).
- Advanced research institutions such as Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD) (France), INTSORMIL and International Center for Biosaline Agriculture (ICBA) and National Institute of Nutrition (NIN) in India.
- CIAT.
- Bilateral or multilateral ties with NARS.

ICRISAT has tie-ups in the following research areas:

- ICAR: Genetic resources, collection, evaluation, quarantine and conservation – evaluation of sorghum germplasm for nutritional quality and genetic enhancement of sorghum with special reference to basic and strategic research inputs for the ongoing national program through formal and inter-institutional projects.
- SADC: SMIP/ICRISAT has a formal regional collaboration with several southern African countries to improve sorghum for the region.
- WCASRN and CLAN: Breeding nurseries at Cinzana, Longorola, Farako Ba, Samaru, Minjibar, N'Dali and Maradi in WCA through WCASRN; regional and national trials conducted by various NARS in Asia; and exchange of breeding materials in various international and regional nurseries/trials through CLAN. The objective is to identify materials for local adaptation.
- CIRAD and INTSORMIL: Collaborative agreement with ICRISAT in Mali with the goal of improving sorghum for the Sudano-Guinean zone. CIRAD scientists based at Montpellier, France are engaged in basic research on the molecular basis of head bug resistance and the role of temperature/photoperiod in adaptation and grain quality. All ICRISAT's regional programs

collaborate and exchange seed and information with INTSORMIL and advanced research institutions in developed countries.

- CIAT: To identify hybrid parents and hybrids developed at ICRISAT-Patancheru for soil acidity tolerance in collaboration with Latin American NARS.
- ICBA: To identify hybrid parents developed at ICRISAT-Patancheru for soil salinity tolerance in collaboration with Indian NARS.
- ICRISAT is engaged with University of Georgia, Purdue University, Texas A&M University, etc in the sphere of biotechnology.

Partnership with private sector

The enhanced research and development capabilities of private sector seed companies over time and their emergence as a major channel for delivering ICRISAT's seed-based technologies to sorghum farmers and producers especially in India, and other developing countries (eg, Indonesia and Egypt), prompted ICRISAT to recognize that the Institute's traditional relationship with public sector breeding programs, though important, was no longer the sole route to farm-level adoption of the hybrids developed based on ICRISAT-bred research products. This realization was all the more pertinent following the succession of funding shocks in ICRISAT and other CGIAR centers (Reddy et al. 2001).

This led to conceptualization and initiation of Sorghum and Pearl Millet Hybrid Parents Research Consortia during 2000 at ICRISAT-Patancheru, the first of its kind in the entire CGIAR system (Reddy et al. 2001) to provide complementary expertise in the area of hybrid development, seed production and dissemination to the clientele and partial funding support to ICRISAT's hybrid parents research with an explicit understanding that the research products from this research will still remain in the public domain and ICRISAT will retain the exclusive rights on its research products. This consortium was later restructured in 2004 with expanded participation of the private sector companies and higher levels of funding support from each company. The new structure still enables to keep the research products in the public domain with free access to public sector as well. The number of members in the consortium increased from seven in 2000 to 17 in 2005, reflecting the value and relevance of ICRISAT's research to farmers.

Considering that the availability of seed of improved varieties is a major constraint for farm-level adoption in southern Africa, the SADC/ICRISAT

SMIP, based at Matopos Research Station in Zimbabwe, established a collaborative pilot project with SeedCo, a regional seed company to develop seed systems to make available the seed of improved cultivars to farmers in rural areas. The project called Small Seed Packs was aimed to test commercial demand for seed of open-pollinated varieties of sorghum in rural markets when delivered in small seed packs. The results of the tie up with SeedCo have been spectacular in Zimbabwe. Approximately 55% of the sorghum seed placed in urban shops was sold. The main reasons buyers cited for purchasing the seed were to try new varieties and replenish depleted seed stocks and they were satisfied with the seed prices. The varied sizes of seed packs allowed farmers to purchase seed according to their budget and needs. Most of the retailers were willing to collect the seed from SeedCo. Farmers made a series of suggestions for improving seed delivery. These included getting the seed into retail shops earlier and maintaining the stock over an extended period.

Developmental activities

Hybrid parents developed at various ICRISAT locations are shared with national programs. Sorghum scientists' field days provide an opportunity for the national breeders to select materials developed at ICRISAT locations, and to get feedback on the relevance of ICRISAT's research to NARS. In both India and a few countries in Africa, breeder seeds of ICRISAT-derived hybrid parents are multiplied by ICRISAT to meet national demand. These together with the dissemination of hybrids to national programs, particularly public sector research organizations, through international and/or regional trials and/or nurseries and by directly supplying hybrids based on specific request have enhanced NARS capacity in sorghum breeding and had an impact on production and productivity globally.

Impacts

Hybrid parents bred at ICRISAT-Patancheru have been extensively exploited in Asian countries compared to Latin American and African countries. The greatest impacts of hybrid parents have been realized from India and China. Initially, when private sector seed companies were in their infancy, public sector-bred cultivars played a predominant role in hybrid development and their dissemination to the target clientele. But as the private sector seed companies developed their own research and development infrastructure, they took the lead in the development and marketing of large number of hybrids based on hybrid parents bred at ICRISAT-Patancheru. In India, more than 4 million ha is occupied by over 54 hybrids developed by seed companies based on parental lines or their derivatives bred at ICRISAT-Patancheru. An ICRISAT-private sector hybrid, JKSH 22, known for its high grain yield potential, bold grain and earliness (5–10 days compared to the most popular hybrid CSH 9) showed remarkable adoption covering 1500 ha in 1994 to 210,000 ha in 2002 (about 0.5% of the total rainy season sorghum area) (Reddy et al. 2004a) (Fig. 3.5).

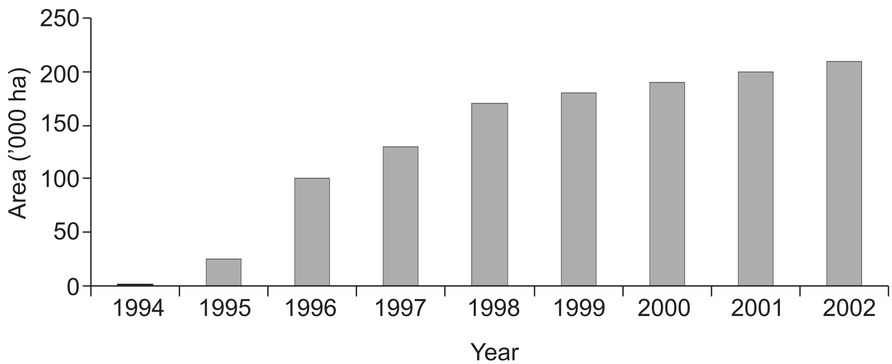

Figure 3.5. Area covered under JKSH 22, an ICRISAT-private sector partnership sorghum hybrid in India.

During 1994 to 2002, seed production of JKSH 22 earned farmers, on an average, over US$0.31 million year^{-1} in Andhra Pradesh and Karnataka states and US$2.7 million year^{-1} from commercial cultivation in Maharashtra and other sorghum-growing states in India. During 2001/02 to 2003/04, a total of 29,800 t of certified hybrid seed of ICRISAT-private sector hybrids was produced which fetched a total income of US$18.8 million to farmers in Andhra Pradesh and Karnataka (Reddy et al. 2004a).

The adoption of another ICRISAT-private sector partnership hybrid, VJH 540 with its high yield potential increased from 650 ha in 1997 to 142,000 ha in 2003 in rainy season sorghum areas in major sorghum-growing states in India, as evidenced from the increased seed sales of this hybrid from 6.5 t in 1997 to 1420 t in 2003 (Reddy et al. 2005a) (Fig. 3.6).

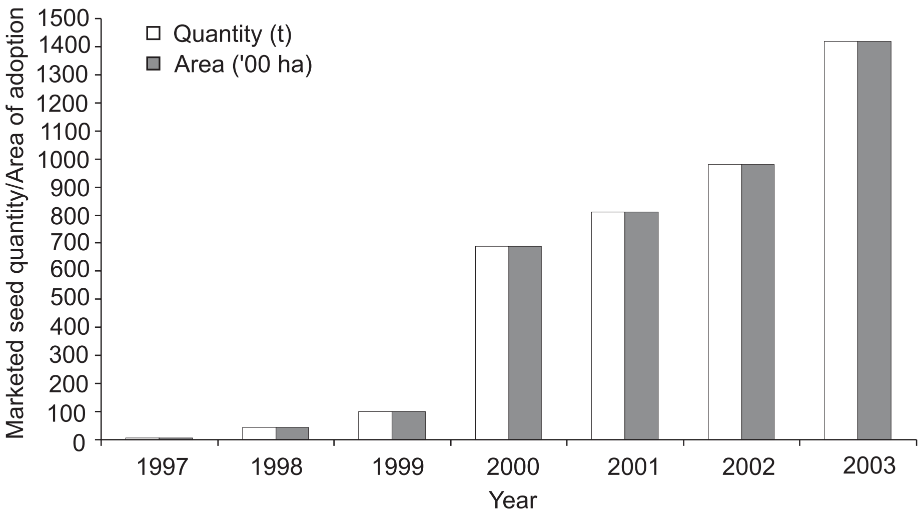

Figure 3.6. Area of adoption and seed sales of VJH 540, an ICRISAT-private sector partnership sorghum hybrid in India.

These are only illustrative examples of the ICRISAT-bred hybrid parents and the power of partnership to exploit the complementary expertise between ICRISAT and the private sector to develop and deliver desired products. Apart from this, several other private sector hybrids based on ICRISAT sources such as MLSH 296, VIKI 540, GK 4009 and GK 4013 are widely adopted in India. High rate of adoption of ICRISAT-based hybrids is due to bold grain, higher grain and fodder productivity. The adoption of hybrids in China is more than 94% (Deb and Bantilan 2003).

Recommendations

Trait-based breeding for A-lines and selections from pure lines developed in various projects at ICRISAT-Patancheru resulted in the development of a large and diverse set of hybrid parents. The characteristics of these hybrid parents are available in ICRISAT website: http:/www.icrisat.org/grep/homepage/sorghum/breeding/pedigreemain.htm. Although some hybrid parents have been developed in Africa, particularly in ESA, they have not been characterized so far. However, additional characterization (eg, scoring of high-yielding A-lines and R-lines for insect pests and diseases resistance) including the traits stipulated in DUS testing and finger-printing, if funding is available, and documentation of the information and maintenance of these valuable sets of hybrid parents both in Asia and Africa centers need to be given top priority.

The heritable and workable CMS systems and the sustainable heterosis for most of the economic traits under various abiotic and biotic stresses in sorghum are the greatest gifts of nature to humanity. So, efforts should be intensified to make the fruits of these gifts available to sorghum farmers/ producers in Africa by intensifying research on hybrid parents and hybrids development and seed systems. There is a need to identify commercially viable hybrids among newly developed *guinea*-based hybrids and standardize hybrid seed production techniques to bring the benefits of hybrid technology to Sudananian and Guinean zones of WCA. Programs to improve hybrid parents for good seedling establishment, stay-green trait and resistance to *Striga* and stem borer with good grain quality traits in high-yielding background should be initiated immediately in all the regions in Africa.

Although high-yielding hybrid parents had significant impact on the development of hybrids for rainy season adaptation in India, farmers still prefer to have hybrids with high grain yield and size. Grain yield and size of the presently available hybrid parents are moderate (about 3.0 t ha^{-1} in seed parents and about 4.0 t ha^{-1} in restorer parents with 100-seed mass of about 2.2 g in both hybrid parents). Therefore, concerted efforts need to be made to breed hybrid parents with higher grain yield and size (at least by 20%) than the existing levels. To achieve this, seed parents are to be further diversified by crossing *durra* and *caudatum*-based B-lines with *guinea* and *bicolor*-based B-lines. Similarly, restorer parents are to be diversified by crossing *kafir* and *caudatum*-based R-lines with *durra*-based R-lines.

Sorghum hybrid parents did not have noticeable impact on the development of suitable hybrids for postrainy season adaptation in India. The landrace pollinator-based hybrids had the required traits for postrainy season adaptation with farmer-preferred grain quality traits, except that they lacked resistance to shoot fly and had intermediate grain luster. It is therefore expected that if improved A-lines with resistance to shoot fly and grain luster become available, they can contribute to enhanced acceptability of hybrids by farmers for postrainy season cultivation.

The male fertility restoration ability of restorers in hybrids for postrainy season adaptation could be enhanced by screening and selecting male parents within the popular postrainy season adapted landraces for low temperature tolerance, apart from restoration of male fertility in A_1 CMS system-based hybrids as a short-term strategy. Similarly, seed parents (A_1) may be screened to identify the ones that support high fertility restoration.

The A_4 (Maldandi) cytoplasm is relatively less susceptible to shoot fly than the other CMS systems. Recovery from shoot fly damage is better in A_4 (Maldandi), A_3, and A_2 cytoplasms than the A_1 cytoplasm. The shoot fly survival and development is poor on A_4 (Maldandi) and A_4 (VZM) CMS systems (Sharma et al. 2005). Therefore, seed parents with A_4 (Maldandi) cytoplasm should be exploited for developing shoot fly resistant hybrids in future. Considering the emergence of aphids as a serious pest on postrainy season sorghum, aphid resistance should also receive priority.

The use of A_4 (Maldandi) CMS system requires the availability of potential restorers. However, restorer frequency on A_4 (Maldandi) is very low. Nevertheless, the restorer frequency on A_4 (Maldandi) could be increased by transferring restorer genes from the identified restorers to the maintainers through repeated selection and backcrossing of the progenies derived from the recurrent maintainer line. Restorer frequency on A_4 (Maldandi) could be increased by another approach. Extensive use of Maldandi sources while diversifying A_4 (Maldandi) CMS-based seed parents is expected to increase restoration frequency.

Once, sufficient number of A_4 CMS system-based seed parents and restorers are identified, it is possible to deploy A_4 CMS system along with A_1, and A_2 CMS systems, which would provide the required nuclear and CMS diversity to counter any unforeseen biotic and abiotic stresses.

The development of hybrids resistant to grain mold and shoot fly has been met with partial success. The strategic research has clearly established the need for shoot fly resistance and GMR in both the hybrid parents to increase the probability of developing resistant hybrids while maintaining acceptable grain yield. Therefore, it is necessary that efforts are to be intensified to breed hybrid parents for resistance to these major biotic stresses for rainy season adaptation. For this, hybrid parents are to be diversified with *bicolor* germplasm (for GMR in Asia and some parts of Africa) and rainy season *durras* (for shoot fly resistance in Asia). It is also important to use diverse shoot fly resistant sources with different resistance mechanisms to build greater stability of shoot fly resistance into the hybrid parents.

The marker-assisted introgression of putative quantitative trait loci (QTLs) with large and consistent effect on the expression of glossiness, a proven trait associated with shoot fly resistance on linkage group (LG) J, which co-mapped with regions associated with DH% under high shoot fly pressure (Sajjanar 2002) would hasten and complement the conventional breeding efforts of enhancing resistance levels of hybrid parents.

The uniqueness of GMR in different sources and large genotype by environment interactions calls for identification of stable QTLs in different sources for their introgression into elite agronomic background through marker-assisted selection (MAS) to complement conventional breeding efforts.

Diversification of hybrid parents for rainy season adaptation for the development of alternative crop-products such as grains for animal (poultry and cattle) feed and stalks for bio-fuel production need to be intensified. Sweet sorghum as an alternative raw material for bio-fuel production has a bright future considering the energy crisis in India. Development of sweet sorghum hybrids should be given strategic importance to derive maximum benefit, as the hybrids, besides producing higher millable cane yield and juice yield, are early to mature and photoperiod insensitive compared to varieties. Photoperiod insensitivity is utmost important to facilitate planting at different dates to ensure round-the-year supply of sweet sorghum to the distilleries for ethanol production. At present, heterosis for sweet-stalk trait is not marked, as the available A-lines have low stalk-sugar content. Genetic diversification for stalk-sugar content of A-lines with resistance to shoot fly and stem borer while maintaining the existing levels of stalk-sugar content of the R-lines would help tap heterosis for stalk-sugar content, besides millable stalk yield and extractable juice yield.

While the concept of multi-line hybrids for rainy season adaptation involving isonuclar alloplasmic A-lines and common restorers to provide stability to productivity is a possibility in near future, three-way-cross hybrids to combine farmer-preferred grain quality-evident traits coupled with high grain and fodder yields and shoot fly resistance required for postrainy season adaptation is a distant possibility.

Single cut forage sorghum hybrids for rainy season and multicut hybrids with enhanced green fodder yields for summer irrigated areas need to be developed through screening of seed parents for rejuvination/ratoonability, high biomass and sweet-stalk to support raising dairy industry. The improvement of restorer parents for high biomass with reduced but effective tillers having soft and sweet stems and disease resistance is the key to further enhance the green fodder yield productivity of sorghum-sudan grass forage sorghum hybrids. For this purpose, the variability in the cultivated sorghums (*S. bicolor*) particularly *dochna* types that originated in Myanmar and other higher biomass types with sweet-stalk (also brown midrib) and foliar disease resistance needs to be exploited.

The number of genes governing the inheritance of male fertility restoration of all the available CMS systems needs to be determined using the isonuclear alloplasmic A-lines and common R-lines, to preclude the influence of background nuclear genotype.

The ability to develop insect resistant cultivars, use of MAS and development of transgenic plants with insect resistance will depend on the precision of resistance screening techniques. While techniques to screen for resistance to major insect pests (shoot fly, stem borer and midge) have been standardized long ago (Sharma et al. 1992), there is a need to standardize the techniques to screen for resistance to aphids, an emerging pest problem.

Summary

The discovery of heritable and workable CMS system [designated as *milo* cytoplasm (A_1)] coupled with demonstration of substantial hybrid heterosis for grain yield/forage yield and other traits of importance in almost every situation, ie, in normal production environments and in stressful environments led to commercial exploitation of hybrid technology in sorghum way back in 1960s. Since then, exploitation of heterosis has become a matter of routine activity all over the globe in regions/countries with strong NARS and adequate seed production backup. Hybrids among others have significantly contributed to productivity. Taking cue from complete devastation of Texas CMS-based maize hybrids in USA due to outbreak of helminthosporium leaf blight, several alternative CMS systems [(A_1, A_2, A_3, A_4 (Maldandi), A_4 (VZM) and A_4 (Guntur)] have been discovered/developed for use in hybrid development programs.

Hybrid breeding program involves the improvement of two genetically diverse but complementary lines (seed parents and pollinators) to exploit heterosis. The hybrid development and hybrid parents research strategy at ICRISAT has undergone significant changes since its inception in 1978. External environment, donors' and NARS perceptions of changing crop requirements and opportunities, and NARS capacity are the most important factors that influenced these changes. Consequently, seed parents research at ICRISAT-Patancheru could be traced under three phases, Phase I (1978–88), Phase II (1989–98) and Phase III (1999 onwards). While grain yield and grain food quality-evident traits along with geographic adaptation traits such as maturity received greater emphasis to match the cropping season and region-specific requirements in phase I, trait-specific breeding seed parents for defensive traits such as resistance to biotic and abiotic stresses received due emphasis in Phase II. An efficient method of seed parents development involving simultaneous selection for resistance to specific stress based on resistant families, and for grain yield based on individual plants within the selected resistant families from F_4 onwards and converting maintainer selection into seed parents was conceptualized and followed to develop defense response trait-based seed parents within shortest possible time period of seven years. The development of appropriate genetic materials such as isogenic lines for plant height, plant pigmentation, leaf glossiness, leaf trichome density and isonuclear alloplasmic A-lines for all the CMS systems for conducting strategic research received emphasis in Phase II. Phase III marked the beginning of race-specific and alternative CMS-based diversification of seed parents. Diversification of seed parents for resistance to biotic stresses was scaled down to only two major yield constraints – shoot fly and grain mold – all the while maintaining higher grain yield. Identification/development of seed parents for sweet-stalk trait, soil salinity-tolerance, and grain micronutrients (Fe and Zn) and β-carotene contents are some of the programs initiated during Phase III. At ICRISAT-Patancheru, A_1 CMS system was the primary focus while A_2 received secondary importance. Strategic research in areas such as assessment of CMS effects on mean performance, combining ability and heterosis for traits of economic importance, and delineating the method of developing hybrids for resistance to grain mold and shoot fly and for forage and sweet-stalk yields were given due emphasis during Phase III. The seed parents research over the years in three phases led to the development of 732 A-/B-lines. All these A-/B-lines (barring a few recently developed) have been designated. The characteristics of these hybrid seed parents are available in ICRISAT website: http:/www.icrisat.org/grep/homepage/sorghum/breeding/pedigreemain.htm Five A-/B-lines, which were found promising during 2005, are yet to be designated.

Restorer program at ICRISAT-Patancheru rested on varietal development program, wherein grain quality traits and yield potential were given major emphasis during 1972–78, and resistance to biotic and abiotic stresses during 1979–88. Varietal improvement program was de-emphasized at ICRISAT-Patancheru, while it was strengthened in ICRISAT centers in Africa from 1989 onwards. The program on varietal/restorer improvement has been renewed in the last three years at ICRISAT-Patancheru, though at a low key with the availability of private sector funds.

Varietal/restorer improvement programs led to the identification/development of large number of restorers for A_1 and A_2, dual-restorers for A_1 and A_2 and common restorers on all the available CMS systems at ICRISAT-Patancheru. So far, 1015 restorers on A_1, 182 on A_2, two on A_3 and four on A_4 CMS systems have been identified at ICRISAT-Patancheru. All these R-lines have been designated and their characteristics are available in ICRISAT website: http:/www.icrisat.org/grep/homepage/sorghum/breeding/pedigreemain.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 (Maldnadi), A_4 (VZM) and A_4 (Guntur) CMS systems have been identified. Further, during 2005, 14 high-yielding restorers have been identified. These 14 along with 36 new R-lines are yet to be designated. Several promising restorers for soil acidity tolerance, sweet-stalk trait, grain micronutrients and β-carotene contents, multicut trait and soil salinity tolerance have been identified.

In ESA, at Matapos, 36 A_1 CMS-based A-lines and 23 R-lines have been developed/identified primarily for use in grain sorghum hybrid development. Three *guinea* landraces-based A-lines were developed at ICRISAT, Mali, and seven inter-racial [*guinea* landrace (Bimbiri Soumale) × *caudatum* varieties] derivatives-based A-lines were developed at the IER for Sudananian and Guinean zones of WCA. A set of 12 *guinea*-based A-/B-lines of diverse geographical origin is currently in advanced stages of development.

Of the several non-*milo* CMS systems, only A_2 has been commercially exploited to diversify CMS-base of seed parents, and hence cytoplasm and nuclear base of hybrid parents and hybrids, considering its stability for male sterility and relatively higher restorer frequency, and substantial heterosis for grain yield and other traits of importance and free from any undesirable effects on these traits.

Considering *sui generis* PPV&FR Act in India and similar acts in several other developing countries under TRIPS agreement, ICRISAT seeks to counter infringement by others on its sorghum hybrid parents by placing them in the public domain through establishing them a prior art. In the first stage, a total of 319 designated A-/B-lines and 160 R-lines were evaluated during 2004 rainy season at ICRISAT-Patancheru (in red and black soils) and postrainy season (in black soil in two locations) for the traits stipulated in DUS test guidelines of India. The data are being processed. The remaining designated and to be designated hybrid parents will be characterized as per DUS testing guidelines and documented in due course.

The studies have suggested the involvement of at least two genes for male fertility restoration on A_1 and three on A_2 cytoplasm. However, these studies are not based on common nuclear genetic background and common R-lines;

and the results are variable. With the availability of isonuclear alloplasmic A-lines and common restorers on all the available CMS systems, the genetics of fertility restoration could be more clearly established.

Early maturity, bold white grain (for food use) and colored grain (for brewing purposes), and high grain yield coupled with resistance to *Striga* and stem borer were the traits that received importance in hybrid development and testing programs in African countries. In India, early maturity, bold, white and lustrous grain and high grain and fodder yields coupled with resistance to grain mold (in rainy season) and shoot fly (in both rainy and postrainy seasons) were the major traits that received greater importance while developing and testing hybrids. Large numbers of A_1 CMS system-based hybrid parents bred at ICRISAT-Patancheru have been supplied to several countries in different regions on specific requests. In addition to the hybrid parents, the hybrids developed at ICRISAT-Patancheru were sent to different regions for testing in nurseries or trials. Several superior hybrids based on ICRISAT-bred hybrid parents have been released for commercial cultivation in different regions. The greatest impacts of ICRISAT-Patancheru-based hybrid parents research have been realized from India and China. The private sector seed companies are the major beneficiaries of ICRISAT-Patancheru-bred hybrid parents (especially A-lines) in India. Over 54 hybrids based on hybrid parents or their derivatives bred at ICRISAT-Patancheru have been developed and marketed in India (especially A-lines). Impacts of a few selected hybrids in terms of acreage planted and yield advantages are described.

Apart from India, China has derived substantial benefits from hybrid parents bred at ICRISAT-Patancheru 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.

Strategic research results have indicated that A_2 offers immediate CMS option for diversifying hybrid parents, and hence hybrids. The hybrid parents need to be further diversified for *guinea*, *feterita* and *bicolor* races for grain yield and *dochna* types that originated in Myanmar and other higher biomass types with sweet-stalk (also brown midrib) for multicut forage yield. Considering higher levels of shoot fly resistance, A_4 (Maldandi) CMS system needs to be tapped for the development of hybrids for postrainy season adaptation, having grain quality traits and shoot fly resistance levels that match with the popular variety M 35-1.

New frontiers of research such as identification of genes from wild species for shoot fly resistance and *Bt*-genes for stem borer resistance, identification of suitable molecular markers for resistance/tolerance to grain mold, soil salinity, soil acidity and grain micronutrients deficiency and deploying them to improve hybrid parents and improvement of seed parents for sweet-stalk trait and programs to develop marketing channels for promotion of sweet sorghum hybrids are proposed. Research areas that need to be followed in future to improve and diversify hybrid parents for traits important to different regions are proposed.

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4. Hybrid Pigeonpea: Research and Development

KB Saxena and RV Kumar[1]

The alarmingly large population of India, which has recently crossed the dubious one-billion mark, is one of the most important constraints in the socioeconomic development of the country. In a recent report published by the World-Watch Institute (Washington, DC, USA), an environmental research organization, it is predicted that by 2050 India will have 600 million more people to feed. This prediction paints a rather grim picture as far as the future food security of the country is concerned. This population burst is forcing fractionalization of the small landholdings by each passing generation, and this is increasing the dependency rate on a unit cultivable land. Providing appropriate quantities of quality food to its population with limited resources is a big challenge for the country. Stretching agricultural areas horizontally, increasing cropping intensities, and intensive use of inputs have their definite boundaries and, therefore, for producing additional food we have no option except to increase productivity of the food crops. Since the food production balance will always remain in the favor of cereals, the issue of protein availability, especially in the rural areas, assumes great significance. The majority of the food protein in India comes from pulses, grown invariably in marginal lands. This scenario is not likely to change and the shortage of protein would continue to affect the under-privileged masses. To meet this challenge, a concerted effort is needed to increase production and productivity of protein-rich crops. Among these, pigeonpea (*Cajanus cajan*) suits most because it is drought tolerant, needs minimum inputs, and can produce reasonable quantity of protein-rich food even under unfavorable environments. The genetic enhancement efforts in the past have succeeded in reducing the crop duration and in developing varieties resistant to major diseases. The adoption of new pigeonpea varieties in India has helped in increasing its area from 2.3 million ha in 1950 to 3.8 million ha in 1998. However, no increase has been witnessed in the productivity of the crop that has remained at about 700 kg ha^{-1}. To achieve a breakthrough in yield potential of the crop, research on the exploitation of hybrid vigor was undertaken at the International Crops Research Institute for the Semi-Arid

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Tropics (ICRISAT), Patancheru, Andhra Pradesh, India. This chapter reviews the progress of the past 32 years in breeding hybrid pigeonpea and discusses the constraints and prospects of this technology.

Special features of pigeonpea

Maturity range

The traditional pigeonpea cultivars and most landraces are of long (>250 days) to medium (160–180 days) maturity duration. However, through breeding efforts, some early-maturing types have also been developed recently and the earliest-maturing line MN 8 flowers in 45 days and matures in 85 days at Patancheru (17°N). Thus, in pigeonpea almost a continuous variation for maturity extending from 85 to over 250 days exists (Table 4.1). This variation not only plays a major role in diversification of cropping systems but also provides an opportunity for extending pigeonpea cultivation to new production niches. The plants of early-maturing varieties are relatively short and produce less biomass and require high (330,000 plants ha^{-1}) plant population for maximizing yield and such types are invariably cultivated as a sole crop. On the contrary, the longer-maturing cultivars which are traditionally grown either as intercrop or perennial hedges produce greater biomass. In any commercial hybrid breeding program, the cross combinations involving parents from diverse maturity groups must be avoided, as the large-scale seed production of their hybrids will be difficult and uneconomical.

Table 4.1. Standard maturity groups of pigeonpea based on time to flower at Patancheru, India.

Maturity group	Time to 50% flower (days)	Reference cultivars
0	<60	ICPL 88039
I	61–70	Prabhat
II	71–80	UPAS 120
III	81–90	Pusa Ageti
IV	91–100	ICP 6
V	101–110	BDN 1
VI	111–130	C 11
VII	131–140	Hy 3C
VIII	141–160	ICP 7065
IX	>160	NP(WR) 15

Photoperiod sensitivity

Pigeonpea is a short-day plant and its flowering is induced by long periods of darkness. The photoperiod sensitive reaction in pigeonpea is positively linked to its maturity duration and biomass production. The recently developed early-maturing genotypes are relatively less sensitive to photoperiod and the longer-duration types are most sensitive. For efficient seed production of hybrids, a good understanding of this phenomenon is essential for maximizing the productivity by adjusting plant population in accordance with the planting dates. For example, if a photosensitive genotype is planted during the long days of mid-June, then the plants will produce greater biomass, more branching and more pods, and a population of about 66,600 plants ha^{-1} will be sufficient for realizing optimum yields. On the contrary, in the late (September–October) sowings, the plants of the same variety will remain short, flower quickly and produce only few branches and pods. Therefore, for establishing optimum biomass and recording high yields more than 330,000 plants ha^{-1} would be required.

Perenniality and ratoonability

Pigeonpea is a perennial shrub and this unique trait of the species helps in its adaptation to stress environments because it has a strong deep root system, large food reserves, and some undefined in-built stress compensation mechanisms. These factors encourage regeneration of vital plant parts. For example, if there is a sudden loss of flowers due to severe insect damage or short spells of drought or low temperature, then the plants will produce a second flush of flowers and pods as soon as the environmental conditions become conducive for growth and development. Similarly, when pigeonpea plants are harvested by cutting the main stem and branches, then a second flush of vegetative and reproductive growth appears, provided the available soil moisture is sufficient. This ability of regeneration (or ratooned growth) can be exploited to benefit, especially in seed multiplication of important genetic stocks and precious nucleus and foundation seed.

Pollination and fertilization

The efficiency of any hybrid seed production program depends on the effectiveness of controlled natural mass pollen transfer mechanism from male parent to female parent. This ensures economical production of quality hybrid seed. In practice, it is achieved by developing productive male-sterile lines and by fertilizing them with male-fertile lines with the help of a natural pollinating agent under natural conditions. In pigeonpea, the phenomenon of natural cross-pollination was known in the early part of the 20th century, when Howard et al. (1919) reported 14% natural outcrossing at the Imperial Agricultural Research Institute, Pusa, India. Since then, several studies (Saxena et al. 1990) at different locations using different genetic materials have indicated a large variation (0–70%) in the extent of natural outcrossing (Table 4.2). The natural outcrossing in pigeonpea occurs primarily due to insect visitations. The large yellow and red flowers attract various insects and when these sit on the open flowers, a lot of pollen gets stuck to their bodies during the process of tripping; cross-pollination occurs when they visit other flowers within or across the field and repeat the tripping. Pathak (1970) reported *Apis mellifera* and *Apis dorsata* as the main pollinating vectors. At Patancheru, Williams (1977) observed various insects visiting pigeonpea but the *Megachile* spp and *A. mellifera* were found responsible for its pollen transfer. She estimated between 5,500 and 107,333 pollen grains on the body of each insect and more than 90% of these pollen grains belonged to pigeonpea. In Kenya, Onim (1981) reported that each insect visit to the flower lasts between 15 and 55 seconds and 24 insect species are responsible for natural outcrossing in pigeonpea. In pigeonpea, natural outcrossing was always considered a major bottleneck in the breeding program until ICRISAT scientists utilized this phenomenon in the genetic enhancement of yield through hybrid breeding.

In pigeonpea, there are 10 stamens in di-adelphous (9+1) configuration. Of these, four have short filaments and six, including the odd posterior one have long filaments. Bahadur et al. (1981) postulated that pollen grains produced by short stamens are predominantly responsible for self-fertilization, whereas those produced by long stamens are utilized in insect-aided outcrossing. Self-pollination occurs in the buds before their petals open while cross-pollination takes place at a later stage when the petals of the flowers unfold and insects visit the flowers to collect nectar.

Once a flower bud becomes visible, it takes about two weeks to bloom. In a young pigeonpea bud, the stigma is placed slightly above the level of anthers, and the style is curved at the tip in such a way that the stigmatic surface is directed towards the anthers. The anther filaments start dehiscing in the closed bud a day before the flower opens. The duration of flower opening (6–48 h) depends on environmental conditions. It has also been found that the stigma becomes receptive for pollination 68 h before anthesis, and remains in

Table 4.2. Natural outcrossing recorded in pigeonpea at various locations in different countries.

Country/Location	Outcrossing (%) Mean	Range
India		
Pusa		2.3–12.0
Pusa		1.6–3.4
Nagpur		3.0–48.0
Nagpur	25.0	
Niphad	16.0	11.6–20.8
West Bengal	30.0	
Ranchi		3.8–26.7
Coimbatore	13.7	
Coimbatore		10.0–70.0
Varanasi		10.3–41.4
Badnapur		0.0–8.0
Hyderabad	27.9	
Hyderabad		0.0–42.1
Hyderabad		3.0–15.1
Hyderabad		4.0–26.0
Kenya		
Katumani	17.7	
Kibos	12.6	
Makucni	21.0	
Mtwapa	22.0	
Kabete (low pollinators)	23.3	
Kabete (high pollinators)	45.9	
Other countries		
Hawaii	<1.0	
Hawaii	15.9	5.9–30.0
Puerto Rico		5.5–6.3
Trinidad	26.4	
Australia		2.0–40.0
Uganda		8.0–22.0

Source: Saxena et al. (1990).

the same condition for about 20 h after anthesis (Prasad et al. 1977). Reddy and Mishra (1981) reported that the percentage of "selfs" was negligible when flower buds were pollinated with foreign pollen without emasculation. These factors indicate that the foreign pollen has an advantage in affecting fertilization over the plant's own pollen. Such mechanisms in pigeonpea offer a sufficient time gap for foreign pollen to be introduced onto the stigma, and thus favor outcrossing.

Background information

Reddy et al. (1978) made the first serious attempt at ICRISAT to search a male-sterile system that could be used in hybrid production technology. They identified a translucent anther type male-sterile that is controlled by a single recessive gene ms_1. Later, Saxena et al. (1983) reported another source of genetic male sterility, characterized by brown, shriveled and arrowhead anther shape. A single recessive gene ms_2 controls this male sterility. Soon after identifying genetic male sterility, a series of feasibility studies was launched to assess the pod set on the male-sterile plants, study the extent of heterosis and determine the production cost of male-sterile and hybrid seed. In a comparison, it was observed that in the male-sterile and male-fertile sibs the yield plant^{-1} and pods plant^{-1} were similar, suggesting that under field conditions sufficient cross-fertilization occurs, and by natural outcrossing large quantities of hybrid seed can be produced on the male-sterile plants. Further, to study the feasibility of breeding productive pigeonpea hybrids, a large number (over 10,000) of hybrids was produced by hand-pollination and some hybrids had standard heterosis (superiority over the control) of over 100%. The evaluation of early-stage experimental hybrids clearly demonstrated that in pigeonpea sufficient level of heterosis was available for yield that could be exploited through commercial hybrid breeding. Since an efficient seed production system that could provide quality seed at economically viable cost is the backbone of any hybrid breeding technology, the feasibility studies were further extended to seed production technology soon after the breeders were able to identify stable male sterility system. The experience at ICRISAT suggested that a distance of 400 m would be suitable for the production of hybrid pigeonpea seeds (Fig. 4.1). Sometimes due to lack of pollinating insects the pod load on the male-sterile plants is low and flowering continues for a longer time. Under such situations the flowering in the pollinators can be extended by periodically removing the pods and frequent irrigations. The

Figure 4.1. A hybrid pigeonpea seed production plot at ICRISAT, Patancheru, India.

recommended ratio of male-sterile and pollinator rows is 6:1; and it could be changed if the number of pollinating insects is insufficient. The detailed seed production studies in India indicated that the estimated cost of hybrid seed was Rs 6.25 kg^{-1} in Coimbatore (Tamil Nadu) and Rs 13.8 kg^{-1} in Ludhiana (Punjab). These studies also showed that the cost of producing hybrid seed could be reduced further under good agronomic management.

In early efforts, the genetic male-sterile lines of different maturity were used to develop commercial hybrids. Since no commercial hybrid was available in any pulse crop, the release of the world's first pigeonpea hybrid ICPH 8 by the Indian Council of Agricultural Research (ICAR) in 1991 was rightly considered a milestone in the history of breeding pulse crops. Evaluations from 100 yield trials showed ICPH 8 to be superior to the control UPAS 120 by 41% (Table 4.3). In 1993, Punjab Agricultural University (PAU), Ludhiana identified another short-duration pigeonpea hybrid PPH 4 and it outyielded the check by a margin of 14%. In 1994, another short-duration hybrid CoH 1 was released by Tamil Nadu Agricultural University (TNAU), Coimbatore and it recorded 32% higher yield over control. In 1997, TNAU released another pigeonpea hybrid CoH 2 which outyielded the control by 35%. Two

Table 4.3. Genetic male-sterility based pigeonpea hybrids released in India.

Character	ICPH 8	PPH 4	CoH 1	CoH 2	AKPH 4104	AKPH 2022
Adaptability	Central Zone	Punjab	Tamil Nadu	Tamil Nadu	Central Zone	Maha-rashtra
Year released	1991	1994	1994	1997	1997	1998
Parentage	MS Prabhat DT × ICPL 161	MS Prabhat DT × AL 688	MS T 21 × ICPL 87109	MS CO 5 × ICPL 83027	NA[1]	NA
Flowering habit	I[2]	I	I	I	I	I
Time to mature (days)	125	137	117	120–130	130–140	180–200
Grain yield (t ha^{-1})	1.78	1.93	1.21	1.05	NA	NA
Superiority over check	41% over UPAS 120	14% over UPAS 120	32% over Vamban 1	35% over CO 5	64% over UPAS 120	35% over BDN 2

1. NA = Data not available.
2. I = Indeterminate.

more pigeonpea hybrids were released by Dr Punjabrao Deshmukh Krishi Vidyapeeth (PDKV), Akola. The hybrid AKPH 4104 was 64% superior to control while AKPH 2022 recorded 35% superiority over the control.

Advantages of hybrids

Vigor and yield

Inherently, pigeonpea is a slow growing crop particularly in the early stages of growth, which makes it a less efficient crop considering the competition with weeds. In general, pigeonpea hybrids have higher seedling vigor. The differences in growth vigor, which begin to appear during the early seedling stage, become pronounced with time. This attribute of hybrids makes them more suitable for intercropping than varieties as it enables them to establish quickly and utilize light and water resources more efficiently. In an experiment designed to study relative root and shoot growth of pigeonpea hybrids and pure lines, it was observed that one-month-old seedlings of hybrids produced 44% higher shoot mass and 43% higher root mass in Alfisols than pure line cultivars (Table 4.4). Interestingly, pigeonpea hybrids exhibit high crop growth rates while maintaining their partitioning at least at the same level as that of varieties (Chauhan et al. 1994) and thus produce high grain yield (Fig. 4.2). The hybrids have also shown significant improvement in the density of pods

Figure 4.2. A high-yielding pigeonpea hybrid with large pods at ICRISAT, Patancheru, India.

and seeds per pod. High crop growth rates of pigeonpea hybrids eventually result in higher biomass production. A total biomass production of about 20 t ha^{-1} has been recorded in hybrids in subtropical environments. A significant proportion (18–20%) of this biomass is returned to the soil in the form of

Table 4.4. Shoot and root mass (g $plant^{-1}$) of short-duration pigeonpea varieties and hybrid ICPH 8 in pots of Alfisol at different days after sowing (DAS), at Patancheru, India, 1989.

	19 DAS		30 DAS		46 DAS		50 DAS	
Genotype	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
ICPL 87 (variety)	0.36	0.09	1.11	0.29	2.93	0.75	6.21	1.69
ICPL 151 (variety)	0.16	0.06	1.33	0.31	3.37	0.95	5.91	1.56
ICPH 8 (hybrid)	0.26	0.11	1.60	0.41	4.02	1.14	7.69	2.06
UPAS 120 (control)	0.17	0.08	1.20	0.32	3.10	0.92	5.99	1.55
T-21 (control)	0.17	0.07	1.08	0.26	3.27	0.85	5.48	1.52
SEm±	0.06	0.015	0.19	0.07	0.63	0.33	0.71	0.16

fallen leaves, thus contributing to the pool of organic matter. In addition, the harvested stems also provide useful fuel wood.

Response to inputs

Agronomic studies indicated that the hybrids do not need additional fertilizers and have good plasticity at plant populations ranging from 16 to 66 plants m^{-2} without adversely affecting grain yield. The yield advantage of hybrid was also maintained at each population level. Increased yield and biomass was harvested even at low plant populations. This implies that seed requirements of hybrid can be reduced to about half or one-third as compared to the commonly grown varieties. The yield advantage of hybrids was both due to higher total dry matter production as well as their better harvest index. The increased number of pods in hybrids directly contributed to increased grain yield (Table 4.5).

Table 4.5. Yield components of pigeonpea hybrid ICPH 8 and control UPAS 120 at Gwalior and Patancheru, India, 1984.

Genotype	Pods m^{-2}	Seeds pod^{-1}	100-seed mass (g)	Dry matter (t ha^{-1})	Harvest index (%)
Gwalior					
ICPH 8	1170	3.6	6.7	13.62	19.9
UPAS 120	1020	2.8	7.2	10.41	18.7
SEm±	123	0.17	0.35	1.06	1.9
Patancheru					
ICPH 8	620	2.8	7.0	5.87	24.8
UPAS 120	430	2.1	6.4	3.06	24.4
SEm±	56.2	0.13	0.14	0.43	1.50

Disease resistance

Fusarium wilt and sterility mosaic are the major biotic stresses of pigeonpea in India. Together, they cause tremendous yield losses every year. In general, medium- and long-duration types are more prone to these diseases. Evaluation of pigeonpea hybrids along with the best available resistant cultivars [(ICPL 87119 (Asha) and ICPL 87051] as controls in disease-free and sick plots (Table 4.6) indicated that in the sick nursery both the hybrids as well as controls recorded less than 1.0% disease incidence. Large differences were observed in the expression of hybrid vigor under disease-free and sick conditions. In the

Table 4.6. Grain yield (t ha^{-1}) of some disease resistant hybrids and varieties in disease-free and sick plots at ICRISAT, Patancheru, India, 1993 and 1994.

	Disease-free plot			Sick plot		
Genotypes	1993	1994	Mean	1993	1994	Mean
Hybrids						
IPH 1326	2.6	2.5	2.53	2.1	1.2	1.64
IPH 1395	2.2	2.3	2.26	2.0	1.5	1.72
IPH 1327	2.4	1.8	2.13	1.9	1.5	1.67
Mean	2.40	2.2	2.31	2.0	1.4	1.68
Varieties						
ICPL 87119	2.6	1.9	2.25	1.07	0.7	0.88
ICPL 87051	1.5	1.6	1.60	1.32	0.9	1.11
Mean	2.05	1.75	1.93	1.20	0.8	1.00
Heterosis (%)	17.1	25.7	19.7	66.7	75.0	68.0

disease-free plots the hybrids on average were 19.7% superior to the controls; but the expression of heterosis for yield was 50–100% greater in the sick plot. It is, therefore, concluded that in addition to specific anti-fungal/viral mechanisms per se, the hybrids have an extra degree of resilience that enables plants to tolerate and produce more under severe disease pressure than non-hybrids.

Female hybrid seed parents research

Research focus

The primary focus in hybrid pigeonpea research is to develop high-yielding hybrids. Since pigeonpea is invariably grown in marginal stress environments with minimum inputs, the stability of performance will receive due attention. To achieve this, efforts will be made to incorporate resistance/tolerance to most common stress factors such as fusarium wilt and sterility mosaic diseases, drought, salinity and insect pests (particularly the pod borers). Pigeonpea is known to have a large diversity for maturity with each type having its own area of adaptation. At this initial stage of the hybrid breeding program, it will be almost impossible to address each maturity group as far as hybrid is concerned. Therefore, for the next 5–10 years, ICRISAT will focus research activities primarily on medium (160–180 days) and extra-early (<110 days) maturity groups. Among these, since majority of the pigeonpea growing area has medium-maturing types, 75% resources will be allocated for this group only. At present the research activities will be concentrated predominantly in central and southern India for medium maturity group; and in Punjab and Haryana states for the extra-early group.

Development of CMS systems

As discussed earlier, the development of pure breeding cytoplasmic-nuclear male-sterile lines (CMS lines) in pigeonpea would effectively overcome the seed production inefficiencies of genetic male sterility-based hybrids and their parents. Since the search for functional male sterility germplasm succeeded in identifying only the genetic male sterility systems, the efforts to develop cytoplasmic-nuclear male sterility (CMS) were made through planned plant breeding. The first such attempt was made by crossing a wild relative of pigeonpea with a cultivated type (Reddy and Faris 1981). When the wild species (C*ajanus scarabaeoides*) was crossed with fertile F_1 plants of (C. *cajan* × C. *scarabaeoides*), the resulting BC_1F_1 was fertile but in BC_1F_2 generation some male-sterile plants were identified. This male sterility was found to be associated with female sterility and, therefore, it was not pursued further. Ariyanayagam et al. (1995) crossed C*ajanus sericeus* with a short-duration advanced breeding line (ICPX 880227-10-1) of pigeonpea. The F_1 was partially male-sterile and the backcross (BC_1F_1 to BC_3F_1) populations (2–19 plants) were found segregating for male sterility. The maternally inherited male sterility in the BC_3F_1 (15 plants) ranged from 8 to 99%. Further studies conducted in this material using ICPL 85010 as maintainer produced materials, which varied a lot for the expression of male sterility. The reversion of some male-sterile plants to fertility or partial fertility further complicated the selections and stabilization of this trait. Intensive selection during the subsequent five backcross generations, however, resulted in the identification of promising CMS lines (Saxena et al. 1996). This was designated as A_1 cytoplasm. At this time, various research centers of ICAR also joined the efforts to develop CMS lines. Among these, scientists at Gujarat Agricultural University (GAU) succeeded in developing CMS lines with C. *scarabaeoides* (Tikka et al. 1997). Subsequently, Saxena and Kumar (2003) also bred this CMS system and it was designated as A_2 cytoplasm. At PDKV, Akola, the CMS system was developed (Wanjari et al. 2001) from an interspecific cross involving C*ajanus volublis* (A_3 cytoplasm) as a female parent and cultivated pigeonpea as a male parent.

The recently developed CMS system, designated as A_4 cytoplasm (Saxena et al. 2005a), has the cytoplasm of *Cajanus cajanifolius*, another wild relative of pigeonpea (Table 4.7). This wild species is reported to be genetically closest to the cultivated type and differs only by a single gene (De 1974). The male-sterile plants in this material showed no morphological deformity and produced plenty of pollen grains in hybrid combinations with the restorers. This male-sterile source has been reported to be stable at Coimbatore (15° N), Hyderabad (17° N), Jalna (18° N) and Ludhiana (28° N) and it is capable of producing high-yielding hybrids. Therefore, it has a great potential for use in commercial hybrid pigeonpea breeding programs. It was also observed that the frequency of fertility restorers of this CMS source is higher than that of other sources. The details of fertility restorer frequency and other related aspects such as character association, etc would be compiled later.

Table 4.7. Male sterility in F_1 of cross between ICPW 29 (*Cajanus cajanifolius)* and *C. cajan* and backcross generations used in the development of CMS line ICPA 2039 at ICRISAT, Patancheru, India.

Generation	Year	Location	Number of plants		Male sterility (%)
			Total	Male-sterile	
F_1	2000	Field	12	12[1]	–
BC_1F_1	2001	Glasshouse	8	8	100
BC_2F_1	2002	Glasshouse	5	4+1[1]	80
BC_3F_1	2002	Glasshouse	165	165	100
BC_4F_1	2003	Glasshouse	7	7	100
BC_5F_1	2003	Glasshouse	67	67	100
BC_6F_1	2004	Field	1133	1133	100
BC_7F_1	2005	Field	17286	17286	100

1. Partial male-fertile.

Search for new CMS systems

In an attempt to diversify the cytoplasm source further two other wild relatives of pigeonpea were used. In 2002, in an open-pollinated population of *Cajanus lineatus*, a wild relative of pigeonpea, one naturally outcrossed plant with erect growth and different morphological traits was identified. The anthers of this plant had little amount of pollen. The flowering in this off-type plant was profuse but there were no pods. To maintain this genotype, its stem cuttings were grown in a glasshouse in 2003. Of the five cuttings planted, only two survived. These vegetatively propagated progenies did not set any pod. These plants were crossed with ICPL 99044 and from 65 pollinations made, only one pod was set which produced only a single seed. In 2004, this hybrid seed was planted in a glasshouse and the plant was also found to be partially male-sterile with 45% pollen-sterility. This plant also did not produce any pod and it was crossed with ICPL 99044 (BC_1F_1), ICPL 96056, BSMR 736, ICPL 211 and ICP 10948. At present, each cross has produced hybrid pods. In a similar way, an attempt is also being made to develop CMS line from C*ajanus albicans*, another important wild relative of pigeonpea. At present, its male-sterile F_1 hybrid plant is growing in a glasshouse but so far there is no pod set. The hybrid embryo from the pollinated flowers will be excised and grown in artificial medium to produce the backcross plants.

In an exciting study at ICRISAT, for the first time, maternal inheritance of male sterility was found in a cross involving a cultivated pigeonpea line as female parent and its wild relative C*ajanus auctifolius* as a male parent. This source of CMS is perfectly maintained by its wild species parent and there are plenty of fertility restorers among the cultivated types (Mallikarjuna and Saxena 2005). At present, however, it is difficult to find an appropriate maintainer among the cultivated types. Once this endeavor is successful, this source of CMS will be of immense value in the hybrid pigeonpea breeding program.

Basic features of available CMS systems

The CMS system is the most widely accepted means of producing commercial hybrids in important field crops. The expression of CMS, in part, is controlled by the factors carried only through the female parent, which is never lost or diluted in the succeeding generations of reproduction. Nuclear genes generally influence the expression of this trait, and environmental conditions may also alter its expression in many, but not all, gene-cytoplasm combinations. Cytoplasmic male sterility is conditioned by an interaction between nuclear and cytoplasmic factors. The cytoplasmic factor is referred to as 'N' for normal fertile cytoplasm, and 'S' for the sterile cytoplasm. The cytoplasm-nuclear male-sterile line or A-line must be homozygous for '*msms*'; the 'S' cytoplasm and the maintainer line (B-line) must have 'N' cytoplasm and be homozygous for *msms* nuclear genes. The F_1 between A-line and B-line is always male-sterile since the 'N' cytoplasm responsible for fertility in the B-line is not transferred to the F_1. For producing fertile hybrid seed, the A-line in

‘S’ cytoplasm is crossed with a fertile line with fertility restorer nuclear genes, commonly known as *Fr* genes. To sum up, the three-line system is geared for multiplying A-line with the help of B-line and for producing the hybrid seed, the A-line is crossed with the restorer line (R-line).

Breeding of B-lines

ICRISAT is now in the process of identifying elite B-lines (maintainers) among the germplasm and advanced breeding lines (Tables 4.8, 4.9, 4.10 and 4.11). Subsequently, these lines will be characterized for various agronomic traits. The process of systematic breeding of B-lines for yield, adaptation and combining ability will begin within 2–3 years.

Breeding of A-lines

ICRISAT is now in the process of breeding elite A-lines and there is sufficient genetic variability to develop new hybrids in different plant types and maturity groups. Subsequently, these lines will be characterized for various agronomic traits.

Wilt and sterility mosaic disease resistance

A total of 46 medium-duration wilt and sterility mosaic resistant lines were evaluated in Vertisols for productivity in disease-free plots, and for disease reaction in sick plots. In a trial conducted in Vertisols, five lines produced more grain than the control ICPL 87119 (Table 4.12). Of these, ICPL 20096 was the best with grain yield of 3223 kg ha^{-1}. This line has bold seeds with no incidence of either fusarium wilt or sterility mosaic. In another trial also, the yield levels and disease reactions were encouraging. The best line ICPL 20106 produced 3068 kg grain ha^{-1}. ICPL 20136 was the best line with 2270 kg ha^{-1} grain yield and it was found to be free from diseases. These lines will be crossed with existing A-lines to develop new maintainers and restorers for future use.

Helicoverpa resistance

Six advanced breeding lines with tolerance to *Helicoverpa* pod borer were evaluated under insecticide sprayed and unsprayed conditions. Under unsprayed conditions ICPL 20046 recorded highest grain yield (1010 kg ha^{-1})

Table 4.8. Some important characteristics of A-/B-lines derived from *Cajanus sericeus* at ICRISAT, Patancheru, India[1].

ICPA no.	Male sterility[2] (%)	Time to flower (days)	Time to mature (days)	Plant height (cm)	100-seed mass (g)	Seed color	Flowering habit	Disease reaction	
								Wilt	SM
2001	97.7	76	130	150	9.2	B	I	S	S
2022	98.7	92	141	165	8.5	B	I	S	R
2016	96.5	77	129	95	10.0	B	D	S	S
2017	100.0	74	123	120	10.0	B	D	S	S
2018	98.3	87	140	175	11.5	C	D	S	S
2019	99.3	80	130	165	9.0	B	I	S	S
2020	100.0	91	143	170	9.0	B	I	S	S
2015	99.0	74	120	105	11.0	B	D	S	S
2021	100.0	90	144	170	8.8	B	I	S	S
2029	99.0	100	160	160	11.3	B	I	S	S
2028	100.0	100	151	175	10.1	B	I	S	S
2002	98.0	105	154	160	9.4	B	I	R	R
2033	98.3	78	121	110	11.6	W	D	S	R
2006	98.0	58	103	135	11.3	B	I	S	S
2003	96.5	120	178	140	17.8	P	I	R	R
2005	98.0	110	159	150	9.9	Bl	I	S	S
2004	100.0	110	160	145	10.4	B	I	S	R
2035	100.0	45	95	60	8.3	B	D	S	S
2009	98.0	63	109	120	10.0	B	D	S	R
2010	100.0	95	140	180	12.0	W	D	S	R
2012	97.5	60	107	125	11.0	C	D	S	R
2013	100.0	61	109	125	11.0	P	D	S	R
2027	100.0	110	150	160	14.0	W	I	R	R
2007	95.0	75	112	90	11.0	B	D	S	S
2008	100.0	76	111	115	10.0	B	D	NA	NA
2011	97.0	65	108	155	10.5	B	D	S	S
2014	96.0	75	126	115	10.0	C	D	R	R
2025	100.0	133	196	200	11.9	C	I	R	R
2024	100.0	115	183	225	12.5	B	I	R	R
2026	96.0	135	200	220	12.4	W	I	R	R
2067	95.0	65	105	80	9.5	B	D	S	S
2068	93.0	75	125	180	10.3	B	I	S	S
2032	97.0	124	170	221	11.3	W	I	R	R
2030	96.0	145	195	240	12.8	B	I	S	R
Minimum	93.0	45	95	60	8.3	–	–	–	–
Maximum	100.0	145	200	240	17.8	–	–	–	–

1. B = Brown, C = Cream, W = White, P = Purple, Bl = Black, I = Indeterminate, D = Determinate, SM = Sterility mosaic, S = Susceptible, R = Resistant, NA = Data not available.
2. Mean of data recorded in 2000, 2001 and 2002.

Table 4.9. Some important characteristics of A-/B-lines derived from *Cajanus scarabaeoides* at ICRISAT, Patancheru, India, 2003[1].

ICPA no.	Generation	Male sterility (%)	Time to flower (days)	Time to mature (days)	Plant height (cm)	100-seed mass (g)	Seed color	Flowering habit	Disease reaction Wilt	Disease reaction SM
2057	BC_3F_1	100	66	115	95	9.5	B	D	S	S
2052	BC_6F_1	100	64	110	108	8.5	B	D	S	S
2053	BC_5F_1	100	74	125	117	9.7	B	I	S	S
2054	BC_5F_1	100	76	130	120	9.9	B	I	S	S
2055	BC_3F_1	100	128	165	150	9.6	B	I	S	S
2056	BC_3F_1	100	70	125	132	8.8	B	I	S	S
2058	BC_3F_1	100	123	164	145	9.7	B	I	S	S
2059	BC_3F_1	100	120	170	150	9.8	B	I	S	S
2060	BC_2F_1	100	123	170	140	10.1	W	I	R	R
Minimum	–	100	64	110	95	8.5	–	–	–	–
Maximum	–	100	128	170	150	0.1	–	–	–	–

1. B = Brown, W = White, D = Determinate, I = Indeterminate, SM = Sterility mosaic, S = Susceptible, R = Resistant.

Table 4.10. Some important characteristics of A-/B-lines derived from *Cajanus cajanifolius* at ICRISAT, Patancheru, India, 2005[1].

ICPA no.	Generation	Male sterility (%)	Time to flower (days)	Time to mature (days)	Plant height (cm)	100-seed mass	Seed color	Flowering habit	Disease reaction Wilt	Disease reaction SM
2039	BC_7F_1	100	80	125	110	10.5	B	D	S	S
2040	BC_2F_1	100	52	95	81	8.0	C	D	S	S
2041	BC_2F_1	100	86	128	120	12.0	W	D	S	S
2042	BC_2F_1	100	92	132	190	9.0	C	I	S	S
2043	BC_2F_1	100	105	145	200	12.0	B	I	R	R
2044	BC_2F_1	100	116	156	210	9.5	B	I	S	S
2045	BC_2F_1	100	115	156	190	10.0	B	I	S	S
2046	BC_2F_1	100	124	165	210	14.0	P	I	R	R
2047	BC_2F_1	100	110	153	220	12.0	B	I	R	R
2048	BC_2F_1	88	108	150	225	11.5	B	I	R	R
2049	BC_2F_1	54	104	146	195	12.5	B	I	S	R
2050	BC_2F_1	100	116	159	230	13.0	C	I	S	S
2051	BC_2F_1	100	107	150	205	11.5	B	I	S	S
Minimum		54	52	95	81	8.0	–	–	–	–
Maximum		100	124	165	230	14.0	–	–	–	–

1. B = Brown, C = Cream, W = White, P = Purple, D = Determinate, I = Indeterminate, SM = Sterility mosaic, S = Susceptible, R = Resistant.

Table 4.11. Common pigeonpea male sterility maintainers of different cytoplasms at ICRISAT, Patancheru, India.

Line	A_1 cytoplasm	A_2 cytoplasm	A_4 cytoplasm
ICPL 88039	✔	✔	
ICPL 88034	✔	✔	
ICPL 99044	✔	✔	
ICPL 271	✔		✔
ICPL 87091	✔		✔
ICP 7035	✔		✔
MN 1	✔		✔

(Table 4.13). This line produced 1803 kg ha^{-1} yield under sprayed conditions. Only one line (ICPL 20042) exhibited resistance to wilt and tolerance to sterility mosaic. This line did not perform very well under sprayed conditions. These lines will be crossed to the existing A-lines to develop new maintainers and restorers.

Documentation of A-/B-lines

The process of characterization has already begun. The data on the distinctness, uniformity and stability (DUS) traits of elite A-/B-lines will be collected for at least three years and at more than one location before their documentation and designation.

Male hybrid parents research

In a three-parent hybrid breeding system, the *Fr* genes play a major role in producing male-fertile hybrids. Such genes have the ability to overcome the ill effects of pollen-aborting factors residing in the male-sterile genotypes. In a dynamic hybrid pigeonpea breeding program, the *Fr* genes are introgressed through backcrossing in agronomically superior genotypes to develop heterotic hybrid combinations. The *Fr* genes are generally present in primary/secondary gene pools and their mining is done through selection. In a new hybrid breeding program such as pigeonpea, the search for *Fr* gene(s) is done by crossing diverse germplasm with promising CMS lines and then observing their progenies for pollen production and fruit setting through sexual fertilization.

Table 4.12. Performance of pigeonpea medium-duration disease resistant advanced breeding lines during rainy season 2004 at ICRISAT, Patancheru, India.

Line	Grain yield (kg ha^{-1})	Time to flower (days)	Time to mature (days)	Plant height (cm)	Seeds pod^{-1}	100-seed mass (g)	Plant stand	DI[1] (%)	
								Wilt	SM
ICPL 20096	3223	127	185	292	4.1	14.4	43	0	1
ICPL 20098	2766	128	184	288	4.4	14.2	41	0	0
ICPL 20104	2734	126	182	288	4.0	13.2	39	6	0
ICPL 20093	2660	127	183	283	3.6	12.0	41	10	0
ICPL 20094	2619	129	185	280	3.8	10.6	41	4	0
ICPL 20103	2356	131	186	297	3.8	13.9	41	0	1
ICPL 20102	2283	126	181	285	3.8	10.6	40	1	1
ICPL 20101	2253	128	185	287	4.0	13.6	40	2	0
ICPL 20100	2160	127	183	283	4.5	10.7	40	8	0
ICPL 20095	2041	125	181	282	3.7	9.8	30	79	0
ICPL 20105	1949	131	187	295	4.8	13.6	39	1	0
ICPL 20097	1873	131	187	287	4.2	12.6	40	0	0
ICPL 20099	1397	127	184	292	4.5	14.7	42	0	0
ICPL 87119 (control)	2544	125	180	277	3.7	11.8	36	5	0
SEm±	150.5	0.9	1.1	4.6	0.19	0.23	1.8		
Mean	2347.1	127.7	183.8	286.8	4.06	12.54	39.5		
CV (%)	11.1	1.2	1.0	2.8	8.26	3.19	7.9		

1. DI = Disease incidence, SM = Sterility mosaic.

Choice of CMS systems

The A-lines derived from C. *sericeus* did not show high level of stability over the seasons. In the short-duration and some medium-duration lines, a change from male sterility to fertility was observed. Such lines are not preferred in the breeding of hybrids. In the long-duration types, however, no such change was recorded. The hybrids derived from C. *scarabaeoides* exhibit poor fertility restoration. The instability in the expression of male sterility and their fertility restoration traits has, however, limited the use of these cytoplasm sources in practical hybrid breeding programs (Saxena et al. 2005b) and A_4 cytoplasm is being used extensively in the hybrid breeding program.

Table 4.13. Performance of *Helicoverpa*-tolerant pigeonpea selections under unsprayed conditions at ICRISAT, Patancheru, India, 2004.

Line	Grain yield (kg ha^{-1})	Time to flower (days)	Time to mature (days)	Plant height (cm)	Seeds pod^{-1}	100-seed mass (g)	Plant stand
ICPL 20046	1010	121	176	221	3.5	8.4	64
ICPL 97249	996	122	176	212	3.6	8.7	74
ICPL 97250	871	120	174	190	3.6	9.0	54
ICPL 20036	866	116	172	179	3.6	9.1	69
ICPL 20042	551	124	178	189	3.6	9.1	74
ICPL 20058	541	121	175	216	3.6	9.2	74
ICPL 84060 (control)	156	124	178	176	3.7	9.3	40
ICPL 332 (control)	89	120	174	200	3.6	8.3	18
SEm±	232.7	0.6	0.7	11.6	0.09	0.10	8.9
Mean	634.9	121.1	175.5	198.0	3.57	8.90	58.4
CV (%)	73.3	1.0	0.9	11.7	5.05	2.21	30.4

Fertility restoring sources

At ICRISAT-Patancheru, fertility restoring lines were identified for the CMS lines derived from C. *sericeus* (Tables 4.14 and 4.15), C. *scarabaeoides* (Table 4.16) and C. *cajanifolius* (Table 4.17) cytoplasms. Among these cytoplasm sources, the frequency of fertility restoration was highest among C. *cajanifolius* hybrids. In 2004, a total of 352 hybrids was evaluated and of this, 203 (58%) exhibited high level of fertility restoration.

Dual- and multiple-restorers

With the limited experimentation, ICPL 87119, ICP 10650, ICP 12320, ICP 11376, HPL 24-63 and ICEAP 053 were identified as common fertility restorers in all three CMS systems (Table 4.18).

Table 4.14. Fertility restoration of F_1 hybrids involving A_1 male-sterile (*Cajanus sericeus*) lines at ICRISAT, Patancheru, India.

Pollen parent	Fertile plants (%)				
	2000	2001	2002	2003	2004
ICPL 129	95	72	95	95	100
ICPL 89	100	91	95	97	100
ICPL 131	100	80	100	98	100
ICPL 21	–	100	97	96	100
HPL 24	89	92	100	94	98
ICP 10650	–	100	100	100	100
ICP 11912	79	83	84	89	100
ICPL 20	–	85	99	99	100

Table 4.15. Some important characters of pigeonpea fertility restorers of A_1 cytoplasm **identified at ICRISAT, Patancheru, India, 2002–04**[1].

Line	Male fertility (%)	Time to flower (days)	Time to mature (days)	Plant height (cm)	100-seed mass (g)	Seed color	Flowering habit	Disease reaction	
								Wilt	SM
ICPL 129	100	85	133	105	10.0	B	D	S	S
ICPL 90011	100	82	135	95	9.5	B	D	S	S
ICPL 81	93	82	130	145	7.1	B	D	S	S
ICPL 89	100	68	134	150	8.7	B	I	S	S
ICPL 98012	100	83	105	85	8.4	B	I	S	S
ICPL 131	100	110	162	225	9.8	B	I	T	S
ICPL 87119	100	119	173	195	11.2	B	I	R	R
ICPL 89004	91	87	140	168	8.6	B	I	S	S
ICPL 94068	100	126	172	185	10.5	B	I	R	S
ICPL 96053	100	120	191	215	10.8	W	I	R	R
ICPL 99047	91	128	175	222	11.7	B	I	R	R
ICPL 99048	84	122	175	225	11.3	B	I	R	R
ICPL 99050	100	118	175	225	11.1	B	I	R	R
HPL 24-63	100	124	174	205	7.2	B	I	R	R
HPL 24-47	100	118	155	225	10.7	C	I	T	R
HPL 24-48	100	122	178	180	6.4	B	I	R	R
HPL 21-3	100	127	175	260	9.2	C	I	S	R
ICP 10650	96	118	172	180	10.2	B	I	S	R
ICP 11892	100	90	127	205	10.2	B	I	S	S
ICP 12320	100	125	167	267	10.0	B	I	R	S
ICP 11376	100	128	175	260	11.5	B	I	R	R
ICP 13991	100	132	170	250	10.7	B	I	S	R
ICEAP 0053	100	144	208	245	16.8	W	I	S	S

1. B = Brown, W = White, C = Cream, D= Determinate, I = Indeterminate, SM = Sterility mosaic, S = Susceptible, T = Tolerant, R = Resistant.

Table 4.16. Important characters of pigeonpea fertility restorers of A_2 cytoplasm **identified at ICRISAT, Patancheru, India 2002–04**[1].

Line	Male-fertility (%)	Time to flower (days)	Time to mature (days)	Plant height (cm)	100-seed mass (g)	Seed color	Flowering habit	Disease reaction	
								Wilt	SM
ICPL 88034	100	80	137	195	10.1	B	I	S	S
ICPL 161	100	86	132	205	10.8	B	I	S	S
ICPL 87119	100	119	173	195	11.2	B	I	R	R
ICPL 94068	100	126	172	185	10.5	B	I	R	S
ICPL 95007	100	122	194	220	11.6	B	I	R	R
ICPL 96061	97	122	191	232	12.2	B	I	R	R
ICPL 99045	100	104	162	200	11.2	B	I	T	T
ICPL 99047	100	128	175	222	11.7	B	I	R	R
ICPL 99052	100	108	162	205	10.5	B	I	R	R
ICPL 99086	100	142	220	210	10.4	B	I	R	R
HPL 24-9	100	123	165	175	10.0	B	I	T	R
HPL 24-63	100	124	174	205	7.2	B	I	S	S
ICPL 24-7	100	118	158	182	9.8	B	I	T	R
ICP 10650	100	118	172	180	10.2	B	I	S	S
ICP 10934	100	114	147	220	10.8	B	I	S	T
ICP 12320	100	125	167	267	10.0	Bl	I	R	S
ICP 11376	100	128	175	260	11.5	P	I	R	R
ICP 13186	100	94	138	215	10.0	B	I	S	S
ICP 8863	100	110	117	173	9.3	B	I	R	S
ICPL 87051	100	122	180	205	12.2	W	I	R	R
ICEAP 00053	100	144	208	245	16.8	W	I	S	R
ICEAP 00068	100	146	210	240	16.5	W	I	S	R
ICEAP 00554	100	144	210	245	15.2	W	I	S	R

1. B = Brown, Bl = Black, P = Purple, W = White, I = Indeterminate, SM = Sterility mosaic, S = Susceptible, R = Resistant, T = Tolerant.

Breeding of R-lines

At present, ICRISAT is in the process of identifying elite R-lines from the germplasm and among the advanced breeding lines. Subsequently, these lines will be characterized for various agronomic traits. The process of breeding R-lines will be started within 1–2 years.

Table 4.17. Some important characters of pigeonpea fertility restorers of A_4 cytoplasm identified at ICRISAT, Patancheru, India, 2004–05[1].

Line	Male-fertility (%)	Time to flower (days)	Time to mature (days)	Plant height (cm)	100-seed mass (g)	Seed color	Flowering habit	Disease reaction Wilt	Disease reaction SM
ICPL 88034	100	80	137	195	10.1	B	I	S	S
ICPL 88039	100	65	115	180	10.5	B	I	T	T
ICPL 131	100	118	162	225	9.8	B	I	R	R
ICPL 87119	100	119	180	220	11.2	B	I	R	R
HPL 24-63	100	124	174	205	7.2	B	I	S	T
ICP 10650	100	118	172	180	10.2	B	I	S	S
ICP 12320	100	125	167	267	10.0	Bl	I	R	S
ICP 11376	100	128	175	260	11.5	P	I	R	R
ICP 8094	100	142	210	240	9.8	W	I	R	R
ICEAP 00040	100	140	202	260	18.0	W	I	S	T
ICEAP 00053	100	144	208	245	16.8	W	I	S	T
ICP 13092	100	125	190	225	12.3	W	I	R	R
ICPL 20092	92	136	220	140	8.2	W	Df	S	T
ICPL 129	100	85	133	105	10.0	B	D	S	T

1. B = Brown, Bl = Black, P = Purple, W = White, I = Indeterminate, D = Determinate, Df = Dwarf, SM = Sterility mosaic, S = Susceptible, T = Tolerant, R = Resistant.

Table 4.18. Common pigeonpea fertility restorers of different cytoplasms identified at ICRISAT, Patancheru, India.

Line	A_1 cytoplasm	A_2 cytoplasm	A_4 cytoplasm
ICPL 129	✔		✔
ICPL 87119	✔	✔	✔
ICP 10650	✔	✔	✔
ICP 12320	✔	✔	✔
ICP 11376	✔	✔	✔
HPL 24-63	✔	✔	✔
ICEAP 053	✔	✔	✔

Documentation of R-lines

The process of characterization of R-lines has already begun. The data on the critical traits of elite R-lines will be collected for at least three years and at more than one location before their formal documentation.

Development of hybrids

Scanning of literature on gene action and heterosis (Saxena and Sharma 1990) in pigeonpea clearly shows that important economic traits such as yield, number of pods plant^{-1}, plant height, seed size and seeds pod^{-1} are controlled by both additive and non-additive gene action and the level for hybrid vigor for yield is comparable with other crops where the commercial hybrids have made success stories. The discovery of stable male sterility systems, availability of natural outcrossing and evidence of heterotic yield advantage has set a perfect scene for increasing yield through developing high-yielding and widely adapted hybrids to break the persisting yield plateau in pigeonpea.

Primary focus

The primary focus in hybrid pigeonpea research is to develop high-yielding hybrids. Since pigeonpea is invariably grown in marginal stress environments with minimum inputs, the stability of performance will receive due attention. To achieve this, efforts will be made to incorporate resistance/tolerance to most common stress factors such as fusarium wilt, sterility mosaic, salinity and insect pests (particularly the pod borers). Pigeonpea is known to have a large diversity for maturity (extra-early, early, medium and long duration) with each group having its own area of adaptation. At this initial stage of the hybrid breeding program, it will be almost impossible to address each maturity group; therefore, for the next 5–10 years ICRISAT will focus research activities primarily on medium (160–180 days) maturity group for central and peninsular India (Fig. 4.3) and extra-early (<110 days) maturity group for northern India. Among these, since majority of the pigeonpea growing area has medium-maturing types, 75% resources will

Figure 4.3. ICPH 2788, a high-yielding, medium-duration pigeonpea hybrid at ICRISAT, Patancheru, India.

be allocated for this group only. At present, ICRISAT plans to concentrate the research activities predominantly in central and southern India on medium maturity group; and in northern India on the extra-early group.

Preferred plant architecture

In pigeonpea, there are two dominant flowering habits. The determinate types, where the terminal bud is reproductive in nature and the flowers and pods, borne in clusters at the top of the canopy, are more prone to pod borer attack with reduced opportunities of recovery from damage. On the contrary, the indeterminate types have vegetative buds at the top of the canopy and the pods are axillary in origin; hence, in comparison to the determinate types, the insect damage in the indeterminate types is relatively less and the recovery from the damage is also high. Such genotypes produce high yield under low management practices. Therefore, the indeterminate types will be preferred in the hybrid breeding program. Among these types, spreading as well as semi-spreading plant types, which are expected to perform better under intercropping situations will be bred.

Heterosis for yield

During 2004, a total of 138 experimental hybrids were evaluated. These include eight short-duration, 114 medium-duration, and 16 long-duration hybrids. All the short-duration hybrids were based on ICPA 2039, a CMS line derived from C. *cajanifolius*. The long-duration hybrids were based on ICPA 2032, a CMS line with C. *sericeus* cytoplasm. Of the medium-duration hybrids, 28 were based on C. *sericeus* cytoplasm while the remaining hybrids were made by crossing early generation (BC_1F_1) A-lines derived with C. *cajanifolius* cytoplasm.

Hybrids with *C. cajanifolius* cytoplasm

Eight short-duration lines were crossed with ICPA 2039; the fertility restoration in all the hybrids was perfect. All the hybrids produced greater yield than control UPAS 120 (1806 kg ha^{-1}). The best hybrid ICPH 2470 matured in 125 days and produced 3205 kg grain ha^{-1}, exhibiting 77.5% standard heterosis [Tables 4.19(A) and 4.19(B)]. From this trial, three hybrids (ICPH 2470, ICPH 2438 and ICPH 2429) have been selected for further testing.

Table 4.19(A). Performance of short-duration pigeonpea hybrids at ICRISAT, Patancheru, India, 2004.

Hybrid	Plant height (cm)	Pods plant^{-1}	Seeds pod^{-1}	100-seed mass (g)	Time to flower (days)	Time to mature (days)	Grain yield (kg ha^{-1})	Plant stand
ICPH 2470	190	232	3.8	8.9	79	125	3205	38
ICPH 2438	160	181	3.8	9.0	77	122	2404	36
ICPH 2429	180	136	3.8	9.4	73	128	2351	36
ICPH 2431	169	160	3.4	8.3	77	122	2195	34
ICPH 2472	190	194	3.9	9.1	81	135	2150	32
ICPH 2433	162	144	3.2	8.5	81	125	2118	31
ICPH 2436	155	142	3.2	10.5	74	128	2067	34
ICPH 2457	170	126	3.5	9.3	69	122	1876	35
UPAS 120 (control)	160	114	3.4	9.1	78	128	1806	50
SEm ±	10.2	37.6	0.14	0.23	1.2	3.3	171.5	2.6
Mean	170.7	158.9	3.58	9.14	76.6	126.1	2241.2	36.2
CV (%)	8.5	33.4	5.63	3.48	2.3	3.6	10.8	10.3

Table 4.19(B). Standard heterosis (%) for important traits recorded in short-duration pigeonpea hybrids (A_4 cytoplasm) at ICRISAT, Patancheru, India, 2004.

Hybrid	Plant height	Pods plant^{-1}	Seeds pod^{-1}	Seed size	Grain yield
ICPH 2470	18.8	103.5	11.8	–2.2	77.5
ICPH 2438	0.0	58.8	11.8	–1.1	33.1
ICPH 2429	12.5	19.3	11.8	3.3	30.2
ICPH 2431	5.62	40.4	0.0	–8.8	21.5
ICPH 2472	18.8	70.2	14.7	0.0	19.0
ICPH 2433	1.25	26.3	–5.9	–6.6	17.3
ICPH 2436	–3.12	24.6	–5.9	15.4	14.5
ICPH 2457	6.25	10.5	2.9	2.2	3.9

To generate information on fertility restoration and have some idea about yield potential, the experimental hybrids involving four early generation A-lines were evaluated. Among the medium-duration hybrids, ICPH 2658 was found to be the best with grain yield of 3636 kg ha^{-1}. This hybrid exhibited 40% grain yield superiority over the control ICPL 87119 (2593 kg ha^{-1}) [Tables 4.20(A) and 4.20(B)]. This hybrid has brown seed and its 100-seed mass is also

Table 4.20(A). Performance of pigeonpea medium-duration hybrids (A_4 cytoplasm) at ICRISAT, Patancheru, India, 2004.

Hybrid	Grain yield (kg ha^{-1})	Time to flower (days)	Plant height (cm)	Pods $plant^{-1}$	Seeds pod^{-1}	100-seed mass (g)	Plant stand
ICPH 2658	3636	122	240	143	4.1	10.7	64
ICPH 2715	3071	118	232	202	4.2	10.0	58
ICPH 2704	2938	115	252	143	4.1	11.5	74
ICPH 2750	2889	120	248	135	4.0	11.7	58
ICPH 2717	2694	126	260	192	4.0	11.8	68
ICPH 2664	2599	122	240	182	4.1	10.4	51
ICPH 2691	2506	118	248	162	3.8	12.4	70
ICPH 2793	2412	115	238	156	4.0	8.8	62
ICPH 2716	2330	114	230	206	3.8	8.2	70
ICPH 2695	2277	122	225	160	4.3	12.2	38
ICPH 2755	2225	131	236	159	4.4	11.2	56
ICPH 2796	2032	115	218	152	3.9	8.7	69
ICPH 2678	1999	102	230	158	4.0	9.1	74
ICPH 2732	1979	130	251	212	4.4	10.7	56
ICPH 2783	1847	115	242	117	3.9	10.8	52
ICPL 87119 (control)	2593	128	232	144	4.1	10.9	86
SEm±	252.9	2.5	10.0	21.2	0.31	0.43	3.2
Mean	2501.8	119.4	238.9	163.9	1.04	10.56	62.9
CV (%)	14.3	3.0	5.9	18.3	10.98	5.70	7.1

good (10.7g). The other promising hybrids were ICPH 2715 (3071 kg ha^{-1}), ICPH 2751 (2710 kg ha^{-1}), ICPH 2682 (2971 kg ha^{-1}), ICPH 2704 (2938 kg ha^{-1}) and ICPH 2750 (2889 kg ha^{-1}).

The performance levels of these hybrids should be considered with caution, since these hybrids were made on male-sterile BC_1F_1s that still had a major proportion of wild species genome. In 2005, plant-to-plant crosses were made between A- and R-lines. Evaluation of these matings will help in identifying specific high-yielding combinations. It is also proposed to multiply the seed of two medium-duration hybrids in isolation for further testing. The fertility restoration in all the hybrid combinations was 95–100% and almost all the fertile plants had pollen load similar to that of control ICPL 87119.

Table 4.20(B). Standard heterosis (%) for important traits in pigeonpea medium-duration hybrids (A_4 cytoplasm) at ICRISAT, Patancheru, India, 2004.

Hybrid	Plant height	Pods $plant^{-1}$	Seeds pod^{-1}	Seed size	Grain yield
ICPH 2658	3.4	–0.7	0.0	–1.8	40.2
ICPH 2715	0.0	40.3	2.4	–8.3	18.4
ICPH 2704	8.6	–0.7	0.0	5.5	13.3
ICPH 2750	6.9	–6.25	–2.4	7.3	11.4
ICPH 2717	12.1	33.3	–2.4	8.3	3.9
ICPH 2664	3.4	26.4	0.0	–4.6	0.2
ICPH 2691	6.9	12.5	–7.3	13.8	–3.4
ICPH 2793	2.6	8.3	–2.4	–18.3	–7.0
ICPH 2716	–0.9	43.1	–7.3	–24.8	–10.1
ICPH 2695	–3.0	11.1	4.9	11.9	–12.2
ICPH 2755	1.7	10.4	7.3	2.8	–14.2
ICPH 2796	–6.0	5.6	–4.9	–20.2	–21.6
ICPH 2678	–0.9	9.7	–2.4	–16.5	–22.9
ICPH 2732	8.2	47.2	7.3	–1.8	–23.7
ICPH 2783	4.3	–18.8	–4.9	–0.9	–28.8

Hybrids with *C. sericeus* cytoplasm

All the test hybrids were developed on ICPA 99044, a medium-duration wilt and sterility mosaic resistant CMS line. A total of 27 hybrid combinations was evaluated. In general, the productivity levels of these hybrids were not very encouraging [Tables 4.21(A) and 4.21(B)]. However, ICPH 2329 (2441 kg ha^{-1}), ICPH 2327 (2201 kg ha^{-1}), ICPH 2352 (2662 kg ha^{-1}), ICPH 2914 (2566 kg ha^{-1}), ICPH 2913 (2477 kg ha^{-1}) and ICPH 2332 (2281 kg ha^{-1}) were up to 14% better than the controls. All the hybrids had high level of resistance to wilt and sterility mosaic.

Sixteen long-duration hybrids were evaluated at Patancheru. Since this location is not ideal for evaluating long-duration hybrids, their performance is likely to be underestimated. Among the long-duration hybrids tested, ICPH 2319 (3017 kg ha^{-1}) was the best with standard heterosis of 61.3% over best check ICPL 366, which produced 1870 kg grain ha^{-1} [Tables 4.22(A) and 4.22(B)].

Multilocational evaluation of hybrids

Multilocational hybrid pigeonpea trials involving 10 medium-duration hybrids and two controls were planted by Ankur Seeds (Nagpur), Zuari Seeds

Table 4.21(A). Performance of pigeonpea medium-duration hybrids (A_1 cytoplasm) at ICRISAT, Patancheru, India, 2004

Line	Grain yield (kg ha^{-1})	Time to flower (days)	Time to mature (days)	Plant height (cm)	Seeds pod^{-1}	100-seed mass (g)	Plant stand	DI[1]	
								Wilt	SM
ICPH 2329	2441	130	184	258	3.8	10.2	28	10	25
ICPH 2327	2201	125	178	252	3.7	11.9	25	0	0
ICPH 2337	2147	126	181	252	3.6	12.9	31	10	0
ICPH 2897	1832	127	181	245	3.7	11.8	28	0	0
ICPH 2898	1808	125	179	260	3.7	12.1	18	0	0
ICPH 2900	1775	131	185	260	3.5	11.2	29	0	0
ICPH 2334	1763	127	181	255	3.5	12.2	28	0	0
ICPH 2326	1745	125	179	250	3.5	12.8	18	0	0
ICPH 2899	1659	128	183	246	3.7	11.0	34	0	0
ICPH 2336	1569	130	184	240	3.7	12.8	32	0	0
ICPL 87119 (control)	2181	124	178	240	3.5	10.9	44	0	0
ICP 8863 (control)	1904	117	171	232	3.6	8.6	44	5	81
SEm±	135.1	1.1	1.5	5.0	0.10	0.33	2.4		
Mean	1918.9	126.2	180.3	249.1	3.61	11.53	29.8		
CV (%)	10.0	1.2	1.2	2.8	3.96	4.04	11.6		

1. DI = Disease incidence, SM = Sterility mosaic.

Table 4.21(B). Standard heterosis (%) for important traits in medium-duration hybrids (A_4 cytoplasm) at ICRISAT, Patancheru, India, 2004.

Hybrid	Plant height	Seeds pod^{-1}	Seed size	Grain yield
ICPH 2329	7.5	8.6	–6.4	11.9
ICPH 2327	5.0	5.7	9.2	0.9
ICPH 2337	5.0	2.9	18.3	–1.6
ICPH 2897	2.1	5.7	8.3	–16.0
ICPH 2898	8.3	5.7	11.0	–17.1
ICPH 2900	8.3	0.0	2.8	–18.6
ICPH 2334	6.3	0.0	11.9	–19.2
ICPH 2326	4.2	0.0	17.4	–20.0
ICPH 2899	2.5	5.7	0.9	–23.9
ICPH 2336	0.0	5.7	17.4	–28.1

Table 4.22(A). Performance of pigeonpea long-duration experimental hybrids (A_1 cytoplasm) at ICRISAT, Patancheru, India, 2004.

Hybrid	Grain yield (kg ha^{-1})	Time to flower (days)	Time to mature (days)	Plant height (cm)	100-seed mass (g)	Plant stand
ICPH 2319	3017	140	176	233	11.8	19
ICPH 2307	2855	141	175	250	9.1	34
ICPH 2306	2600	141	176	275	10.2	30
ICPH 2896	2579	141	174	258	8.9	28
ICPH 2308	2383	139	179	245	9.4	30
ICPH 2310	2268	141	179	263	9.4	34
ICPH 2305	2225	138	170	240	10.2	24
ICPH 2311	2092	140	179	253	9.9	30
ICPH 2323	1086	150	186	243	11.9	18
ICPL 366 (control)	1870	158	209	253	11.0	44
MAL 13 (control)	1407	164	206	230	10.4	41
SEm±	264.5	0.6	1.5	3.3	0.15	2.4
Mean	2283.3	144.0	181.7	248.1	10.22	31.2
CV (%)	16.4	0.6	1.2	1.9	2.02	10.7

Table 4.22(B). Standard heterosis (%) for important traits In pigeonpea long-duration hybrids (A_1 cytoplasm) at ICRISAT, Patancheru, India, 2004.

Hybrid	Plant height	Seed size	Grain yield
ICPH 2319	–7.9	7.3	61.3
ICPH 2307	–1.2	–17.3	52.7
ICPH 2306	8.7	–7.3	39.0
ICPH 2896	2.0	–19.1	37.9
ICPH 2308	–3.2	–14.5	27.4
ICPH 2310	4.0	–14.5	21.3
ICPH 2305	–5.1	–7.3	19.0
ICPH 2311	0.0	–10.0	11.9
ICPH 2323	–4.0	8.2	–41.9

Table 4.23(A). Performance of pigeonpea medium-duration hybrids (A_1 cytoplasm) at JK Seeds, Medchal, India, 2004.

Hybrid	Grain yield (kg ha^{-1})	Time to flower (days)	Time to mature (days)	Plant height (cm)	100-seed mass (g)	Plant stand
ICPH 2899	3038	122	192	185	11.0	28
ICPH 2307	2727	137	205	190	9.0	32
ICPH 2900	2514	137	192	184	11.0	26
ICPH 2305	2491	132	202	151	9.0	26
ICPH 2337	2117	123	190	188	12.0	30
ICPH 2336	2008	130	206	167	12.0	22
ICPH 2308	1951	131	202	185	9.0	34
ICPH 2898	1875	115	172	177	11.0	26
ICPH 2334	1666	122	186	169	11.0	22
ICPH 2897	1601	122	203	166	11.0	20
ICP 8863 (control)	1276	111	168	177	9.0	28
SEm±	227.6	2.0	2.3	15.6	0.00	2.5
Mean	2137.7	124.8	190.9	173.7	10.42	26.5
CV (%)	15.1	2.3	1.7	12.7	0.00	13.2

(Medchal), and JK Seeds (Medchal). At JK Seeds farm, ICPH 2899 produced 3.04 t grain ha^{-1}, recording a yield advantage of 27% over the control [Tables 4.23(A) and 4.23(B)]. In Nagpur (Ankur Seeds), hybrid ICPH 2898 recorded 4.2 t ha^{-1} grain yield [Tables 4.24(A) and 4.24(B)]. At the Zuari Seeds farm, the best hybrid ICPH 2308 (2.04 t ha^{-1}) recorded 38% superiority over the control ICPL 87119 [Tables 4.25(A) and 4.25(B)]. Considering the overall performance, the hybrid ICPH 2307 was found to be the best and it outyielded the controls ICPL 87119 by 8% and ICP 8863 by 24% [Tables 4.26(A) and 4.26(B)].

In the multilocational trials conducted by Mahyco also, the hybrids performed well. In the early-maturing group, three hybrids significantly outyielded the control in a multilocational trial, with TK 030003 (1.78 t ha^{-1}) recording 41% superiority over the control (Table 4.27). Among medium-duration hybrids, the superiority of hybrids over control ranged from 25 to 37%. Hybrid TK 030625 recorded the highest yield of 2.64 t ha^{-1} (Table 4.28). In the mid-late maturity group, hybrid TK 030861 (2.88 t ha^{-1}) outyielded the control ICPL 87119 by a margin of 47% (Table 4.29). In the long-duration group, two hybrids (TK 030039 and TK 030040) produced more than 4 t grain ha^{-1}, recording about 43–48% superiority over the control (Table 4.30).

Table 4.23(B). Standard heterosis (%) for important traits in pigeonpea medium-duration hybrids (A_1 cytoplasm) at JK Seeds, Medchal, India, 2004.

Hybrid	Plant height	Seed size	Grain yield
ICPH 2899	25.0	10.0	27.2
ICPH 2307	28.4	–10.0	14.1
ICPH 2900	24.3	10.0	5.2
ICPH 2305	2.0	–10.0	4.3
ICPH 2337	27.0	20.0	–11.4
ICPH 2336	12.8	20.0	–15.9
ICPH 2308	25.0	–10.0	–18.3
ICPH 2898	19.6	10.0	–21.5
ICPH 2334	14.2	10.0	–30.3
ICPH 2897	12.2	10.0	–33.0

Table 4.24(A). Performance of pigeonpea medium-duration hybrids (A_1 cytoplasm) evaluated at Ankur Seeds, Nagpur, India, 2004.

Hybrid	Grain yield (kg ha^{-1})	Time to flower (days)	Time to mature (days)	Plant height (cm)	100-seed mass (g)	Plant stand
ICPH 2898	4196	140	190	272	11.8	13
ICPH 2900	3371	153	206	266	9.8	13
ICPH 2308	3205	144	194	240	9.1	12
ICPH 2337	3125	142	192	260	11.8	12
ICPH 2897	3028	141	195	264	11.0	14
ICPH 2899	2872	141	192	254	11.8	12
ICPH 2334	2708	142	196	255	12.2	13
ICPH 2307	2664	146	195	268	8.1	14
ICPH 2336	2641	141	194	246	10.8	11
ICPH 2305	2314	159	206	266	9.5	14
ICP 8863 (control)	3780	124	174	232	10.2	13
ICPL 87119 (control)	2972	120	180	226	12.4	14
SEm±	363.0	1.1	3.2	12.2	0.48	0.7
Mean	3073.1	141.1	193.0	254.1	10.72	13.0
CV (%)	16.7	1.1	2.4	6.8	6.27	7.5

Table 4.24(B). Standard heterosis (%) for important traits in pigeonpea medium-duration hybrids (A_1 cytoplasm) evaluated at Ankur Seeds, Nagpur, India, 2004.

Hybrid	Plant height	Seed size	Grain yield
ICPH 2898	20.4	–4.8	41.2
ICPH 2900	17.7	–21.0	13.4
ICPH 2308	6.2	–26.6	7.8
ICPH 2337	15.0	–4.8	5.1
ICPH 2897	16.8	–11.3	1.9
ICPH 2899	12.4	–4.8	–3.4
ICPH 2334	12.8	–1.6	–8.9
ICPH 2307	18.6	–34.7	–10.4
ICPH 2336	8.8	–12.9	–11.1
ICPH 2305	17.7	–23.4	–22.1

Table 4.25(A). Performance of pigeonpea medium-duration hybrids (A_1 cytoplasm) evaluated at Zuari Seeds, Medchal, India, 2004.

Hybrid	Grain yield (kg ha^{-1})	Time to flower (days)	Time to mature (days)	Plant height (cm)	100-seed mass (g)	Plant stand
ICPH 2308	2037	124	178	210	8.5	20
ICPH 2307	1852	126	185	213	9.2	16
ICPH 2899	1667	123	180	165	11.0	12
ICPH 2334	1667	124	184	175	13.0	10
ICPH 2336	1574	123	182	205	14.0	14
ICPH 2337	1574	122	184	205	14.0	13
ICPH 2305	1574	127	173	197	10.0	20
ICPH 2897	1389	122	181	205	12.0	10
ICPH 2900	1111	125	181	218	9.5	7
ICPH 2898	1019	122	183	200	14.0	12
ICP 8863 (control)	1296	120	182	180	8.5	13
SEm±	131.7	1.8	0.4	11.9	0.79	1.8
Mean	520.1	123.1	181.1	196.0	11.33	13.5
CV (%)	12.3	2.1	0.3	8.6	9.85	19.0

Table 4.25(B). Standard heterosis (%) for important traits in pigeonpea medium-duration hybrids at Zuari Seeds, Manoharabad, India, 2004.

Hybrid	Plant height	Seed size	Grain yield
ICPH 2308	15.4	–30.3	37.5
ICPH 2307	17.0	–24.6	25.1
ICPH 2899	–9.3	–9.8	12.6
ICPH 2334	–3.8	6.6	12.6
ICPH 2336	12.6	14.8	6.3
ICPH 2337	12.6	14.8	6.3
ICPH 2305	8.2	–18.0	6.3
ICPH 2897	12.6	–1.6	–6.2
ICPH 2900	19.8	–22.1	–25.0
ICPH 2898	9.9	14.8	–31.2

Table 4.26(A). Mean grain yield (kg ha^{-1}) of pigeonpea hybrids (A_1 cytoplasm) evaluated **at five locations in central India.**

Hybrid	Nagpur	Ravalcol	Patancheru	Hyderabad	Jalna	Mean
ICPH 2307	2664	2727	2342	1852	1819	2281
ICPH 2899	2872	3038	2187	1667	1484	2250
ICPH 2898	4196	1875	2245	1019	1244	2116
ICPH 2308	3205	1951	2159	2037	1069	2084
ICPH 2337	3125	2117	2231	1574	1252	2060
ICPH 2900	3371	2514	1646	1111	1511	2031
ICPH 2336	2641	2008	1918	1574	1652	1959
ICPH 2305	2314	2491	2247	1574	1113	1948
ICPH 2897	3028	1601	2256	1389	1363	1927
ICPH 2334	2708	1666	1975	1667	1334	1870
ICPL 87119 (control)	2972	2389	2256	1481	1425	2105
ICP 8863 (control)	3780	1276	1807	1296	1063	1844
SEm±	363.0	227.6	296.4	131.7	–	
Mean	3073.1	2137.7	2105.8	1520.1	1360.5	
CV (%)	16.7	15.1	19.9	12.3	14.4	

Table 4.26(B). Standard heterosis (%) for grain yield in pigeonpea hybrids (A_1 cytoplasm) at five locations in India, 2004.

Hybrid	Nagpur	Ravalcol	Patancheru	Hyderabad	Jalna	Mean
ICPH 2307	–10.4	14.1	3.8	25.1	27.6	8.4
ICPH 2899	–3.4	27.2	–3.1	12.6	4.1	6.9
ICPH 2898	41.2	–21.5	–0.5	–31.2	–12.7	0.5
ICPH 2308	7.8	–18.3	–4.3	37.5	–25.0	–1.0
ICPH 2337	5.1	–11.4	–1.1	6.3	–12.1	–2.1
ICPH 2900	13.4	5.2	–27.0	–25.0	6.0	–3.5
ICPH 2336	–11.1	–15.9	–15.0	6.3	15.9	–6.9
ICPH 2305	–22.1	4.3	–0.4	6.3	–21.9	–7.5
ICPH 2897	1.9	–33.0	0	–6.2	–4.4	–8.5
ICPH 2334	–8.9	–30.3	–12.5	12.6	–6.4	–11.2

Table 4.27. Grain yield (t ha^{-1}) of three pigeonpea short-duration Mahyco-bred hybrids at six locations in India, 2004.

Location	TK 030003	TK 030009	TK 030006	UPAS120 (control)
Jalna	1.3	1.6	1.3	1.2
Sarwadi	1.3	1.4	1.6	1.0
Yeotmal	2.1	2.0	1.9	1.9
Gulbarga	2.3	1.6	1.4	1.2
Shamshabad	1.3	1.3	1.3	1.0
Khargone	2.4	1.6	1.4	1.2
Mean	1.78	1.58	1.49	1.26
Heterosis (%)	41	25	18	–

Source: Mahyco, India.

Linkages with partners

ICRISAT strongly believes in harvesting more through joining hands with its partners. This partnership is broad-based and involves public and private sector institutions. In a recently developed partnership project with ICAR and financially supported by Integrated Scheme of Pulses, Oilseeds and Maize (ISOPOM), Ministry of Agriculture and Cooperation, Government of India, a joint program was formulated to develop, evaluate and make available pigeonpea hybrids in the next five years. In this project six ICAR institutions [Indian Institute of Pulses Research (IIPR), Kanpur; GAU, SK Nagar; PAU,

Table 4.28. Grain yield (t ha^{-1}) of three pigeonpea medium-duration Mahyco-bred hybrids at different locations in India, 2004.

Location	TK 030625	TK 040174	TK 030555	ICP 8863 (control)
Jalna	2.3	2.3	2.1	1.7
Sarwadi	3.3	2.9	2.8	2.5
Yeotmal	2.3	2.2	2.2	1.8
Gulbarga	3.0	2.7	2.7	2.3
Shamshabad	2.3	2.4	2.0	1.6
Khargone	3.0	2.8	2.8	1.8
Mean	2.64	2.54	2.44	1.96
Heterosis (%)	37	30	25	

Source: Mahyco, India.

Table 4.29. Grain yield (t ha^{-1}) **of five pigeonpea medium-late Mahyco-bred hybrids at** different locations in India, 2004.

Location	TK 030861	TK 030851	TK 030812	TK 030511	ICPL 87119 (control)
Jalna	2.4	2.6	2.3	2.6	2.0
Sarwadi	2.7	2.5	2.4	1.7	2.1
Yeotmal	2.9	3.0	2.8	2.6	1.8
Gulbarga	3.4	3.1	1.9	3.6	2.1
Shamshabad	3.1	2.9	2.4	3.2	1.8
Khargone	2.8	2.6	2.5	1.7	2.2
Mean	2.88	2.78	2.38	2.55	1.96
Heterosis (%)	47	42	21	30	–

Source: Mahyco, India.

Ludhiana; TNAU, Coimbatore; PDKV, Akola; and Agriculture College, Navasari] are joining hands with ICRISAT. The highlight of this partnership is the sharing of responsibilities to achieve a common goal.

In India, the private seed sector has played an important role in achieving self-sufficiency in food availability. This sector's contribution to cereals [maize (*Zea mays*), sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*)], oilseeds [sunflower (*Helianthus annuus*), castor (*Ricinus communis*)], fiber [cotton (*Gossypium* sp)] and a number of vegetable and fruit crops is well recognized and documented. Although this sector markets numerous hybrids each year, the seed industry is always on the lookout for new products and

Table 4.30. Grain yield (t ha^{-1}) of four long-duration Mahyco-bred hybrids at different locations in India, 2004.

Location	TK 030039	TK 030040	TK 030706	TK 030712	Bahar (control)
Jalna	4.0	3.6	3.9	3.9	2.8
Sarwadi	4.3	3.9	3.8	3.8	3.0
Yeotmal	4.6	4.4	4.3	4.4	3.1
Gulbarga	4.3	4.4	3.7	3.7	2.8
Shamshabad	4.3	4.2	3.9	3.8	2.7
Khargone	3.9	3.8	3.4	3.6	2.8
Mean	4.21	4.08	3.83	3.86	2.85
Heterosis (%)	48	43	35	36	

Source: Mahyco, India.

pigeonpea hybrid is one such commodity. Therefore, ICRISAT shares the other partnership platform with nine private seed companies (Table 4.31). Since it is a new commodity, ICRISAT is helping them in establishing their core hybrid breeding research programs by providing seed materials, production technology and training. Every year, the cropping season starts with a planning and review meeting with each partner separately and the interaction continues throughout the season including monitoring visits.

At present, the Government of Peoples' Republic of China is the only international partner. The Yunnan Academy of Agricultural Sciences (YAAS), Kunming; Guangxi Academy of Agricultural Sciences (GxAAS), Nanning; and Chinese Academy of Agricultural Sciences (CAAS), Beijing are ICRISAT's active partners. In China, since pigeonpea is primarily grown for soil conservation and fodder, and this production system needs the genotypes which have (i) faster seedling growth, (ii) rapid establishment of dense canopy, (iii) stronger root system, (iv) drought tolerance, (v) high vegetable and dry seed yield, and (vi) high level of ratoonability and perenniality, ICRISAT believes that the perennial hybrids will be more successful than pure line varieties. The studies conducted at ICRISAT have shown that the hybrids have most of the traits listed above. The hybrid pigeonpea breeding program in China has started recently with training of scientists and by supplying seed materials and production technology.

Table 4.31. Summary of pigeonpea hybrid trials and breeding materials supplied by ICRISAT to partners in 2004.

Seed company/ Institutions	Hybrid trials	Observation nurseries	Breeding lines		Total
			A × B	R	
Seed companies					
Ankur Seeds	4	2	20	13	22
JK Seeds	3	–	10	10	20
Zuari Seeds	3	–	10	34	44
Pradham Biotech	1	1	–	–	–
Mahyco	4	3	18	30	48
Bio Seeds	2	2	10	22	32
Krishidhan	1	2	12	26	38
Nuziveedu Seeds	–	1	18	15	33
ICAR institutions[1]					
IARI, New Delhi	1	–	1	–	1
ARS, Rajasthan	1	–	–	–	–
IIPR, Kanpur	2	–	3	–	3
UAS, Bangalore	1	–	2	–	2
TNAU, Coimbatore	1	–	–	–	–
PAU, Ludhiana	2	–	3	–	3
Total	26	11	107	150	257

1. IARI = Indian Agricultural Research Institute; ARS = Agricultural Research Station; IIPR = Indian Institute of Pulses Research; UAS = University of Agricultural Sciences; TNAU = Tamil Nadu Agricultural University; PAU = Punjab Agricultural University.

Technology transfer

In this partnership of hybrid pigeonpea breeding program, ICRISAT's major strength is the sharing of knowledge, breeding materials and experience. To initiate the hybrid breeding program with partners, a total number of 191 breeding lines, 20 hybrid trials and 6 observation nurseries were supplied during 2004 season. The research agenda is often guided by present and future needs of the farmers and seed industry.

New frontiers and strategies

Pigeonpea still remains a wild plant even after centuries of cultivation as it has retained its unique characteristics such as perenniality, indeterminate growth, low harvest index and photo-thermal sensitivity. However, its multiple uses and role in sustaining agricultural productivity makes it a favorite crop of small holding rainfed farmers. In the last few decades, a significant progress has been made in domesticating the crop by developing short-duration and determinate types but a large scope for its further improvements still exists. The promotion of disease resistant pure line varieties has helped in stabilizing the productivity and in increasing the production at the national level.

Progress so far has not been enough to meet the demand, as the productivity has shown no sign of improvement. The advent of hybrid technology has given us hope. The present achievements have established the hybrid technology but a lot has to be done in the next decade to show the impact of this technology. More human and financial resources will be required to develop the parental materials suitable for diverse environments in India. The next most important target will be to develop hybrids with insecticidal genes with high quality. The seed production package has to be worked out for each agro-ecological system of the country.

Summary

Pigeonpea is an important legume crop with global production of 2.9 million t harvested each year from over 4.2 million ha of rainfed lands. The demand for pigeonpea in India is increasing and to meet the domestic needs over 300,000 t of pigeonpea seed is imported from Myanmar (Burma) and Africa. Over the last 50 years the productivity of pigeonpea has recorded no significant increase. The stagnation of productivity for such a long period is a matter of serious concern, and hybrid pigeonpea technology offers good scope for breaking the yield barrier. ICRISAT has led research on hybrid pigeonpea, and the release of the world's first hybrid (ICPH 8) in 1991 is considered a milestone in pigeonpea improvement history. The 25–30% superiority of this hybrid could not benefit Indian farmers because ICPH 8 was developed by using a genetic male-sterile line, and seed production bottleneck impeded the commercial hybrid seed production. This release, however, encouraged the pigeonpea breeders to overcome the seed production constraint by developing a more efficient CMS system.

ICRISAT took this challenge and succeeded in developing CMS systems by crossing wild relatives of pigeonpea as female parent with the cultivated type as male parent. Among these, the CMS system derived by crossing C. *cajanifolius*, and designated as A_4 cytoplasm, is the best. In the past four years ICRISAT not only diversified the genetic base of A-lines but also

successfully bred their fertility restorers. Enhanced emphasis was given to incorporate disease (fusarium wilt and sterility mosaic) resistance in the hybrid parents to produce high-yielding, disease resistant hybrids. The first generation of CMS-based hybrids have shown significant levels of hybrid vigor with >25% yield advantages. This technology has been shared with a number of public and private seed companies and research institutions. ICRISAT is also giving importance to human resource development and capacity building of partners. Each year a number of scientists and technicians are trained in hybrid breeding technology. The adoption of this technology is slowly increasing and ICRISAT is pleased to share hybrid breeding technology with partners in both public and private sectors globally. The CMS-based hybrids will be available for production and cultivation in the next 2–3 years.

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About ICRISAT

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is a nonprofit, non-political organization that does innovative agricultural research and capacity building for sustainable development with a wide array of partners across the globe. ICRISAT's mission is to help empower 600 million poor people to overcome hunger, poverty and a degraded environment in the dry tropics through better agriculture. ICRISAT belongs to the Alliance of Future Harvest Centers of the Consultative Group on International Agricultural Research (CGIAR).

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