Global Sorghum Genetic Enhancement Processes at ICRISAT

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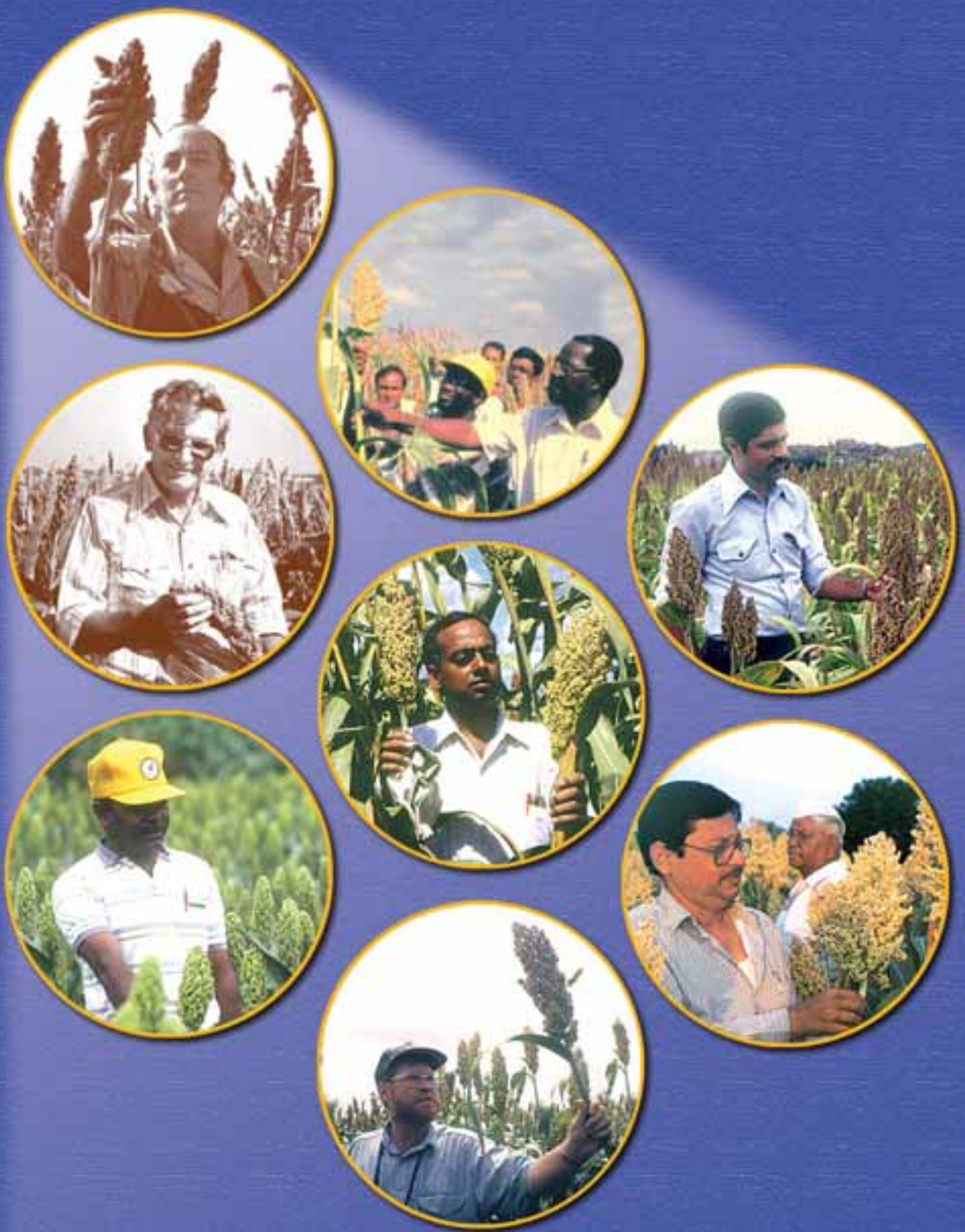

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BVS Reddy[1], Prakasha Rao[2], UK Deb[3], J W Stenhouse[2], B Ramaiah[2] and R Ortiz[2]

4.1. Introduction

The global production of sorghum in 2003 is about 59 million t with an average productivity of 1.34 t ha^{-1} (FAO http://www.fao.org). Despite advances in breeding improved cultivars, productivity has increased only marginally. Productivity recorded at research stations in African countries and in India, Myanmar, Pakistan and Thailand in Asia was 3.5-4.0 t ha^{-1} in the rainy season. In China, it is about 12 t ha^{-1} at research stations but only 0.8-2.5 t ha^{-1} in farmers' fields. This productivity gap of about 9-11 t ha^{-1} remains a challenge for agricultural scientists and extension specialists to bridge. Several biotic and abiotic stresses account for this gap.

The NARS need more research support in developing countries where sorghum productivity is much lower (about 1 t ha^{-1}) than in developed countries (3.5 t ha^{-1}) (Doggett 1988). The genetic enhancement efforts at ICRISAT are aimed at meeting this need. ICRISAT scientists located in Asia (at Patancheru, Andhra Pradesh, India); West Africa (at Bamako, Mali and Kano, Nigeria); Eastern Africa (Nairobi, Kenya); Southern Africa (Bulawayo, Zimbabwe) and Latin America (El Batan, Mexico) have been conducting sorghum improvement research in collaboration with NARS scientists.

This chapter briefly describes the global sorghum breeding processes followed over the years at ICRISAT, Patancheru. It also discusses the status of various germplasm sources identified and utilized in developing male-sterile lines and pure-line materials, exploitation of the male-sterility system, screening techniques and breeding concepts, the genetics and mechanisms of resistance, the materials tested in international trials and the cultivars released from ICRISAT-developed materials.

4.2. Evolution of Sorghum Breeding at ICRISAT

ICRISAT has been engaged in sorghum improvement since 1972. Its breeding program has seen several results: segregating families, populations with specific traits, intermediate products such as restorers or varieties, male-sterile lines, etc, with resistance to various biotic and abiotic factors. Improved sorghum cultivars (varieties and hybrids) developed by NARS in collaboration with ICRISAT have been released in several countries. Since its establishment in 1972, ICRISAT has made deliberate attempts to diversify the germplasm base to enhance yield levels and to identify sources of resistance to pests and diseases and use them to develop varieties and seed parents.

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Incorporating diverse germplasm into elite breeding materials widens the gene base but requires time, effort and resources. The transfer of undesirable traits appears to be an unavoidable consequence of the introgression process. ICRISAT's role has been to emphasize the long-term goals of developing diverse source materials and intermediate products that are essential for future gains. In utilizing genetic resources, ICRISAT pursues three broad approaches: (1) transfer of genes for specific traits such as disease or pest resistance from the germplasm source into an agronomically desirable background; (2) formation of gene pools for specific traits, which results in diversity of the 'genetic background' as well as for the target trait; and (3) development of new methods for effective utilization of genetic resources such as application of molecular marker-assisted selection.

Breeding concepts and objectives and the mode of research involving partners have undergone several changes since the initiation of sorghum improvement at ICRISAT. The external environment, the perceptions of development investors, NARS capacities and ICRISAT's research agenda have influenced the evolution of the global breeding program. For the sake of convenience, we discuss this evolution – which is continuing – in six major phases:

1. Wide adaptability and high grain yield (1972-1975)
2. Wide adaptability and screening techniques (1976-1979)
3. Regional adaptation and resistance breeding (1980-1984)
4. Specific adaptation and resistance breeding (1985-1989)
5. Trait-based breeding and sustainable productivity (1990-1994)
6. Upstream research and intermediate products (1995 onwards)

4.2.1. Wide Adaptability and High Grain Yield (1972-1975)

This period was characterized by the generous support of development investors and an immediate need to develop varieties with wide adaptability and higher grain yield. The emphasis was on wide adaptability with the premise that the materials developed at ICRISAT-Patancheru would be adapted in various SAT regions of the world. Higher grain yield, primarily in the red grain background, was the major breeding objective. Population improvement through recurrent selection was carried out in 33 populations collected from the USA (from the universities of Nebraska, Purdue and Kansas) and Australia, and from the programs in West Africa (Nigeria) and East Africa (Tanzania). Nine populations such as the Indian diallel population (white grain), the tropical conversion population (Puerto Rico), high-altitude population, etc, were also improved. Multi-environment testing for grain yield was carried out initially at Patancheru in varied soils and seasons (ICRISAT 1975). Resistance to shoot fly, grain mold and *Striga* was considered important later on and programs to identify resistant sources were initiated. Studies on grain characters that contribute to food and nutritive traits such as high lysine content were also begun. NARS involvement during this phase was confined to providing information on constraints to sorghum production and final testing of advanced breeding lines for adoption.

4.2.2 Wide Adaptability and Screening Techniques (1976-1979)

The major research thrusts during this period were (a) identifying high-yielding genotypes; (b) developing efficient screening techniques for yield constraints; and (c) identifying sources of resistance. New variability was generated by crossing male-sterile plants in populations with select germplasm lines or named cultivars to select for high grain yield. Population breeding approaches

-source populations, backup populations, advanced populations and fast-lane populations – were improved for high grain yield and wide adaptability through wider testing of S_1/S_2 progenies. International trials were initiated in Africa, Asia and South America (ICRISAT 1976a) to identify materials with high grain yield potential and wide adaptability. Greater emphasis was laid on breeding photoperiod-insensitive varieties with earliness. Screening techniques to identify sources of resistance to major pests and diseases (including *Striga)* were given major emphasis during this phase. Thus, in addition to breeding for high grain yield, research was initiated to develop materials with resistance. While retaining the emphasis on population improvement, programs for wide adaptability, high grain yield and specific pedigree breeding were also initiated for (a) drought resistance; (b) stalk rot resistance and postrainy season adaptability; (c) downy mildew resistance; and (d) grain mold resistance in cream colored grain genotypes. The sorghum program allocated 50% of its resources to population improvement, and 50% to work on specific adaptability, including grain nutritional quality. A major shift in selection from red-grained to white-grained genotypes occurred during this phase. Research on foodgrain quality was pursued with greater vigor. The target materials were expanded to include seed parents and hybrids in addition to varieties. A regional program based in Burkina Faso in West Africa started working on regional adaptability towards the end of 1978 (ICRISAT 1978b), the details of which can be found in Chapter 5 of this book.

4.2.3. Regional Adaptation and Resistance Breeding (1980-1984)

This phase was characterized by (a) intensive testing of varieties in international trials for high grain yield in various regions and in international nurseries for resistance to various pests and diseases; (b) initiation of work on regional adaptability including tolerance to early-, mid- and late-season drought; (c) breeding for high grain yield and resistance to various pests and diseases to ensure sustainability of production; (d) large-scale production and testing of hybrids; and (e) further refinement of various screening techniques. Collaborative research was initiated at various locations in India (Anantapur, Bhavanisagar, Bijapur and Dharwad), West Africa (Burkina Faso), East Africa (Nairobi) and Latin America (Mexico) to serve regional needs. Thus, three regional programs were established in addition to the global program at Patancheru. The scope of the West Africa program was expanded to include breeding for *Striga* resistance in Africa in addition to regional adaptation. Materials bred at Patancheru were introduced and evaluated in all the regional programs. This enabled ICRISAT to identify several promising lines adapted to various regions. Screening techniques for resistance to grain mold, downy mildew, rust, anthracnose, leaf blight, charcoal rot, shoot fly, stem borer, midge and *Striga* were refined. Similarly, techniques to screen materials for emergence under high temperatures and crusting, and for tolerance to early-, mid- or late-season drought were also developed. Both population improvement (with recurrent selection) and pedigree breeding programs were given equal emphasis. White-grain types that are useful in preparing various foods (ICRISAT 1985) were preferred, and, as a result, grain color variability in the breeding materials was lost. Thus, by the end of this project the initial program of breeding for wide adaptability was diversified into regional programs by taking advantage of various ICRISAT sites in Africa and Latin America.

4.2.4. Specific Adaptation and Resistance Breeding (1985-1989)

This period was characterized by regional network trials and development of high-yielding and pest/disease-resistant pure lines. In addition to the International Sorghum Varieties and Hybrids

Adaptation Trials (ISVHAT), the Asian Regional Sorghum Hybrids Adaptation Trial (ARSHAT), the Asian Regional Sorghum Varietal Adaptation Trial (ARSVAT), the Eastern Africa Co-operative Sorghum Screening Nursery (EACSSN), and the West Africa Sorghum Hybrid Adaptation Trials (WASHAT) were conducted. For the first time, networking gave member countries greater participation in planning these trials, including the opportunity to test their own materials in other countries. In addition to the sites in West Africa, East Africa and Latin America, ICRISAT established another research location at Bulawayo, Zimbabwe, for Southern Africa. Concerted efforts were made to identify the major abiotic and biotic constraints in each region and a breeding program was initiated to develop multifactor-resistant (MFR) populations and targeted populations (Table 4.1) As a result, there was a shift from developing high-yielding populations to MFR populations. Later, R/MFR, B/MFR and BR/MFR populations were merged to form ICSP 1BR/MFR and ICSP 2BR/MFR populations for rainy-season adaptation (Africa and Asia), and the BR/MFR population was continued as ICSP 3BR/MFR population for the postrainy season. In addition, a pedigree-breeding program for specific adaptability was carried out to develop high-yielding varieties with resistance to appropriate insect pests and diseases at each of the locations. Thus, season and location specificity were factored within, combining high grain yield and a set of resistant factors. At least seven geographic areas – Latin America (low altitude and high altitude), West Africa, East Africa, Southern Africa and Asia (rainy and postrainy seasons) – were addressed during this phase.

Table 4.1. Multifactor-resistant (MFR) populations developed at ICRISAT.

Population	Important traits incorporated	Traits monitored
ICSP 1R/MFR and ICSP 2B/MFR	Resistance to grain mold, stem borer or shoot fly and midge	Improved grain yield, charcoal rot, stand establishment, *Striga* and food quality
ICSP 3R/MFR and ICSP 4B/MFR	Stand establishment and resistance to grain mold and *Striga*	Improved grain yield, charcoal rot, stem borer or shoot fly, midge and food quality
ICSP 5BR/MFR	Improved grain yield and resistance to stem borer or shoot fly and *Striga* and food quality	Charcoal rot, grain mold, midge and stand establishment

4.2.5. Trait-based Breeding and Sustainable Productivity (1990-1994)

By the late 1980s, many NARS had enhanced their crop improvement programs, and were involved in planning the crop improvement programs of International Agricultural Research Centers (IARCs) aimed at specific adaptability. Therefore, during 1989/90, a major review of the efficiency of various breeding programs was undertaken at ICRISAT and the following decisions were taken:

- Population improvement would be scaled down to gene pool development as it was not found to be as efficient as pedigree breeding in meeting short-term goals.
- Combining several resistance traits at one time is less efficient. Hence, a trait-based breeding approach was suggested.
- Intermediate products such as seed parents, restorers and gene pools were suggested as the target materials for the ICRISAT-Patancheru program, and finished products (varieties and hybrids) for the Africa-based programs.
- A participatory mode of research planning and execution would be followed, involving the NARS on the basis of their needs.

- Since A/B-lines were susceptible to most of the diseases and pests, major emphasis would be placed on incorporating resistance into high-yielding seed parents at ICRISAT-Patancheru.
- Materials would be tailored to production systems in specific areas within the region. On the basis of the amount and duration of rainfall, growth period of the crop, temperature and soils, a total of 29 production systems (PSs) in the semi-arid tropics were identified.

Thus, the global sorghum improvement program was reoriented to develop materials suitable to 12 PSs in Asia, 6 in West Africa, 6 in East and Southern Africa and 5 in Latin America. The severity of the constraints to sorghum productivity in each PS was prioritized and formed the main focus of research in sorghum breeding (Table 4.2).

Table 4.2. Drought and biotic constraints and their severity affecting sorghum productivity in the SAT.

		Low rainfall			Medium rainfall						High rainfall		Post-rainy	Low temp. high elev.	
		Asia PS[1]	WA PS[2]	E&SA PS[3]	Asia PS		WA PS		E&SA PS		WA PS	E&SA PS	Asia PS	E&SA PS	LA PS[4]
Themes/ constraints[5]	Rank[6]	1	13	19	4	7	9	14	15	20	21	16	22	8	23	26
Striga	18			4		3		5	5	5	5	5				
Grain/stover	22	3	4	3	3	5	5	5	5	5	5	4			5	4
Stem borer	34		4	3	4	3	3	5	5	5	3	5		4		
Grain mold	35		3			3	4	3	4		4	5	5		3	
Low temperature	44														5	
Head bugs	46		3			3	4	4	5	3		5				
Anthracnose	48				3			4	5	3	5	5			4	
Midge	49											4			4	
Acidic soil	61															
Drought	65	3	5	5			3	5	4	5	3			4		
Leaf blight	66									3	5				4	3
Foliar diseases	72								3			3				4
Shoot fly	76						4		3			4		5		
Forage	86		3					4								3
Sooty stripe	100							4	4		4	4				
Long smut	101		5	3				5	4			3				
Storage pests	102		4	3				4	3	4	4	3			3	
Ergot	104								4		3	4				

1. Asia PS = Asian production systems.
2. WA PS = West African production systems.
3. E&SA PS = East and Southern African production systems.
4. LA PS = Latin American production systems.
5. Severity was measured on a scale of 1 to 5, where 1 = least severe and 5 = most severe. The analysis is based on ICRISAT project planning exercise, 1994.
6. Ranking of constraints across crops at ICRISAT; Source: ICRISAT (1992a).

Dynamic crop improvement programs were conducted by ICRISAT at Patancheru (India), Bamako (Mali), Kano (Nigeria), Nairobi (Kenya) and Bulawayo (Zimbabwe). At Patancheru, the emphasis during these years was on strategic research–development of techniques and intermediate products for utilization by the NARS programs in Asia. Accordingly, an extensive program of diversifying and breeding new milo cytoplasmic male-sterile lines for earliness, introgression with *Durra* and *Guinea* races, incorporating bold and lustrous grain characters, and resistance to *Striga*, shoot fly, stem borer, midge, head bug, grain molds, downy mildew,

anthracnose, leaf blight and rust was carried out (ICRISAT 1993a). The usefulness of single-cross male-sterile F_1s in developing three-way-cross forage hybrids was also examined (ICRISAT 1995). Strategic research was carried out to gain knowledge on stability of alternative cytoplasms, identification of differential minimum testers for various male-sterile cytoplasms, conversion of improved resistance sources into male-steriles using alternative cytoplasms, development of isonuclear lines, genetic methods of rectifying low temperature-induced female sterility in 296A and development of restorer lines for alternative cytoplasms (ICRISAT 1995). Information was generated on the role of early seedling vigor and growth rate in biomass accumulation. A restorer breeding program was undertaken to develop high-yielding lines with resistance to shoot fly, stem borer, midge and grain mold, and significant gains were realized in combining midge resistance and high grain yield in restorers or varieties.

Novel populations or trait-specific gene pools for bold grain and high productive tillering were developed. Test crosses involving progenies of postrainy-season landraces as pollinators were examined for their fertility restoration ability under cool nights and for productivity in the postrainy season. Variability for restoration was quite significant, indicating the possibility of selection within and among landraces. The frequency of hybrids with productivity was higher in landrace hybrids than in bred restorer hybrids (Reddy and Stenhouse 1994). Unlike other released cultivars, landrace hybrids mimic landraces in the postrainy season and, therefore, would have better acceptance. Progress in improving cultivars by introducing desirable resistance or earliness for adaptation to specific regions was reported at other ICRISAT locations (ICRISAT 1991; ICRISAT 1992b; ICRISAT 1992c; ICRISAT 1993b and ICRISAT 1993c). Chapters 5 and 6 provide further details of sorghum research in Africa and Latin America, respectively.

4.2.6. Upstream Research and Intermediate Products (1995 Onwards)

The sorghum improvement program was further reviewed in 1994, and emphasis was laid on upstream research including biotechnology tools. The partnership mode of conducting research to develop improved intermediate products at ICRISAT-Patancheru and finished products (varieties and hybrids) at other ICRISAT locations in Africa was emphasized.

The current emphasis is to produce parental lines (seed parents and pollen parents) and gene pools. Accordingly, the objectives of the program are to breed resistant seed parents and restorer lines, to develop specific new gene pools and novel plant types and to identify and use molecular markers. The breeding programs in Africa will continue to develop high-yielding cultivars (varieties and hybrids) with resistance to *Striga* and head bug which are endemic to the region.

ICRISAT's Medium Term Plan (1994-98) (ICRISAT 1992a) reassessed various constraints to sorghum production in the SAT on a global basis, giving less emphasis to minor local factors. It prioritized further the importance of these constraints to provide a rational basis for the allocation of resources and time. Eighteen research themes (see Table 4.2) were thus reduced to 13 (Table 4.3). All the 13 major themes are being addressed through global research projects. Many of these constraints are common to some production systems. ICRISAT's global sorghum projects take into account these common features as well as the individual requirements of different regions. Table 4.4 lists the main constraints to sorghum production in Asia and Africa, as identified in the MTP 1994-98, and the strategies adopted by breeders working in the regional programs to address them. In general, the occurrence of a constraint, the comparative advantage of a location or region and research need (Table 4.3) provide the basis for emphasis on a type of research in any region. In Asia,

the NARS have considerable strength in terms of scientific manpower and research infrastructure, and the private seed industry is well established. So, ICRISAT mainly develops suitable intermediate products such as hybrid parents and random-mating gene pools with specific traits for Asia. In Africa, the NARS in general are still developing their research infrastructure, the private seed industry is still in its infancy and public seed services are not yet strong. So, in that region, ICRISAT develops finished products such as varieties and hybrids.

Diversification of the genetic base of breeding lines is an important objective, which is achieved by intercrossing resistant sources of diverse origin – often of different races – with agronomically elite lines. At ICRISAT-Patancheru, recurrent selection is practised in broad-based, random-mating

Table 4.3. Ranking of 13 constraints or themes relevant to sorghum in 10 production systems of the SAT[1].

	Production Systems (PS)									
	Asia				West and Central Africa			East and Southern Africa		
Constraint/theme[2]	PS 4	PS 7	PS 8	PS 9	PS 14	PS 15	PS 16	PS 19	PS 20	PS 21
Drought			4	3	5	4		5	5	3
Low temperature										
Grain molds		3		4	3	4	5			4
Anthracnose	4				4	5	5		3	4
Leaf blight						3	3		3	5
Foliar diseases						3	4			
Stem borer	4	3	4	3	5	5	5	3	5	3
Midge		5		4	5	4	4			
Head bug		3		4	4	5	5		3	5
Shoot fly			5	4						
Striga		3			5	5	5	4	5	5
Grain and stover yield	3	5	3	5	5	5	4	3	5	5
Forage sorghum		3			4					

1. Source: Medium Term Plan, ICRISAT 1994-98 (ICRISAT 1992a).
2. Severity measured on a scale of 1 to 5, where 1 = least severe and 5 = most severe. Analysis based on ICRISAT project planning exercise, 1994.

Table 4.4. Important constraints to sorghum production targeted for genetic improvement in Asia and Africa.

Constraint/theme	Asia	West and Central Africa	Eastern Africa	Southern Africa
Drought	++[1]	+[2]	+	++
Low temperature	_[3]	_	++	_
Grain molds	++	+	_	_
Anthracnose	++	++	_	_
Leaf blight				
Foliar diseases	+	++	_	_
Shoot fly	++	_	+	_
Striga	+	++	+	++
Stem borer	++	++	+	+
Midge	++	+	+	_
Head bug	+	++	_	_
Grain and stover yield	++	++	++	++

1. ++ = Basic, strategic and applied research.
2. + = Applied and adaptive research.
3. _ = No emphasis.

populations or gene pools for specific traits [such as maintainer (B), restorer (R), high tillering (HT), large grain (LG)], and resistance to shoot pests, grain molds and head pests. In West and Central Africa (WCA), the development of random-mating populations of *Guinea* and *Caudatum* races has been completed and another *Guinea* × *Caudatum* type population is under development. Random-mating populations for early maturity have been developed in Southern Africa. These populations will have good agronomic backgrounds and adaptability while preserving their broad genetic variability. Another important goal is to broaden the cytoplasmic-genetic diversity of hybrid parents. Grain yield improvement of several female parents of non-milo origin ($A_2/A_3/A_4$) and incorporation of resistance factors in A_1 cytoplasmic male-sterile lines is being pursued using backcrossing procedures.

Farmers are involved in ICRISAT's selection processes through visits to germplasm and preliminary cultivar nurseries on station. Groups of farmers are invited to the station through extension agencies and nongovernmental organizations (NGOs). They are asked to evaluate the entries on a simple scale of 1 to 5 (1 = excellent, 5 = very poor) on an overall basis or for individual agronomic traits, depending upon the targets of the trial. Their scores are compared with agronomic data collected independently to help identify their preferences. Thus, the farmers' impressions and visual scores of preliminary or advanced entries in comparison with their own local checks are integral to participatory selection of cultivars. Conclusions from such exercises help retarget breeding and selection procedures on the basis of farmer-preferred traits. The best cultivars emanating from advanced trials are tested in on-farm trials managed by the farmers themselves. On-farm trials are organized in collaboration with NARS and NGOs, and are monitored by multidisciplinary teams (socioeconomists, breeders, crop protectionists and agronomists) from ICRISAT and NARS.

4.3. Germplasm Utilization

Successful development of new varieties and hybrids depends largely on the availability of source germplasm with desirable traits such as disease and pest resistance, drought tolerance and improved grain quality. The identification and incorporation of desirable traits into a wide range of germplasm is important to expand the gene pool. ICRISAT's screening program identified additional germplasm lines with desirable traits.

4.3.1. Grain Yield and Agronomic Desirability

The major germplasm sources utilized in varietal improvement so far include temperate lines from the USA, *Zera-zera* lines from Ethiopia and Sudan and some lines of Indian origin. The male-sterile gene sources used were mainly CK 60, 172, 2219, 3675, 3667 and 2947. These were further diversified by using parents such as CS 3541, BTX 623, population derivatives (Bulk-Y, Indian Synthetic, FLR, US/R, US/B, Serere, Diallel and WAE), IS 517, IS 1037, IS 2225, IS 3443, IS 6248, IS 10927, IS 12611, IS 12645, IS 19614, E 12-5, E 35-1, ET 2039, Lulu 5, M 35-1 and Safra. The basic germplasm sources used in the development of restorer parents and varieties were IS 84, IS 1151, IS 3687, IS 3691, IS 3922, IS 3924, IS 3941, IS 6928, IS 12622, IS 18961, IS 19652, ET 2039, Safra, E 12-5, E 35-1, E 36-1 and GPR 168.

Although germplasm from different regions of the world was used, the number of lines involved was very few. This has led to a yield plateau in rainy-season genotypes and only marginal yield increases in postrainy-season genotypes. To break this plateau, efforts are being made to involve accessions recently collected from Ethiopia, Yemen, Cameroon, Nigeria, Russia and China.

4.3.2. Resistance to Biotic and Abiotic Stresses

The main strategy adopted to reduce losses due to insect pests and diseases including *Striga* has been the incorporation of resistance to these pests and diseases. Systematic screening of germplasm accessions was initiated in 1974/75 to identify sources of resistance to important pests and diseases. This was intensified during the past decade in collaboration with NARS. So far, the bulk of the germplasm and breeding material has been screened for most of the important pests and diseases. This has facilitated the identification of several sources of resistance.

The most exhaustive germplasm screening was carried out for resistance to shoot fly and stem borer. Many of the sources of resistance were found to exhibit low infestation under high pest pressure. The sources identified are predominantly of Indian origin, while a few are from Ethiopia, Nigeria, Sudan and USA. The stable sources of resistance (Table 4.5) for shoot fly and stem borer were IS 1082, IS 2205, IS 5470, IS 5480, IS 5604 (India), IS 18554, IS 18577 (Nigeria), IS 2312 (Sudan), IS 18551 (Ethiopia), IS 2122, IS 2134 and IS 2146 (USA). Besides, other Indian germplasm lines such as M 35-1 (IS 1054), BP 53 (IS 18432), Karad Local (IS 18417) and Aispuri (IS 18425) were used as resistance sources.

Extensive screening of germplasm was also carried out for midge and many resistant sources were identified. Notable among these are DJ 6514 (IS 18700), IS 18961, S-GIRL-MR 1 (IS 18699), TAM 2566 (IS 18697), IS 3443, IS 12573C and AF 28 (IS 18698). The lines DJ 6514 and IS 3443 were used at ICRISAT to develop ICSV 197 (SPV 694), an improved midge-resistant variety.

Success was also achieved in the identification and utilization of disease resistance sources. Highly stable resistance sources (Table 4.5) were identified for all foliar diseases. The tan-pigmented plant type was found to be associated with resistance to foliar diseases. Grain mold resistance was found to be moderate in the white-grain background. E 36-1, QL 102 and QL 104 have been identified as the most stable resistant sources for charcoal rot disease.

Multiple disease resistances are available in some lines. Based on multilocational evaluation over the years, the following lines were found to have multiple disease resistance: ICSV 1, ICSV 120, ICSV 138, IS 18758 and SPV 387 (anthracnose and rust); IS 3547 (grain molds, downy mildew, anthracnose and rust); IS 14332 (grain molds, downy mildew and rust); IS 17141 (grain molds and anthracnose); IS 2333 and IS 14387 (grain molds and downy mildew); and IS 3413, IS 14390 and IS 21454 (grain molds and rust). These lines are currently being used in the breeding programs.

Resistance to *Striga* has been reported in several indigenous sources. Based on extensive laboratory and field screening, many *Striga*-resistant lines were identified from the germplasm. However, many of these sources could not be used in the breeding programs because of their undesirable agronomic base. Some germplasm lines used in *Striga* resistance breeding were: IS 18331 (N 13), IS 87441 (Framida), IS 2221, IS 4202, IS 5016 and IS 9830. Some of the breeding lines like IS 555, IS 168, SPV 221 and SPV 103 proved to be useful resistant sources. The *Striga*-resistant variety SAR 1 developed at ICRISAT from the cross IS 555 × IS 168 was released for cultivation in *Striga*-endemic areas. Several other promising selections derived from these resistance sources, both from ICRISAT and Indian programs, have been identified.

Nearly 1300 germplasm lines and 332 breeding lines were screened for early- and mid-season drought stress. The most promising ones for various droughts are: E 36-1, DJ 1195, DKV 3, DKV 4, DKV 17, DKV 18, IS 12611 and IS 6928 for early-season and terminal drought, and DKV 1, DKV 3, DKV 7, DJ 1195, ICSV 272, ICSV 273, ICSV 295 and ICSV 572 for mid-season stress.

Table 4.5. Resistant germplasm sources and improved lines identified at ICRISAT.

Constraint	Resistance sources	Improved lines: R-lines	Improved lines: A-B lines
Drought			
Seedling emergence	IS 301, Naga White, D 71463, D 71464	IS 1045, IS 2877, D 38060, D 38061, D 38093, ICSV 88050, ICSV 88065, SPV 354	VZM1-B, 2077B
Early	IS 824, IS 1037, IS 3477, IS 8370, IS 10596, IS 10701, E 36-1, DJ 1195	ICSV 88056, ICSV 88057, ICSV 88059, ICSV 88063, IS 24025, SAR 35	ICSB 3, ICSB 6, ICSB 11, ICSB 37, ICSB 54, ICSB 88001, ICSB 2219B
Midseason	IS 1347, IS 13441, DJ 1195	ICSV 213, ICSV 221, ICSV 210, ICSV 272, ICSV 273, ICSV 295, ICSV 572, D 71463, D 71464, DKV 1, DKV 3, DKV 7	ICSB 58, ICSB 196B, ICSB 2077B
Terminal	DJ 1195, M 35-1, IS 6928, IS 12611, IS 22314, IS 22380, E 185-2	D 38001, D 71283, D 71464, IS 13441, DKV 3, DKV 4,	ICSB 17, 296B
Acidic soils	Real-60, ICARAVAN, SBL 107 and other INTSORMIL products	DKV 17, 18 A 2267-2, ICSR 102, ICSR 110, ICSR 143, ICSR 91020-1, ICSR 93033, ICSV 93042	ICSB 89002, SPMD 94006, SPA 2-94013, SPA 2-94021, SPA 2-94039, SPAN 94046, ICSB 38
Striga	IS 18331 (N 13), IS 87441 (Framida), IS 168, IS 555, IS 2221, IS 4202, IS 5016, IS 9830	SAR 1, SAR 29, SAR 36, ICSV 697, ICSV 760, ICSV 761, SPV 103, SPV 221	SRN 4882B, SPST 94001, SPST 94002, SPST 94006, SPST 94010, SPST 94018, SPST 94026, SPST 94030, SPST 94034
Insects			
Shoot fly	PS 19349, IS 1054, IS 1082, IS 2312, IS 2313, IS 2134, IS 2146, IS 2195, IS 2205, IS 5604, IS 18417, IS 18551	20-67 ICSV 702, ICSV 705, ICSV 708, PS 21318	ICSB 51, ICSB 101, ICSB 102, SPSFR 94006, SPSFR 94007, SPSFR 94022, SPSFR 94036, SPSFPR 94002, SPSFPR 94007, SPSFPR 94012, SPSFPR 94025
Stem borer	IS 1044, IS 1151, IS 2122, IS 2123, IS 2205, IS 2375, IS 5470, IS 5480, IS 5604, IS 18425, IS 18432, IS 18554, IS 18577	ICSV 112, ICSV 700, ICSV 702, ICSV 714, ICSR 7, ICSR 38, ICSR 63, ICSR 125, ICSR 89066, PB 14698-2, PB 15621	ICSB 25, ICSB 37, ICSB 67, ICSB 70, ICSB 101, ICSB 102, SPSBR 94005, SPSBR 94011, SPSBR 94013, SPSBR 94017, SPSBPR 94010, SPSBPR 94011, SPSBPR 94013
Midge	AF 28, DJ 6514, IS 12666C, TAM 2566, S-Girl-MR-1(IS 18699), IS 3443, IS 18961, IS 12573C,	ICSV 112, ICSV 197, ICSV 745, ICSV 743, ICSV 89057	ICSB 3, ICSB 24, ICSB 25, ICSB 82, ICSB 102, SPMD 94006, SPMD 94010, SPMD 94016, SPMD 94022, SPMD 94025, SPMD 94045, SPMD 94060
Head bug	Mali Sor 84-2, Mali Sor 84-7, IS 2573C	ICSV 92030, IS 2761, IS 9692, IS 17610, IS 17645	ICSB 13, ICSB 26, ICSB 37, ICSB 38, ICSB 42, SPHB 94004, SPHB 94007, SPHB 94011, SPHB 94014

...continued

Table 4.5. ***Continued***

Constraint	Improved lines		
	Resistance sources	R-lines	A-B lines
Diseases			
Grain mold	IS 2333, IS 2501, IS 2815, IS 3436, IS 9225, IS 9470, IS 10288, IS 14332, IS 14387, IS 14390, IS 15119, IS 17141, E 35-1, CS 3541, CS 3555, CS 3573, CS 9225, CS 12658	ICSV 96094, ICSV 96105, GM 950187, GM 950199	ICSB 11, ICSB 17, ICSB 37, ICSB 42, ICSB 51, ICSB 70, SPGM 94001, SPGM 94002, SPGM 94005, SPGM 94008, SPGM 94011, SPGM 94035,
Anthracnose	IS 2058, IS 3575, IS 3547, A 2267-2, IRAT 204, TRL 74C-57	ICSV 112, ICSV 173, ICSV 91020, ICSV 91021, SPV 387, ICSR 91001, ICSR 91006, IS 6928, IS 8354	SPGM 94060, ICSB 38, ICSB 55, ICSB 101, ICSB 89004, ICSB 91001, 296B, PM 7061A, SPAN 94010, SPAN 94021, SPAN 94029, SPAN 94033, SPAN 94035
Leaf blight	A 2267-2, IS 2906, IS 18417, IS 18425, IS 18758, IS 19667, IS 19669	ICSV 1, ICSV 120, ICSV 138, ICSR 91022, ICSR 91025	ICSB 26, ICSB 53, ICSB 88004, ICSB 91002, BTX 2755, SPLB 94004, SPLB 94007, SPLB 94010, SPLB 94023
Rust	A 2267-2, IS 3413, IS 2816C, IS 3574C, IS 13896, IS 18417, IS 21454, IS 29016	ICSV 91022, ICSV 91023, ICSV 197, ICSR 91027, ICSR 91029	ICSB 3, ICSB 11, ICSB 22, ICSB 70, ICSB 72, ICSB 101, SPRU 94001, SPRU 94005, SPRU 94009, SPRU 94011
Downy mildew	QL 3 (IS 18757), UChV2, SC 414-12, SP 36257, IS 3547, IS 20450	ICSR 113, ICSR 89008, ICSR 90003, ICSR 90012, ICSR 90016, ICSV 91019	ICSB 11, ICSB 37, ICSB 51, ICSB 88001, ICSB 90004, SPDM 94001, SPDM 94006, SPDM 94022, SPDM 94035, SPDM 94060
Ergot	ETS 2454, ETS 3135, ETS 3147	ICSR 64, ICSR 160, ICSR 89014, ICSR 89049, ICSR 89067	ICSB 12, ICSB 15, ICSB 18, ICSB 70, ICSB 84, ICSB 101, ICSB 88001, ICSB 88009, ICSB 88015
Charcoal rot	E 36-1, QL 101, QL 102, QL 104	SPV 504, SPV 86, CS 3541,	296B, ICSB 17 ICSB 37

4.3.3. Conversion

Tropical landraces do not flower in temperate countries such as the USA, when they are grown in the summer where the day length is more than 13 hours. Most sorghum breeders recognize the positive correlation between plant height and grain yield; so they develop tall sorghums to withstand hazards associated with production (Miller 1982). Generally, maximum productivity is achieved at about 1.75-1.80 m height and flowering at 68-70 days (Rao and Rana 1982). A conversion program was initiated jointly by the Texas Agricultural Experiment Station and the United States Department of Agriculture (USDA) in the early 1960s to change the tall and late or nonflowering sorghums from the tropics (in USA) into short, early forms. This involved substituting up to four to eight genes that control height and maturity to obtain the desired type. The scheme essentially involved backcrossing (at Mayaguez, Puerto Rico) early and dwarf F_3s selected from F_2s (grown at Texas, USA) to the landrace. This was repeated four times before final

crosses were made at Mayaguez involving the landrace as female to capture the landrace cytoplasm as well. This program had nearly 1279 converted lines (Miller 1982), and contributed to breeding programs in USA and other countries. BTX622 and BTX623 are examples that contributed yield potential to various seed parent programs in several parts of the world. Reddy and Stenhouse (1994) elaborated on the Puerto Rican conversion program carried out at Mayaguez.

At ICRISAT-Patancheru, a program to convert tall, late-flowering *Zera-zera* landraces (from the Ethiopia-Sudan border) was initiated in 1979. Later, *Kauras* and *Guineanses* (from Nigeria) were also included for conversion. Several short- and early-flowering lines were selected. Early and dwarf plants have been selected in the rainy season and backcrossed in the postrainy season at ICRISAT-Patancheru. The converted *Zera-zeras* and yellow-endosperm *Kauras* contributed extensively to various programs (ICRISAT 1986). The converted (short) *Guineanses* were least productive and hence least preferred (ICRISAT 1988).

Tall, late-maturing and photoperiod-sensitive landraces were crossed with three dwarf, early-maturing, day-neutral genotypes (IS 10513, IS 18729 and IS 10927) to convert into dwarf and early types for use in breeding programs. The photoperiod-sensitive landraces involved were eight *Zera-zeras* (IS 24706, IS 24721, IS 24722, IS 24728, IS 24741, IS 24743, IS 24756 and IS 24759), three *Guineas* (IS 24885, IS 24886 and IS 27043), five *Kauras* (IS 24704, IS 24737, IS 24750, IS 24881 and IS 27044) from Nigeria, four *Durra-Caudatums* (IS 29017, IS 29018, IS 29027 and IS 29054) and two *Durras* (IS 29054 and IS 29102) from Yemen.

4.3.4. Populations for Multiple Resistances

Three populations are under development at ICRISAT-Patancheru. These are ICSP 1BR/MFR (resistance to grain mold, stem borer, shoot fly and midge), ICSP 2BR/MFR (resistance to grain mold and *Striga*, and improved stand establishment), both with rainy-season adaptability, and ICSP 3BR/MFR (resistance to stem borer, shoot fly and rust, with improved grain quality) with postrainy-season adaptability. Several resistance sources from the germplasm were transferred to these populations:

- ICSP 1BR/MFR and ICSP 2BR/MFR (rainy-season) populations
  - From India (8 lines), Ethiopia (3), Sudan (2), Nigeria (1), Zimbabwe (2), Egypt (1), USA (9) and Australia (2).
  - Resistance to shoot fly (3 lines), stem borer (6), midge (5), grain mold (1), leaf diseases (3) and *Striga* (1), good grain (3), stand establishment (3) and early and dwarf (13)
- ICSP 3BR/MFR (postrainy-season) populations
  - From India (13 lines), Ethiopia (27), Nigeria (12), Sudan (8), Botswana (8), Cameroon (8), Yemen (12), Malawi (1), South Africa (1), Egypt (1), USA (6), Mexico (1) and Australia (3).
  - Bold grain (20); with postrainy-season adaptability and resistance to terminal drought (29), photoperiod-sensitive (2), temperature-insensitive (28), resistant to shoot fly and stem borer (4), downy mildew (1), stay green (6), stand establishment (3) and early and dwarf (3).

4.3.5. Sorghums with Special Traits

High-lysine sorghums. The high-lysine sorghum lines IS 11167 and IS 11758 from Ethiopia were used in the breeding program for transferring the gene to a desirable agronomic background. Some promising high-lysine derivatives (with both shrivelled and plump grains) have been obtained.

Sweet sorghums. Several sweet-stalk lines were selected from the germplasm. Prominent among these were IS 2266, IS 3572, IS 8157, IS 9639, IS 9890, IS 14790, IS 15428, IS 15448, IS 20963 and IS 21100. These materials were screened across locations and were found to be very promising.

Forage sorghums. Forage sorghum germplasm was systematically evaluated over several years for various yield and quality traits, for which a wide range of variability has been noted. The lines identified with desirable forage attributes were IS 1044, IS 12308, IS 13200, IS 18577, IS 18578 and IS 18580. In respect of quality parameters, IS 1059, IS 2944, IS 3247, IS 4776 and IS 6090 were selected for low hydrocyanic acid (HCN), and IS 3247 and PJ 7R for low tannin content. The need for further critical evaluation of germplasm materials and their utilization in forage sorghum improvement is evident. This work is being strengthened and the National Research Centre for Sorghum (NRCS), Hyderabad (India), has a good program on forage sorghum improvement (Vidyabhushanam et al. 1989).

4.4. Recent Research Thrusts

Genetic enhancement research at ICRISAT has always maintained complementarity with its partners, especially the NARS of developing countries. The recent thrust in genetic enhancement research at ICRISAT has been on the development of breeding materials to augment resistance to different abiotic (drought, low temperature, acidic soil) and biotic constraints (*Striga*, diseases and insect pests) to increase grain yield and enhance genetic diversity to achieve sustainability in sorghum productivity.

4.4.1. Abiotic Constraints

Drought. Drought is one of the most important factors affecting sorghum production. It may affect growth in the early-, mid- or late-season after flowering. Research carried out at ICRISAT (during 1976-84) showed that globally adapted drought-resistant genotypes cannot be bred, and that it is possible to breed genotypes adapted to specific environments. Morphological traits associated with drought endurance and escape, such as good seedling emergence and vigor, earliness, stay-green, tillering, recovery from early- and mid-season stress, pollination gap, better seed set and grain filling, good panicle exertion and reduced stalk lodging are the components of drought resistance. Screening techniques for traits associated with various droughts were developed (ICRISAT 1982), and some germplasm lines and breeding lines tolerant to specific drought environments were identified (Table 4.5). The complex nature of stress, the wide array of physiological mechanisms and adaptation to diverse forms of drought require careful targeting of selections for specific production systems rather than for drought resistance *per se*.

Low temperature. In the tropical highlands of East Africa, sorghum is traditionally grown at 1500-2000 m above mean sea level where the minimum temperature during the crop season varies from 0°C to 12°C. This results in poor germination, retarded plant growth, poor pollen production and seed set. Screening and selection for low temperature has been carried out at Kabete and Muguga in Kenya. Several germplasm accessions collected from the high altitudes of Uganda, Kenya, Rwanda and Ethiopia were found to be promising and were used in the breeding program.

Acidic soils. Soil acidity due to high levels of Al^{3+} saturation is widespread in vast areas (*Illanos*, *savannas*, *cerredos*) in Colombia, Brazil, Bolivia and Venezuela. Some areas in Zambia and Zimbabwe are known to be highly acidic. During the late 1980s, the INTSORMIL program

developed acid soil-tolerant varieties suitable for production systems in Latin America (Table 4.5). With funding from the Inter-American Development Bank (IDB), a large number of grain sorghum (378 male-sterile lines, 784 restorer lines, 94 forage sorghums) and pearl millet lines (61) were screened for four consecutive seasons (1995-98) in varied Al^{3+} concentrations in Colombia in collaboration with CIAT, Cali, Colombia, and NARS in the region. High-yielding male-sterile lines, restorer lines and forage sorghum lines tolerant to Al^{3+} soil (Table 4.5) were identified and distributed to various agencies in the region. It is planned to develop acid soil-tolerant sorghum hybrids and evaluate them in the production systems.

4.4.2. Biotic Stresses

Striga. This parasitic weed is most common in Asia and Africa. It proliferates when sorghum is grown under poor management. The biology and establishment of *Striga* has been investigated in detail. Some mechanisms of resistance such as low strigol production and mechanical resistance have been elucidated. Several field and laboratory screening techniques to evaluate sorghum resistance to *Striga* have been developed. Lines that are tolerant to different species of *Striga* are agronomically poor. More detailed information on the physiological and genetic basis of the host-parasite interaction is needed to distinguish the mechanisms of resistance operating in various *Striga*-resistant or -tolerant cultivars in the world collection and breeding stocks. In spite of this complexity, pedigree and backcross breeding techniques have been applied with moderate success in selecting for improved varieties such as SAR 1 to SAR 36 and seed parents such as SPST 94001, SPST 94018 and SPST 94034. At ICRISAT-Patancheru several *Striga*-resistant male-sterile lines have been developed (Table 4.5). In view of the cumbersome screening procedures required for the identification of *Striga*-resistant plants and the complex mechanisms involved, marker-assisted selection approaches are being explored. A collaborative project with the University of Hohenheim, Germany, to search for restriction fragment length polymorphism (RFLP) markers which can tag *Striga* resistance genes and assist breeders in transferring them to agronomically improved cultivars is in progress at ICRISAT.

Diseases. Among the diseases, grain mold, anthracnose and foliar diseases such as leaf blight are considered to be the most important to various production systems (Table 4.3).

In all sorghum production systems, grain molds can reduce the yield and quality of short-duration cultivars if they mature in wet and humid weather, particularly when rains extend beyond their normal duration. Important parasitic fungi causing grain molds are generally the same in Asia and Africa. They include *Fusarium, Curvularia, Phoma* and *Colletotrichum* species, as well as a complex of saprophytic molds such as *Aspergillus* and *Cladosporium* species. The parasitic fungi invade and destroy the endosperm while the saprophytic fungi cause relatively less damage and affect only the pericarp. The problem of grain molds could be complicated and accentuated when associated with an attack of head bugs.

Artificial screening for grain mold resistance is carried out under supplementary sprinkler irrigation to increase humidity. Threshed grains are visually rated on a scale of 1 to 9 for percentage discoloration and mold attack. A high level of resistance to grain molds has been identified at ICRISAT-Patancheru as a result of screening the world collection. Most of the resistant accessions belong to the *Margaretiferum* subrace of the *Guinea* race, have a red or brown pericarp and are associated with tannins and/or phenolic compounds such as flavan-4-ols. However, among white grain types, a very hard endosperm and involute glumes that protect the developing grain from

fungal invasion until physiological maturity are the two known mechanisms of grain mold resistance. Grain color, pericarp thickness, presence of tannins, polyphenols, flavan-4-ols and grain hardness are controlled by major genes but some polygenes also seem to be affecting the level of phenolic compounds and endosperm hardness.

Current breeding efforts include both pedigree selection and population improvement. Pedigree selection using artificial screening for grain mold resistance has resulted in improved high-yielding lines and hybrid parents with red grains. Progress has been less successful with white grain types. A random-mating population with white grains and *Guinea*-type panicle and glume traits is under improvement at ICRISAT-Patancheru. Male-sterile lines with white, red and brown grain color and resistance to grain molds were developed (Table 4.6). ICRISAT scientists and scientists at Texas A&M University, Texas, USA, are investigating the possible role of antifungal proteins that inhibit growth of molds.

Among the various fungal diseases that attack sorghum, anthracnose caused by *Colletotrichum graminicola* is a potentially serious disease in the production systems of India, WCA and East Africa. Hot and humid weather favors the fungus which causes lesions that spread and kill leaves, sheath, stem, peduncle and panicles depending upon the cultivar and the stage of the crop. Grain yield losses up to 50% or more can occur in severe epidemics. Variation in anthracnose races between the regions is known but more information on inter- and intraregional variability is needed. Resistance to anthracnose has been identified in some germplasm accessions and breeding lines (IS 9225, A 2267-2, IS 12658 and ICSB 38) (Table 4.5). Resistance to this fungus appears to be governed by major dominant genes. Some sources of resistance identified in India were susceptible in WCA, while others have proved to be resistant across locations. Often, introductions from other regions into WCA were susceptible to anthracnose. Some local landraces of WCA exhibit horizontal type of resistance. Further investigations were carried out to identify other sources and to develop broad-based and durable resistance.

Pedigree selection and backcrossing methods were practised in crosses involving resistant parents with the aid of visual scores (1-9 rating) and susceptible checks. Advanced progenies were evaluated in disease hot spot locations in each region in observation nurseries sown under natural conditions. Pathologists confirm the resistance status under artificial inoculation. Several male-sterile lines resistant to anthracnose were developed (Table 4.6) following this procedure at ICRISAT-Patancheru.

Other leaf diseases of sorghum [such as leaf blight (*Exserohilum turcicum*), sooty stripe (*Ramulispora sorghi*), gray leaf spot (*Cercospora sorghi*), oval leaf spot (*Ramulispora sorghicola*) and rust (*Puccinia purpurea*)] are of less importance globally but cause significant grain and forage yield losses individually or collectively in susceptible cultivars in specific production systems. For example, sooty stripe can be serious in PSs 14 and 15 in WCA, while leaf blight causes significant losses in PSs 20 and 21 and to a lesser extent in WCA. In India, rust can be a serious problem in postrainy-season sorghum in PS 8. Foliar leaf diseases are generally confined to the lower leaves of tall local landraces but can damage most of the leaf area when they occur on susceptible dwarf cultivars. Foliar leaf disease resistance assumes high importance when attempts are made to reduce the height and improve the harvest index of landraces. Several germplasm and breeding lines with resistance to a few or more leaf diseases (IS 3555, IS 3575, IS 9225, IS 12658, ICSB 38, BTX631, A 2267-2 and Tegemeo) have been identified.

Table 4.6. Male-sterile lines available with ICRISAT and their characteristics.

Type of A/B lines	ICSA numbers	No. of lines retained	Agronomic score: Plant height (m) at maturity		Agronomic score: Days to 50% flowering		Yield parameters: Grain yield (t ha^{-1})	Yield parameters: 100-grain weight (gm)
			Rainy	Postrainy	Rainy	Postrainy		
High-yielding lines	1-102	71	1.0-2.6	0.9-1.4	60-74	65-92	0.5-5.4	1.9-4.5
	88001-88020	13	1.3-1.9	1.0-1.5	63-72	60-80	2.5-4.0	2.5-3.2
	89001-89004	4	1.3-1.5	1.0-1.2	66-72	76-80	3.2-3.6	2.6-3.2
	90001-90004	4	1.3-1.5	1.2-1.4	68-70	68-75	2.0-3.4	2.4-3.1
Downy mildew-resistant lines	201-259	59	1.1-2.0	1.0-1.7	65-87	70-86	1.7-6.3	1.5-3.9
Anthracnose-resistant lines	260-295	36	1.1-2.1	1.1-1.9	62-75	66-79	1.5-5.1	1.5-3.8
Leaf blight-resistant lines	296-328	33	1.4-2.1	1.0-1.9	65-83	69-89	1.1-6.5	2.3-4.3
Rust-resistant lines	329-350	22	1.1-2.1	1.0-1.9	63-82	66-80	1.7-6.1	2.1-3.7
Grain mold-resistant lines	351-408	58	1.6-2.2	1.0-2.0	58-72	64-78	0.8-5.0	1.7-4.1
Shoot fly (rainy)-resistant lines	409-436	28	1.5-2.0	1.0-2.0	68-76	66-84	1.9-6.2	2.0-3.5
Shoot fly (postrainy)-resistant lines	437-463	27	1.1-2.1	1.0-1.8	65-78	70-84	1.5-5.3	1.4-3.5
Stem borer (rainy)-resistant lines	464-474	11	1.3-2.1	1.3-2.1	65-76	66-78	1.9-4.5	2.2-3.9
Stem borer (postrainy)-resistant lines	475-487	13	1.7-2.8	1.5-2.0	61-75	69-81	2.2-4.4	1.8-3.1
Midge-resistant lines	488-545	58	1.2-2.0	1.0-1.8	59-81	67-87	2.1-5.8	2.2-4.1
Head bug-resistant lines	546-565	20	1.5-1.9	1.1-1.8	61-72	66-80	1.7-5.3	2.5-3.5
Striga-resistant lines	566-599	34	1.2-2.2	1.0-1.9	54-80	64-79	1.3-5.4	1.7-3.5
Acidic soil-tolerant lines	600-614	15			72-84			
Early-maturing lines	615-637	23	1.1-2.0	1.0-1.7	55-67	60-71	1.0-4.7	2.0-3.6
Durra (large grain) lines	638-670	33	1.2-2.2	1.1-2.0	50-76	66-90	1.2-4.7	2.0-4.1
Tillering lines	671-674	4	1.3-1.4	1.1-1.7	54-72	61-79	1.0-4.5	2.3-4.0
Stay-green lines	675-687	13	1.2-1.5	1.1-1.9	57-75	61-79	1.0-4.5	2.3-4.0
A_2 cytoplasmic lines	688-738	51	1.2-2.4	1.1-2.0	63-81	65-82	1.5-5.7	1.9-3.9
A_3 cytoplasmic lines	739-755	17	1.6-2.1	1.3-1.9	65-77	66-80	2.6-5.2	2.1-3.8
A_4 cytoplasmic lines	756-767	12	1.4-2.1	1.2-1.5	64-75	69-74	2.0-4.7	2.0-3.8

Major genes govern resistance to most of these leaf diseases. Breeding for multiple disease resistant cultivars with high grain yield has been generally successful with pedigree selection. Several hybrid parents with good levels of multiple leaf disease resistance are available. Breeders initially select, on an empirical basis, plants with clean leaves or higher proportion of green leaf area in the early segregating generations of crosses involving resistance sources. Further evaluation and selection in advanced generations in the presence of susceptible checks is carried out using a 1 to 9 rating scale (where 1 < 10% of leaf area diseased; 9 refers to > 80% of leaf area diseased). Advanced breeding lines are further evaluated in disease hot spot locations for specific leaf disease resistance in cooperation with pathologists. Although good progress is being made in breeding for leaf disease resistance, more detailed information on the genetics of resistance, variability of pathogen species and sources of horizontal resistance is required to develop improved cultivars

with broad-based and durable resistance. Following this strategy, several male-sterile lines (Table 4.6) resistant to rust and leaf blight diseases were developed.

Insect pests. Stem borer, shoot fly, midge and head bug are known to cause considerable yield losses in various production systems. A different complex of stem borer species attacks sorghum in different parts of the SAT and causes damage at various stages of the crop -- India: *Chilo partellus*; East Africa: *Busseola fusca* (higher altitudes) and *C. partellus* (intermediate altitudes); Southern Africa: *C. partellus, B. fusca, Sesamia calamistis* and *Eldana saccharine;* WCA: *B. fusca, S. calamistis* and *E. saccharine.* Overall, *C. partellus* is the most important species in Asia, East and Southern Africa while *B. fusca* is important in WCA. Consequently, ICRISAT sorghum breeding efforts on resistance to stem borer in India and WCA are focussed on *C. partellus* and *B. fusca,* respectively. Stem borer resistance is evaluated on the basis of the percentage of dead hearts, the extent of leaf damage, stem tunnelling, panicle damage and recovery. Screening is carried out under either natural infestation in staggered late sowings or artificial infestation with egg masses or early instar larvae of *C. partellus.* Techniques for artificially rearing *Busseola* have been developed together by ICRISAT and the Centre de Cooperation Internationale en Recherché Agronomique pour le Développement (CIRAD), France. Only a modest level of resistance to stem borer is known (IS 1044, IS 2205, IS 5613, IS 2123, IS 18551, PB 14698-2 and PB 15621) but immunity is absent. Resistance across species is limited (Seshu Reddy and Davies 1979) and needs confirmation through artificial intensive screening. Hitherto, stem borer resistance evaluations at ICRISAT-Patancheru relied heavily on low percentage of dead hearts. However in future other components of resistance such as recovery, extent of tillering and leaf damage may need to be considered. The threshold levels of resistance required in the target production systems also need to be determined. Stem borer-resistant sources are agronomically poor. A genetically broad-based random-mating population with shoot pest-resistant sources (98 accessions and 17 breeding lines) has been developed at ICRISAT-Patancheru and improved by S_1/S_2 testing procedures. Inheritance of stem borer resistance seems to be different under natural and artificial conditions and needs further study. In our experience, correlation between natural and artificial screening results has been generally low.

Breeding lines identified at ICRISAT-Patancheru are subjected to screening tests in hot-spot locations in East and Southern Africa and selections are made. Several borer-resistant male-sterile lines (Table 4.6) and pollinators and varieties were developed at ICRISAT-Patancheru. In WCA, a random-mating population with sources of resistance to *B. fusca* and adapted high-yielding lines are being developed and pursued through recurrent selection procedures. The International Institute of Tropical Agriculture (IITA), Nigeria, is working on screening techniques for resistance to *B. fusca* in maize, and ICRISAT cooperates and exchanges information on insect-rearing techniques.

Shoot fly (*Atherigona soccata*) causes widespread damage to sorghum in Asia and Africa. Research on shoot fly resistance has been going on since the 1970s at ICRISAT-Patancheru and at NRCS, India. Screening for resistance is carried out by late sowing of test materials between early-sown infester rows applied with a fly attractant, namely fishmeal.

Only low levels of primary resistance to shoot fly have been observed in some cultivars such as IS 1054, IS 2313 and IS 18551. Low levels of primary resistance have been incorporated into a few improved cultivars such as ICSV 702 and ICSV 705. By incorporating these improved varieties and restorers in backcrosses, several improved shoot fly-resistant male-sterile lines were developed (Table 4.6). However, hybrid parents with improved agronomic characters such as seed size coupled with shoot fly resistance are particularly needed to produce postrainy-season hybrids. Resistance to shoot fly has been observed to be polygenic and additive under modest levels of infestation, although

susceptibility is dominant under severe infestation. Sorghum plants with 'glossy' leaves and trichomes under the leaf surface have been associated with shoot fly resistance and are used as markers in empirical selection. Hitherto, pedigree breeding and backcross breeding were used (supported by artificial screening) at ICRISAT-Patancheru to breed hybrid parents resistant to shoot fly and adapted to the rainy-season production systems. A broad-based shoot pest population has been developed from 78 germplasm accessions and several breeding lines. Use of wild sorghum *S. versicolor* and *S. arundinacium* to obtain qualitatively different sources of resistance is a future objective. Absolute resistance to shoot fly was noticed in wild sorghum relatives (*S. dimidiatum* and *S. australiense*). Efforts are underway to exploit and introgress these using molecular markers. G × E studies showed that trichome development is season (temperature)-dependent (Jayanti 1997).

Currently, improved shoot fly-resistant lines bred in Asia are being screened in Eastern and Southern Africa and WCA, and successful selection has been carried out since there is no variation in the insect pest. Selected lines are crossed to other pest-resistant sources such as head bug-resistant lines. In Eastern Africa, recovery resistance will receive more attention since it is adapted to the local production systems.

Sorghum grain midge *(Contarinia sorghicola)* is known to cause significant grain losses on late-maturing cultivars or late planted sorghum crops in Asia, Africa and America. Complete grain yield losses can be observed in severely affected susceptible cultivars.

Serious attacks of midge have been reported in Maharashtra state of India, northern Nigeria, Burkina Faso, Niger and many other countries. An infester row technique using staggered dates of sowing late in the season, and a 1 to 9 scale of damage rating was used in the identification of resistant sources (Sharma et al. 1992). Final screening for midge resistance in cages under no-choice conditions is done to confirm high degree of resistance. Short and tough glumes, faster development of fertilized ovaries and other antibiotic mechanisms are associated with midge resistance. Inheritance of midge resistance has been found to be mostly polygenic and additive although recessive behavior has been reported in some cultivars. Several improved varieties such as ICSV 197 and ICSV 745 and hybrid parents have been developed at ICRISAT-Patancheru using pedigree selection and backcrossing techniques. However, these are mostly based on a single source of resistance, DJ 6514, which does not hold up its resistance at high altitudes and in the low temperatures in Eastern Africa. Obviously, there is a need to identify more stable and diverse sources of resistance. Some agronomically poor landraces from Kenya and one from Ghana (Nunaba) were found to be resistant to midge. Further intensive screening of local germplasm and multilocational tests in India and Africa may enable researchers to find more stable and diverse sources of resistance. An immediate objective would be to incorporate midge resistance expressing even at low temperatures (PS 21) in Eastern Africa into agronomically improved cultivars. At Patancheru, the emphasis has been to diversify improved high-yielding and resistant cultivars and hybrid parents, and recombine multiple resistances to pests. Several improved midge-resistant seed parents (Table 4.6) and midge-resistant restorers or varieties were developed using pedigree and backcross breeding materials. A random-mating restorer (R) population with sources of resistance to midge and head bug and another maintainer (B) population with sources of resistance to midge and shoot fly have been developed (Appendix 4.1). Detailed studies on mechanisms of resistance and their inheritance were carried out at Patancheru. In WCA. advanced midge-resistant lines bred at Patancheru are being crossed to locally adapted elite materials to obtain improved resistant cultivars.

A number of head bug species (*Calocoris angustatus* in Asia, *Eurystylus oldi* in West and Central Africa) are known to feed and damage developing grains of sorghum. Guinea cultivars with

lax panicles and involute glumes that cover the grain till physiological maturity were less damaged by head bugs than improved cultivars with exposed soft grains. Agronomically good cultivars such as Mali Sor 84-7 and some *margaretiferum* types are known to possess high levels of resistance to *E. oldi*. Resistance to *Calocoris* has also been observed in some brown grain types with lax panicles. Using Mali Sor 84-7 in crosses with the high yielding B-lines, several head bug-resistant male-sterile lines were developed at ICRISAT-Patancheru (Table 4.6).

Mechanisms of resistances to head bugs are only partially known. Rapid grain filling and maturity are supposed to be associated with resistance. Very hard grains, involute glumes and unspecified phenolic compounds also contribute to head bug resistance. Resistance in Mali Sor 84-7 to *Eurystylus* attack has been found to be recessive. The high levels of head bug infestation required for uniform screening are achieved by adjusting and staggered sowing in the crop season. Artificial infestation of individual panicles with *Eurystylus* using nylon or plastic bag cages is also practised. Pedigree and backcross breeding supported by artificial screening of advanced generations under cages is followed. Some promising head bug-resistant breeding lines are on advanced tests. Selection for free-threshing but extended glumes, which reduce damage due to *Eurystylus*, also appears promising. More detailed information is required on the resistance mechanisms to different head bug species important in Asia and West and Central Africa, particularly the genetics of these mechanisms.

4.4.3. Grain Yield, Stability and Adaptation

Improved grain yield and adaptation to the target or primary sorghum production system is the main objective, wherein breeding lines are improved for various biotic and abiotic stress factors combined with high yield potential adapted to a production system. Adaptation to different sorghum production systems requires cultivars with a specific maturity, grain type and a specific combination of resistance factors. For example, improved postrainy-season sorghums in India (PS 8) would require, in addition to higher grain and fodder yields, tolerance to drought, shoot fly and lodging and grain quality suitable for 'roti'. On the other hand, in the Northern Guinean Zone of WCA (PS 16), improved sorghum lines should have longer maturity and hard grains with suitable resistance to *Striga*, anthracnose, grain mold, stem borer, midge and head bug. In Southern Africa (PS 19), sorghum cultivars with early maturity, drought resistance (seedling, midseason and postflowering) and resistance to *S. hermonthica* need to be combined with high yield. Breeding lines and improved resistance sources are exchanged between the breeding programs at different ICRISAT locations. However, cross adaptation of breeding lines has been good only between Asia (PS 7 and 9) and Southern Africa (PS 19, 20 and 21) and to some extent Central America (PS 27). The soils and the biotic stress factors (stem borer, head bug and *Striga*) affecting sorghum in WCA are different from those in Asian production systems, and there seems to be poor cross-adaptation of cultivars. A certain degree of photosensitivity seems to confer advantages on sorghums adapted in the Sudano-Guinean Zone of Africa where the length of the rainy season is highly unpredictable.

The adaptability of highland sorghum in Eastern Africa is governed by tolerance to low temperatures. Therefore, breeding should be *in situ* to incorporate and select for local adaptability in certain production systems in Africa, although some stress factors are common to several production systems. Improved breeding lines and hybrid parents with resistance to shoot fly, midge, grain mold and foliar diseases and bred at ICRISAT-Patancheru are supplied to the African locations for incorporation in locally adapted germplasm or elite lines. The segregating progenies

are normally grown in a set of diverse locations in each region to screen for important biotic and abiotic factors. Selections for appropriate maturity, panicle and grain type are made and further evaluated at the same set of locations in the following generations. Thus, we ensure local adaptation and improved yield by incorporating exotic materials into local germplasm.

4.4.4. Genetic Diversification

Diversification of the genetic base of breeding lines is another important objective and is achieved by intercrossing resistance sources of diverse origin, frequently of different races, with agronomically elite lines. At ICRISAT-Patancheru, recurrent selection (with mass selection S_1 and S_2 testing) in broad-based, random-mating populations or gene pools with specific traits such as maintainer (B), restorer (R), high-tillering, large grain, shoot pest resistance, grain mold resistance and head pest resistance is in progress. In WCA, the development of random-mating populations of *Guinea* and *Caudatum* races has been completed and another *Guinea* × *Caudatum* type population is also under development.

Random mating early-maturity populations have been developed in Southern Africa. These populations being developed or selected in different regions will assure long-term improvement of sources of resistance to different biotic factors in desirable agronomic backgrounds and adaptation, while preserving broad genetic variability. Another important goal is to broaden the cytoplasmic-genetic diversity of hybrid parents. Grain yield improvement of several female parents of non-milo origin ($A_2/A_3/A_4$ cytoplasm) and incorporation of resistance factors in A_1 male-sterile lines are being pursued using backcrossing procedures. Details of various male-sterile lines available are given in Table 4.6.

4.5. Genetics and Mechanisms of Resistance

4.5.1. Diseases

In general, the genetics of resistance to various diseases caused by a given strain of fungi, bacteria and virus is simple. For example, three races are known for kernel smut, and resistance to each is controlled by an incomplete dominant genetic system, *Ss*$_1$, *Ss*$_2$ and *Ss*$_3$. The head smut resistance gene is dominant. A partially dominant gene controls milo disease resistance. Resistance to anthracnose is inherited as a dominant trait and is controlled by a single gene. Similarly, resistance to rust is also controlled by a single dominant gene. While resistance to leaf blight is controlled by a single recessive gene (House 1985), downy mildew resistance is controlled by more than two loci, possibly three with different interactions (Reddy et al. 1992b). Grain mold resistance is complex (House 1985). Stay green, a trait related to terminal drought tolerance, is inherited as a dominant trait in the F_1s of E 36-1 hybrids (Reddy and Stenhouse 1993). Among the diseases, grain mold and anthracnose are considered important in India. It was shown by Reddy et al. (1992a) that grain mold-resistant (red-grained) hybrids can be produced by crossing susceptible red-grained female parents and white-grained restorer lines. It was established that the presence of flavan-4-ols in moderate levels in red-grained females and the hardness found in white-grained restorers were not separately sufficient to cause resistance in the parental lines; but the traits were inherited by the F_1 hybrids and resulted in resistant hybrids. Reddy and Singh (1993) have shown that a single dominant gene controls resistance to anthracnose and that the effect of cytoplasm on resistance is not significant. More information on the genetics of disease resistance can be found in Thakur et al. (1997).

4.5.2. Insect Pests

The genetics of resistance to pests is more complex. Shoot fly (predominantly in Asia), stem borer (*Chilo* spp in Asia and Eastern and Southern Africa and *Busseola* spp in WCA), midge and head bug (*Calocoris* spp in India, Nigeria and Mali) are important pests. Nonpreference is the predominant mechanism, and it is quantitatively inherited mostly through additive gene action for resistance to shoot fly (Rao et al. 1974; Sharma et al. 1977). Rana et al. (1981) reported that F_1 is almost intermediate between the two parents for shoot fly resistance. Resistance was found to be partially dominant under low to moderate shoot fly pressure but not under heavy infestation. Most resistant varieties have glossy lines in the seedling stage (Maiti et al. 1980); most of them belong to the *Durra* group (Maiti et al. 1984). Also, the majority of shoot fly-resistant sorghum cultivars have a high density of leaf trichomes. Maiti and Bidinger (1979) noticed that trichomes on the abaxial surface of the leaf deterred egg-laying. In addition, Maiti et al. (1980) did not observe any differences in cuticle thickness or in the degree of lignification of leaves between trichomed and trichome-less lines. Omori et al. (1983) suggest that glossy expression in sorghum seedlings could be utilized as a simple and reliable selection criterion for shoot fly resistance. When shoot fly-resistant male-sterile lines and maintainers were evaluated, the male-steriles were more susceptible to shoot fly than the maintainers in both rainy and postrainy seasons at ICRISAT (Reddy 1998, unpublished data), indicating that male-sterile cytoplasm (A_1) is more susceptible to shoot fly than male-sterility maintainer cytoplasm.

Inheritance and gene action studies based on hybrid group means in relation to parental-line group means indicated dominance, intermediate or overdominance for susceptibility (as measured by egg count and dead heart percentage) in various hybrid and parent groups. Dominant gene action was observed for low seedling vigor and nonglossiness under low temperature conditions. Season specificity for trichome density was reflected in the hybrid groups depending upon the type of parents involved. Low density (associated with susceptibility) appeared to be additive. In the hybrids with postrainy-season-bred resistant (PRBR) female lines, trichome expression during the rainy season was lower than during the postrainy season. Similarly, hybrids with rainy-season-bred resistant (RBR) female lines supported low density in the postrainy season and high density in the rainy season. The same was observed in the parents *per se*. In respect of uniformity in recovery among the hybrid groups, those involving rainy season-bred females recovered well in the rainy season and postrainy season-bred female hybrid groups recovered well in the postrainy season. This again demonstrated the effectiveness of season-specific breeding that had been used in developing these resistant female groups. This might also have been due to the existence of different biotypes. This needs further confirmation, especially in no-choice experiments.

In general, only hybrids of resistant female lines × postrainy-season landraces or resistant female lines × resistant-bred lines were resistant to shoot fly in both rainy and postrainy seasons (Jayanti 1997).

Information on mechanisms of resistance to stem borer is limited. Both tolerance and antibiosis have been reported (Jotwani 1976). Rana and Murty (1971) reported that resistance to stem borer is polygenically inherited. The F_1 hybrids were intermediate for primary damage (leaf feeding), but better than mid-parent for secondary damage (stem tunnelling). While additive (A) and A × A interactions explained resistance to primary damage, secondary damage was controlled by additive and nonadditive gene interactions. Morphological traits such as shoot length, ligular hairs, leaf angle and seedling vigor have been reported to be associated with resistance to spotted stem borer. Reddy and Taneja (1993) studied the correlation of various traits with dead hearts and

found that the length of the second internode, measured 45 days after emergence or at maturity, and the length of the seventh, measured at maturity, were significantly and negatively correlated with dead heart formation in both rainy and postrainy seasons. By comparing the isogenic lines for plant height, they found that the dominant gene had no effect on dead hearts caused either by shoot fly or stem borer. Sharma (1993) found that shoot length measured at 40 days after emergence, ligular hair and leaf angle were significantly and negatively associated with dead heart formation. Widstrom et al. (1984) studied the gene effects governing resistance to midge. Most of the crosses expressed highly additive gene effects. Sharma et al. (1996) studied the combining ability of midge resistance and found that general combining ability was predominant. Information on the genetics of head bug resistance is scanty, but it appears that both male and female parents should have resistance to produce resistant hybrids for insect pests.

4.5.3. *Striga*

Resistance to *Striga* may be due to the absence of chemical signals or stimulants from the host eliciting *Striga* germination, post-germination chemical and nonchemical barriers to growth through the host roots, mechanical barriers to the establishment of haustoria or due to antibiosis and avoidance. Considerable research was done at ICRISAT-Patancheru on screening for low stimulant (strigol) production during 1975-1980 (ICRISAT 1976b; ICRISAT 1981a), early thickening of root walls in resistant genotypes (Maiti et al. 1984) and the deep root system in resistant genotypes (ICRISAT 1983). Ramaiah (1987) reported that in three out of the five sorghum parents studied, susceptibility was dominant over resistance; resistance was dominant in one, and partially dominant in the other. Using pot studies, Hess and Ejeta (1992) established that resistance was inherited as a recessive trait controlled by one or two genes in SRN 39. A single gene check for *Striga* resistance was postulated based on specific components such as the absence of strigol tolerance. However, if levels of production of strigol were considered, quantitative inheritance of *Striga* resistance was reported in some genotypes (Ramaiah et al. 1990).

Based on an evaluation at two sites each in Mali and Kenya, Haussman et al. (2000) reported that the heritabilities (in a broad sense) were 0.84, 0.79 and 0.89 in nine parental lines and 0.70, 0.78 and 0.88 in 36 F_2s of nine parental lines-half diallel for number of *Striga* plants emerged at 85 days after sowing, area under *Striga* severity-progress curve and grain yield, respectively. General and specific combining ability mean squares were significant for all and their interaction with locations were significant for all traits studied.

4.6. Screening Techniques

Effective disease and insect pest screening techniques are crucial for identifying sources of resistance. Developing a screening technique requires an understanding of the biology or epidemiology of the insect and disease. Effective field screening techniques have been developed for downy mildew (Pande and Singh 1992), stalk rot (Mahalinga et al. 1989; Pande and Karunakar 1992), anthracnose (Pande et al. 1994), leaf blight (Sifuentes et al. 1993), sooty stripe (Thomas et al. 1993), ergot (Tegegne et al. 1994; Musabyimana et al. 1995) and grain mold (Bandyopadhyay and Mughogho 1988).

Effective screening techniques were also developed for screening for resistance to shoot fly. It involves creating uniform infestation and scoring for dead hearts through the stark's interlards and fish

meal techniques (Agrawal and House 1982), glossiness (Maiti et al. 1980) and trichomes (Maiti and Bidinger 1979). Screening for resistance to stem borer involves conducting nurseries with natural infestation in hot-spot locations or placing first instar larvae in the whorls of young seedlings with a dispenser (Agrawal and House 1982) and scoring for leaf damage or dead hearts. Midge resistance screening is carried out through natural infestation in delayed sowing (with materials grown as per maturity groups) in hot-spot locations followed by cage screening (Agarwal and House 1982). Screening for resistance to head bug is done through natural infestation by sowing the materials in hot-spot locations after adjusting the sowing dates so that flowering coincides with maximum bug density. Infester rows with susceptible lines are sown where genotypes of different maturity groups are involved. Final selection is made through the head cage technique (Sharma 1997).

The technique of screening sorghum lines for low strigol production was standardized at ICRISAT-Patancheru and several lines were screened (ICRISAT 1978a). Screening for mechanical resistance based on thick-walled endodermic cells and associated sclerenchyma tissue was also developed (ICRISAT 1977). Among the other techniques developed were a field screening based on a checkerboard to differentiate between genotypes (ICRISAT 1983), the double pot technique (Parker et al. 1977) and the agar gel assay (Hess et al. 1992) to assess the quantity of strigol. Several techniques to screen for drought resistance were developed — emergence under high temperature (ICRISAT 1981b), emergence under soil crusting (ICRISAT 1981b), recovery from early seedling stress (ICRISAT 1981b), recovery from mid-season stress (ICRISAT 1981b), tolerance to terminal drought using line-source irrigation (ICRISAT 1980; ICRISAT 1981b) and selecting for yield potential and resistance to drought (ICRISAT 1981b).

Reddy (1985) has described techniques to screen for resistance to various drought situations. These have been used by scientists in many developing countries. However, there is scope for further refinement in screening techniques (Thakur et al. 1997).

4.7. Male Sterility and its Exploitation

Several genetic sources of male sterility were identified in sorghum, and all the cases showed that a recessive allele in homozygous condition contributes to male-sterility. These sources (Andrews 1966; Appadurai 1968; Andrews and Webster 1971) are given in Table 4.7. By 1970, ms_3 was widely used in population improvement programs for its stability in expression over a range of environments. The next best in terms of usage is the ms_7 allele. At ICRISAT, ms_3 and ms_7 are being maintained in different bulks.

Cytoplasmic nuclear male-sterility (cms) was discovered in sorghum by Stephens and his colleagues (Stephens and Holland 1954). This makes the commercial production of hybrid seed a

Table 4.7. Genetic male-sterility sources identified in sorghum.

Sterility gene	Sterility features	References
ms_1	Anther without pollen	Ayyengar and Ponnaya (1937); Stephens and Quinby (1945)
ms_2	Empty pollen cells	Stephens (1937); Stephens and Quinby (1945)
ms_3	Empty pollen cells	Webster (1965)
ms_4	Empty pollen cells	Andrews (1966)
ms_5	Empty pollen cells	Barabbas (1962)
ms_6	Micro-anthers without pollen	Barabbas (1962)
ms_7	Empty pollen cells	Andrews (1966)

low-cost affair. Male sterility results from an association of milo cytoplasm with sterility genes found primarily among the *Kafir* race and also in some varieties of other races. The genetics involved is not completely clear; however, when the two genes *ms* c_1 and *ms* c_2 are recessive in the presence of milo cytoplasm, the result is male sterility. Parents used as pollinators in hybrid programs should restore fertility in the hybrids produced when crossed with the male-sterile lines. Several types of cytoplasms were recognized depending upon the pattern of restoration and male sterility in hybrids produced by a set of testers used as pollinators (Schertz and Pring 1982), the most common ones being A_1, A_2, A_3 and A_4. The A_4 cytoplasm consists of at least three variants – VZM, Maldandi and G1. Research at ICRISAT identified the following minimum differential testers (Reddy and Prasada Rao 1991):

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

The A_1 system is better than A_2, A_3 and A_4 (Maldandi), A_3 is better than A_2 and A_4 (Maldandi), and A_2 is better than A_4 (Maldandi) for maintaining the stability of male sterility across environments (Reddy and Stenhouse 1996).

The genetics of fertility restoration is not clear. ICRISAT research showed that the frequency of recovery of restorer plants was least on A_3 than on A_2, A_4 and A_1, indicating that more genes were involved in controlling fertility restoration on A_3 than in the other systems (Reddy and Prasada Rao 1992).

Several researchers have reported the role of temperature in male sterility and its restoration (Downes and Marshell 1971; Li et al. 1981). Research at ICRISAT has shown that restoration is poor at temperatures below 10°C at night before the flowering season in India, and that there is a need to screen for restoration ability for postrainy season sowing (Reddy and Stenhouse 1996). Temperature-induced female sterility in cms female lines like 296A may be reduced by using their nonparental single cross F_1 male-sterile lines (Reddy 1992).

Using A_1 cytoplasmic genetic male sterility, several high-yielding male-sterile lines were developed at ICRISAT-Patancheru. These B-lines were crossed with resistant restorers and several male-sterile lines resistant to various pests, diseases and *Striga,* and lines having special attributes were also developed. Some high-yielding maintainer lines were converted into male sterility using other cytoplasms. Milo (A_1 source) sorghums may have originated in Sudan and belonged to the *Durra* race (Duncan et al. 1991). Diversification for grain yield and resistance has been brought about by involving lines belonging to *Durra* and *Caudatum* races. At ICRISAT-Patancheru, further diversification of male-sterile lines is being attempted involving the *Guinea* race.

4.8. Breeding Concepts Developed

Several concepts such as the use of tropical germplasm with temperate materials to exploit dominant alleles for height, maturity and grain yield; at intermediate optima of maturity (100-110 days) and height (2.0-2.5 m); productivity of hybrids based on the performance of lines *per se* and the availability of high general combining ability for various economic traits were available (Rao and Rana 1982). These concepts were used effectively in ICRISAT programs. ICRISAT scientists further developed the following concepts:

1. Heterosis and landraces. Several *Zera-zera* landraces such as IS 3541, E 35-1, IS 12611, E 36-1, IS 3443 and IS 19614 (race: *Caudatum/Guinea*) were used extensively in this program. By evaluating the hybrids obtained by crossing five representative lines from each of the landraces (*Caudatum, Durra, Guinea, Bicolor* and *Kafir*) to six common (*Caudatum-Kafir* derived) male-sterile lines, it was revealed that *Guinea* restorer lines contributed to the highest heterosis and grain yield *per se* in hybrids across the seasons followed by *Caudatum* restorer lines (Reddy and Prasada Rao 1993). Thus, it became clear that further gains could be made by making use of *Guinea* sorghums; but to do so accompanying problems such as the clasping of glumes to the grain in hybrids of *Caudatum-Kafir* male steriles and *Guinea* restorers need to be corrected.
2. Drought resistance breeding methodology. An approach to breeding for drought resistance and yield potential was established. It involved evaluating materials bred for adaptation for emergence under crust, seedling drought recovery and grain yield under drought-prone and yield potential areas for early-stage drought, mid-season drought recovery and grain yield under drought-prone and yield potential areas for mid-season drought and stay green, non-lodging and grain yield under drought-prone and yield potential areas for terminal drought (Reddy 1986).
3. Landrace hybrids approach to the postrainy season. Postrainy-season sorghum landraces possess excellent adaptive characteristics suited to the prevailing moisture limiting conditions. It was demonstrated that landrace hybrids would have almost all the characteristics preferred by farmers and a 15% superiority in grain yield over cultivated landraces (ICRISAT 1995). Therefore, restorers of postrainy-season landraces can be exploited to produce postrainy season landrace hybrids to break the yield plateau during this season in India.
4. Combining earliness and productivity. It was revealed that earliness, grain yield productivity and biomass can be combined by following S_1 family selection in a gene pool development by incorporating the selected landraces in ms_3 bulk. (Rattunde 1998 unpublished).
5. Breeding methods for specific purposes. ICRISAT-Patancheru has globally released more materials derived from its pedigree program than from its population improvement program. Thus it was reconfirmed that pedigree selection is better than population improvement for short, specific adaptation. Several NARS breeders have found that trait-based gene pools developed at ICRISAT-Patancheru are useful for selecting for specific needs. Thus, it is evident that the targeted gene pool approach is appropriate for a program that aims at a broader geographic mandate.
6. Moving average to evaluate a large number of progenies. A new checkerboard design was developed and used to account for local variation and increase the precision of the experiment for screening for *Striga* resistance (Rao 1985). However, the design requires lot of land and resources; and the fixed checkerboard arrangement is cumbersome to execute under field conditions. Therefore, the moving average concept to screen for resistance to shoot fly, stem borer and *Striga* was developed (Reddy 1993). For example,

   Striga resistance index (%) $= \dfrac{[S-(C1+C2)/2] \times 100}{[1+(C1+C2)/2]}$

   where S = number of *Striga* plants in the test entry and C1 and C2 are the number of *Striga* plants in the two adjacent resistant check plots.
7. Simultaneous selection and conversion method. A breeding scheme involving simultaneous selection for resistance and grain yield and converting the maintainer selections into male-

sterile lines was used effectively to develop male-sterile lines for resistance to pests and diseases in the shortest possible period of four years.

8. Selection methodology for stem borer mechanism. Considering the independence of antibiosis (Singh and Rana 1984) and the differences in patterns of inheritance of resistance to flower and peduncle damage plus dead heart formation, it was proposed that breeding for resistance to stem borer should involve three traits – foliar and stem damage and percentage of dead hearts. A paired plot technique with comparisons between infested and noninfested plots has been used successfully to identify genotypes with resistance to stem borer.
9. Season specificity of shoot fly resistance. Season specificity of trichome development was established based on evaluation of rainy-season- and postrainy-season-developed shoot fly-resistant materials. Therefore, it is suggested that materials should be selected for resistance to shoot fly in the season for which the materials are intended (Jayanti 1997).
10. Combining selection for resistance and grain yield. While breeding for grain yield and resistance, selection for resistance on the basis of family, and selecting single plants within the selected resistant family based on grain yield were found to be most effective (ICRISAT 1995).
11. Method to develop resistance hybrids. It was demonstrated that high-yielding shoot fly- and midge-resistant hybrids could be developed by crossing resistant male-sterile lines with resistant restorer lines. It was also revealed that crossing female lines resistant to shoot fly with postrainy season-landrace restorers or with bred resistant restorers can produce hybrids resistant to shoot fly (Jayanti 1997).
12. Methods to select stable restorers and male-sterile lines. It was demonstrated that efficient and stable restorers could be selected by evaluating their testcrosses or hybrids under conditions where night temperatures are below 13°C during the flowering phase. Conversely, it was shown that stable male-sterile lines could be selected by growing them in environments where the day temperature exceeds 40°C during flowering.
13. Single-cross vs three-way cross hybrids. The seed industry used three-way cross hybrids for commercial hybrids before it was demonstrated that single-cross hybrids were equally productive (Reddy 1992).
14. Selection efficiency in single cross vs multiple crosses. In combining resistance of characters which are simply inherited (eg, resistance to downy mildew) with grain yield, three- or four-way multiple crosses are as effective as single crosses. However, selection for resistance of quantitatively inherited traits such as resistance to stem borer or shoot fly was not effective in four-way crosses (Reddy 1993).

4.9. Limitations and Future Plans

The limitations can be grouped under three heads — technology transfer constraints, research area gaps and funding constraints.

The technology transfer constraints are:

- Insufficient seed production and marketing mechanisms, especially in Africa
- Insufficient support to NARS scientists to popularize products of research partnership with ICRISAT
- Inability of farmers to perceive the advantages of resistance in cultivars derived from ICRISAT/NARS partnership

- Overemphasis on yield in the variety release criteria stipulated by national programs
- Lack of government support to coarse cereals compared to fine cereals.

Participatory Varietal Selection (PVS) and Participatory Varietal Breeding (PVB) may address some of these issues.

The gaps in the research area are:

- Though there has been progress in improving sorghums for grain mold resistance by mostly utilizing grain hardness and flavan-4-ols content, there is a need to exploit other mechanisms such as *Guinea* glume and grain characteristics.
- Research inputs to improve photoperiod sensitive sorghums has been meagre in the past although there is a demand for them in WCA and for postrainy-season sorghum in India. There is a need to devise a breeding strategy and develop suitable products for these areas.
- Farmers demand large-grained sorghum. However, the grain size in the breeding material available is less than acceptable. Selection for hard grain to minimize the effects of mold have resulted in small grains. Currently, a private sector-funded project is emphasizing on large-grained sorghum.
- The *Caudatum* race has been overexploited in breeding. There is a need to diversify the breeding material by involving other races. Studies have shown that the *Guinea* race contributes significantly (after C*audatum*) to higher mean and heterosis for grain yield.
- Of late, there has been an increase in demand for forage in Asia. The variability in forage restorers (Sudan sorghum) is limited and overexploited by the private sector. There is also scope to diversify the genetic base for resistance to leaf diseases (eg, downy mildew) and stay-green ability.
- Biotechnology offers new tools such as transformation using *Bt* gene to augment resistance to stem borer and shoot fly and marker-assisted selection to develop parental lines with resistance to shoot fly, stem borer, *Striga*, acid-soil tolerance and grain mold.
- PVS and PVB may be useful for developing sorghum for the postrainy season in India, and *Guinea* sorghum for WCA.
- Information technology facilitates the development of databases of various breeding products – varieties, seed parents, restorers, hybrids, gene pools and genetic stocks-which can be accessed worldwide.

Funding support in recent years has been highly restricted and at times insufficient, forcing researchers to prioritize research themes. However, as mentioned earlier, ICRISAT's approach has helped tap private sector resources without sacrificing CGIAR's position on keeping the research products under international public goods.

4.10. Conclusions

Sorghum, a self-pollinated crop, is an important food crop in Africa and Asia. It is also used for feed, breweries and industrial products. Domestication occurred as early as 5000 years ago. The availability of male-sterile genes has enabled breeders to not only follow pedigree breeding methods as in other self-pollinated species, but also several recurrent selection procedures developed for cross-pollinated species. The cytoplasmic genetic male-sterile system has helped

exploit heterosis through hybrids. Though varieties and hybrids were initially ICRISAT's target outputs, its breeding processes underwent several changes over the years. Currently, there has been a shift from developing finished products to intermediate products, partnership research with NARS, and from applied research to developmental and upstream research. In future, ICRISAT intends to concentrate on a few targeted set of themes such as resistance to *Striga*, grain mold, anthracnose, shoot fly, stem borer and head bug in the context of production systems. Through marker-aided selection and conventional and participatory breeding methods, it aims to improve intermediate products – restorers, seed parents and gene pools – as international public goods. In Africa it lays more emphasis on developmental aspects, including finished products, while in Asia it focuses on upstream research.

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Appendix 4.1. Populations maintained at ICRISAT-Patancheru.

Name of population	Seed available cycles	Years of improvement	Seed multiplied season	Maintained/ developed at	Original source	Parents incorporated	Male-sterile gene	Target traits
US/B	C_0-C_6	1974-84	89R/90R	Patancheru	PP2, PP6, NP2, NP4	296B, 323B, 2219B, 2077B	ms_3	High yield
US/R	C_0-C_8	1974-84	89R/90R	Patancheru	PP1, PP3, PP5, NP4, NP5, NP8	296B, 323B, 2219B, 2077B	ms_3	High yield
Rs/B	C_0-C_8	1973-84	89R/90R	Patancheru		296B, 323B, 2219B, 2077B, Sel. from US/R-C_1, RS/R, Ind. Syn., FLR 101, FLR 274, RS1 x VGC, IS 12645C, IS 9327	ms_3	High yield
Rs/R	C_0-C_8	1974-83	89R/90R	Patancheru		GGS 370, 1483, Ind. Syn-250, Diallel 876, FLR 101, IS 1082, IS 9327, IS 11758, SPV 249, SPV 393, SPV 351, SPV 475, SAR 2, SAR 4, PS 19230, SB 8104-1, PMs 7348, 7349, 7061, 7495	ms_3	High yield
FL/B	C_0-C_4	1981-84	89R/90R	Patancheru	NP2, NP6		ms_3	High yield
FL/R	C_0-C_4	1981-84	89R/90R	Patancheru	NP1, NP3, NP4, NP5, NP8		ms_3	High yield
WAE	C_0-C_4	1981-84	84R/90R	Patancheru	S_1 selections from Nigerian, WABC and Bulk Y	CS 3541, GG 370, SPVs 86, 422, 424, 393, Ind. Syn-323, ETs 1966, 4789, ISs 6373, 22233, 23555	ms_7	High yield, photo-period sensitivity populations
Tropical conversion	C_0-C_3	1974-76	89R/91R	Patancheru	Puerto Rico population and early lines	Heterozygous material from BC1/BS2S of Puerto Rico conversion program crossed to Serere RS population	ms_3	High yield
Ind.Synthetic	C_0-C_1	1983	91R	Patancheru		GPRs 370, 148, CSV 4, IS 3691, CK 60B, 2219B, E 35-1, FLRs 101, 266, UChV2, SARs 2,4,6, PMs 7061, 7495, 7348, 7349, PB 8284, PS 19230	ms_3	High yield
Good grain	C_0-C_1	1974	91R	Patancheru	Serere	GPR 370 and 120 white corneous sorghums	ms_7	High yield, photo-period sensitivity
Serere	C_0-C_1	1976	90R/91R	Patancheru	RS5DX, RS5DXCSF, RS1 x VGC, Hyd RS	GPR 370 and 120 white corneous sorghums	ms_3	East African adaptation
Serere Elite	C_0-C_1	1976	74R/87R	Patancheru			ms_3	East African adaptation
ICSP1 B/ R MFR	C_0-C_1	1984-89	89R/90R	Patancheru	US/R, RS/R, Ind.Syn.	6 shoot fly, 9 stem borer, 7 midge, 6 downy mildew, 5 leaf diseases, 3 *Striga*, 6 drought, 2 seedling vigor lines	ms_3	Multifactor resistance

...continued

Appendix 4.1. *Continued*

Name of population	Seed available cycles	Years of improvement	Seed multiplied season	Maintained/ developed at	Original source	Parents incorporated	Male-sterile gene	Target traits
ICSP2 B/ R MFR	C_0-C_1	1984-89	87R/89R	Patancheru	US/R, RS/R, Ind.Syn.	39 temperature insensitive, 22 photoperiod sensitive, 9 shoot fly, 2 S*triga*, 13 rabi breeding lines	ms_3	Multifactor resistance
ICSP B/ R MFR	C_0-C_1	1987-89		Patancheru	ICSP1 B/R MFR and ICSP2 B/R MFR	15 shoot fly, 5 stem borer, 7 midge, 6 nonsenescence, 29 photoperiod sensitive and temperature insensitive, 30 bold grain, 17 terminal drought, 9 ms_3 rabi adapted lines, 3 dwarf and early lines	ms_3	Multifactor resistance
ICSP-LG	C_0-C_1	1993-99	93R/99R	Patancheru	US/B C6	ISs 80, 808, 2322, 2409, 9761, 9991, 10469, 10513, 14789, 15551, 15594, 16201, 18372, 18729, 18762, 22643, 23891, 23985, 23986, 24737, 33843, 33844, SS 25, 35, ICSV 735, E 36-1, M35-1	ms_3	Large grain, shoot pest resistance
ICSP-HT	C_0-C_1	1994-99	94R/99R	Patancheru		A 2267, B 24, SSG 59-3, SP 36257, IS 12611, 8 early lines and 3 high-tillering lines, 7 sweet stalk lines, 3 Sudan grass lines, 3 tall, late-maturing tillering lines	ms_3	Tillering
ICSP-B	C_0-C_7	1994-99	94R/99R	Patancheru		10 bold grain lines, 5 midge-resistant lines, 8 dwarf stem borer-resistant lines, PS 19349, 47 progenies of QL3 x 296 B	ms_3	High yield, shoot fly resistance
Early dual-purpose		1976		Patancheru	ICSP-US/R (DP)	ISs 869, 8101, 18758C-591-T, 18758C-618, 19159, 20545, 22500, 23897, 24335, 24436, HC 260	ms_3	Early maturity
Medium/late			90R	Patancheru			ms_3	Medium maturity
Early dual-purpose		1991-97		Patancheru	US/R S1	12 high-biomass landraces: HC 260, ISs 869, 3496, 8101, 19159, 20545, 22500, 23897, 24335, 24436, 18758C-591T, 18758C-618	ms_3	Early maturity
Early, photoperiod-insensitive sorghum population		1996-		Patancheru	MFR steriles, Russian x bold grain R-lines	CSV 15, SPV 881, AKR 150, ICSV 38, CSV 4, RS 29, CB 43, Seredo, Framida, Naga White, ISs 8744, 8785, 18520, 36571		Early maturity, photoperiod insensitivity

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Appendix 4.1. *Continued*

Name of population	Seed available cycles	Years of impro-vement	Seed multiplied season	Maintained/ developed at	Original source	Parents incorporated	Male-sterile gene	Target traits
Conspicum sorghum population		1995-		Patancheru	Grain mold-resistant *Guinea* population steriles	Conspicum landraces _ ISs 7173, 23770, 23773, 23783, 24135, 24173, 24189, 24191, 24196, 24221, 24286, 24296		Yield, yield stability, photoperiod sensitivity
Sudan sorghum population				[US/R(DP)C1 x IS22500]		ISs 366, 921, 3492, 9884, 13444, 18297, 22500, Ajab-Seido (drought tolerant, grain quality line)	ms_3	Yield and early maturity (<95 days)
East African Bulk			87R/90R					Regional adaptation
Indian Diallel			90R	Patancheru	45 entries from world collection		ms_3	High yield
Brown			90R	Patancheru			ms_3	
WABC			91R	Patancheru			ms_3	High yield
Bulk-Y			91R	Patancheru			ms_3	High yield
NP10 BR Bulk			1976	Patancheru			ms_3	High yield
High altitude				Patancheru			ms_3	High yield
PR1 BR Sub Sorghum			1974	Patancheru			ms_3	
Shoot pest	C_0-C_8		1978-96	Patancheru	Resistant lines from advanced populations – US-B/R, RS-B/R, FLB/R, Serere, tropical conversion.	F_2s from crossing among 98 landraces, and 17 breeding lines representing diverse sources for shoot fly and/or stem borer resistance	ms_3/ms_7	Shoot pest resistance
Head pest	C_0-C_5		1985-96	Patancheru	Resistant lines from advanced populations - USB/R, RSB/R, FLB/R, Serere, tropical conversion.	F_2s from crossing among 27 landraces, and 6 breeding lines representing diverse sources of resistance for head bug and midge	ms_3/ms_7	Head pest resistance

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Appendix 4.1. *Continued*

Name of population	Seed available cycles	Years of improvement	Seed multiplied season	Maintained/ developed at	Original source	Parents incorporated	Male-sterile gene	Target traits
Grain mold			1984-97	Patancheru	US/R and US/B	58 mold-resistant and 4 susceptible lines, 27 high-yielding and 14 dwarf and early lines.	ms_3	Grain mold resistance
SDSP-hot/dry				Zimbabwe	TP24R04/TP15R05, P21RB03, 84PP-19M, PP-19			
SDSP-cool/dry				Zimbabwe	TP24R04/TP15R05, TP8, WAE, KP8			
SDSP-drought conditions				Zimbabwe	TP24R04/TP15R05, TP15, TP21RB03, KP9BSO			Drought resistance
SDSP-broad adaptation				Zimbabwe	TP24R04/TP15R05, TP21RB03			
Guinea				Nigeria		13 *Guinea* lines from West Africa	ms_3	Racebased
Caudatum				Nigeria		12 *Caudatum* lines with grain mold resistance, mostly colored, from Mali	ms_3	Racebased
Guinea-Caudatum				Nigeria		Selected improved and adapted landraces, high-yielding lines and a few resistant sources	ms_3	Racebased