Genetic improvement of sorghum in the semi-arid tropics

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Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] – a major cereal of the world after wheat, rice, maize and barley, is a staple food for millions of the poorest and most food-insecure people in the Semi-Arid Tropics (SAT) of Africa and Asia. Being a C_4 species with higher photosynthetic ability, and greater nitrogen and water-use efficiency, sorghum is genetically suited to hot and dry agro-ecologies where it is difficult to grow other food crops. These are also the areas subjected to frequent droughts. In many of these agro-ecologies, sorghum is truly a dual-purpose crop; both grain and stover are highly valued products. In Africa, sorghum is predominantly grown for food purposes, while in USA, Australia, China, etc, it is grown for livestock feed and animal fodder purposes. Unlike in other parts of the world, sorghum is grown both in rainy and postrainy seasons in India. While the rainy season sorghum grain is used both for human consumption and livestock feed, postrainy season produce is used primarily for human consumption in India. Thus sorghum is the key for the sustenance of human and livestock populations in SAT areas of the world.

Production constraints

The yield and quality of sorghum is affected by a wide array of biotic (pests and diseases) and abiotic stresses (drought and problematic soils). These are shoot fly (India and Eastern Africa), stem borer (India and Africa), midge (Eastern Africa and Australia) and head bug [India and West and Central Africa (WCA)] among pests; grain mold (all regions), anthracnose (WCA and Northern India) among diseases and *Striga* (all regions in Africa); drought (all regions) and problematic soils – saline (some parts of India and Middle-East countries) and acidic (Latin America) – which together (except saline and acidic soils) cause an estimated total yield loss to the tune of US$ 3032 million (www.agbiotechnet.com/pdfs/0851995640). The world sorghum productivity is dismally low (0.7 t ha^{-1}) because of these production constraints and the use of traditional cultivars (low-yielding) and traditional production practices during early 1970s.

Genetic improvement

Sorghum has not received wide attention in the scientific community especially in Africa and Asia in the past due to the fact that it is considered a coarse grain and much of its production is at subsistence level. Increased pressures of population growth on food supplies, enhanced utilization of animal products and depleting fossil-fuel reserves has driven attention towards utilizing the full potential of this crop as food, feed, fodder and fuel. Genetic improvement is the cost-effective means of enhancing sorghum productivity for different end-uses. Depending on the production environment and constraints and end-product utilization, the objectives of sorghum improvement programs have been different in different parts of the world. The purpose of this article is to review the sorghum improvement research efforts and its outcomes in different parts of the world.

Sorghum improvement in India

In India, unlike in other countries, sorghum is cultivated in two seasons - *kharif* (rainy) season (June/July-September/October) and *rabi* (postrainy) season (October-December/January). As production environment and production constraints are different, cultivar options are quite different for two seasons (Rana et al. 1997). Initially, development of pure-line varieties using specific adaptation approach was given importance. Several varieties were released within the states. After the discovery of stable and workable cytoplasmic-nuclear male sterility (CMS) system (Stephens and Holland 1954) and as a result of the efforts under the accelerated hybrid sorghum project initiated by the Indian Council of Agricultural Research (ICAR), the first commercial sorghum hybrid CSH 1 was released in 1964. Since then 22 hybrids have been released, some of them (6) with adaptability to postrainy season, which caters to the need of grain for human consumption. CSH 13, a dual-purpose hybrid with high biomass has global adaptability (Rao 1982). The program also released, 13 varieties for rainy season and 8 for postrainy season, but the varieties are not popular with farmers (Reddy and Stenhouse 1994). Considering the potential of sweet sorghum juice as a feedstock for bioethanol production following the Indian Government's initiatives for the production and use of biofuels, considerable progress has been made in the development of sweet sorghum cultivars. The sweet sorghum variety, SSV 84 and a hybrid CSH 22SS have been released for commercial cultivation. Biotechnology tools such as DNA-based markers and genetic transformation have been deployed to address the most intractable and major insect pests, shoot fly and stem borer, in both rainy and postrainy seasons. The Quantitative Trait Loci (QTLs) conferring shoot fly resistance have been identified. Of late, research on production of transgenic sorghums resistant to stem borer using *cry1Ab* gene has gained momentum. Meristem-specific promoters were isolated from sorghum in collaboration with National Research

Centre on Plant Biotechnology (NRCPB), New Delhi, which would help express genes of interest in the shoot meristem to control shoot fly. Intensified research efforts are underway on postrainy season sorghum improvement for higher grain and fodder yields with acceptable grain quality in both the Indian national program and ICRISAT-Patancheru programs. Efforts are also being continued on the development of *kharif* hybrids and new male sterile seed parents with improved resistance to biotic stresses, and grain qualities through exploitation of diverse germplasm and alternative sources of CMS systems (mainly A_2 and A_4).

Sorghum improvement at ICRISAT

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) was established in 1972 at Patancheru, Andhra Pradesh, India with sorghum as one of its five mandate crops. Improvement for yield potential and resistance to drought, *Striga*, grain mold, downy mildew, charcoal rot, shoot fly, stem borer, midge and head bug and wide adaptability received major attention up to 1980. Genetic male-sterility facilitated populations and pure-line varieties were the target cultivars during the initial years. In resistance breeding programs, emphasis was given to developing and standardizing screening techniques and identification and breeding of improved resistance sources. The initial emphasis on red grain types up to 1975 was gradually shifted to white grain types by the end of the 1970s.

During the 1980s, major emphasis was given to regional adaptation and breeding for resistance to biotic stresses (grain molds and insect pests only) in white grain background. Breeding for resistance to drought, downy mildew, charcoal rot and *Striga* was discontinued, while development and improvement of male sterile lines for grain yield and food quality traits were initiated.

Initially, several open-pollinated populations were introduced from the USA, West Africa and East African programs and were reconstituted with selection. A total of 19 improvised trait-specific open-pollinated populations are being maintained at ICRISAT and National Research Centre for Sorghum (NRCS), Hyderabad, India. Several of the hybrid seed parents derived from some of these populations are being extensively used for the development of high-yielding hybrids in China. Later on, several high yielding good grain inbred-lines and *zerazera* landraces (*caudatum*) were extensively involved in breeding at ICRISAT Asia Center (IAC), and *guinea* local landraces along with *caudatum* derived lines at ICRISAT West African center (Reddy and Stenhouse 1994). During 1985–89, major thrust was given for specific adaptation and trait based breeding for resistance traits. A total of 92 high-yielding A-/B-lines, including 17 early-maturity lines and 75 medium maturity lines were developed during this period. By late 1980s many national agricultural research systems (NARS) had enhanced crop improvement programs aimed at specific adaptation. Thus, the global sorghum improvement program reoriented itself to develop materials suited for 12 productive systems (PS) in Asia, six in Western Africa, six in Eastern and Southern Africa and five in Latin America. As a result of this reorientation, at ICRISAT's Asia center (IAC), strategic research on the development of screening techniques, breeding concepts and methods and intermediate products for utilization in partnership with NARS programs was given emphasis during 1990–1994. A total of 567 trait based A-/B-lines (487 A_1, 51 A_2, 17 A_3 and 12 A_4 CMS systems-based) were developed during 1989–98. Besides these, 57 high yielding A-/B-lines were also developed. In addition, an extensive program of breeding new *Milo* cytoplasm 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 mold, downy mildew, anthracnose, leaf blight and rust was carried out (ICRISAT 1993) (Fig. 26). A total of 39 new A-/B-lines (*durra* bold grain 23, *caudatum* 6 and *guinea* 10) based on A_1 cytoplasm and 46 new A-/B-lines (*durra* bold grain 28, *caudatum* 4, *guinea* 5 and *feterita* 9) based on A_2 cytoplasm were developed.

Fig. 26. A rainy season adapted B-line with stem borer resistance.

With a major objective of trait specific breeding, novel populations or trait-specific gene pools for bold grain and high productive tillering were developed. Test crosses involving postrainy season 'landraces' as pollinators were examined for their fertility restoration ability under cool nights and for productivity in postrainy season. Variability for restoration was quite significant indicating the possibility of selection within hybrids (Reddy and Stenhouse 1994).

At ICRISAT, Patancheru a set of 86 diverse sorghum lines involving parental lines of popular hybrids, varieties, yellow endosperm lines, germplasm lines, high digestible protein lines, high lysine lines and waxy lines were evaluated for grain Fe and Zn content.

Significant genetic differences for grain Fe and Zn content and anti-nutritional factors (tannin and phytate content) and agronomic and grain traits were observed. While the grain Fe content ranged from 20.1 ppm (ICSR 93031) to 37.0 ppm (ICSB 472 and 296B) with an average of 28 ppm, grain Zn content ranged from 13.4 ppm (JJ 1041) to 30.5 ppm (IS 1199) with an average of 19 ppm (Fig. 27). Nevertheless, it was evident that substantial genetic variability exists for grain Fe and Zn content and this variation did not appear to be significantly influenced by the environment as reflected from narrow differences between PCV and GCV and high heritabilities. The substantial variability coupled with higher heritability suggests that selection for high Fe and Zn and low tannin and phytate content is effective and hence offers better prospects of breeding Fe and Zn-dense sorghum cultivars in an anti-nutritional factor background.

Sweet sorghum research has been given major emphasis at ICRISAT and 10 new seed parents and 8 restorer lines were developed for use in hybrid development. The sweet sorghum based ethanol technology has become a reality with the establishment of Rusni Distilleries near Hyderabad, India in collaboration with ICRISAT's Agri Business Incubator (ABI). It has become a model for such distilleries all over the world. In collaboration with International Centre for Biosaline Agriculture (ICBA), Dubai and Agriculture Research Station (ARS), Gangavathi, Karnataka, India, ICRISAT has identified 18 lines that are promising under saline conditions. Similarly, improved lines have been developed for fodder quality and quantity and Al^{3+} tolerance. Efforts are underway to tag the QTLs associated with drought tolerance, grain mold resistance and shoot fly resistance.

Fig. 27. ICRISAT-Indian NARS partnership dual purpose sorghum variety.

From 1995 onwards, a partnership mode of conducting research to develop improved intermediate products at ICRISAT, Patancheru, India, and finished products (varieties and hybrids) at other

ICRISAT locations in Africa were being emphasized. Accordingly, the objectives of the program at present are breeding resistant (to biotic and abiotic stresses) seed parents and restorer lines, developing specific new gene pools and novel plant types. However, breeding programs in Africa will continue to develop high yielding cultivars (varieties and hybrids) with resistance to *Striga* and head bug appropriate in the region. At Patancheru center, ICRISAT is giving major emphasis to development of hybrid parents for sweet stalk traits, micronutrient density, salinity tolerance, bold grain types and multicut types.

ICRISAT, working in partnership with NARS, partners helped in release of 200 cultivars in several countries in Asia (53), Africa (112) and Latin America (35).

Sorghum breeding in China

Modern sorghum breeding in China began in the 1920s, and has progressed through three stages: (a) collection, classification and pedigree selection within the best local varieties; (b) cross breeding, using crosses between local varieties or local×exotic for variety production and (c) exploitation of heterosis through the development of single-cross hybrids from inbred parents (Zheng Yang 1997). Heterosis breeding has been the main method of breeding since 1965 in China. The major objectives of sorghum improvement research in China include: grain yield, multiple resistance to abiotic (low temperature and drought) and biotic (aphids and head smut) stresses, grain quality, grain feed and forages for livestock.

Breeding for high yield: Through a program of selecting the best introduced seed parents, and then evaluating Chinese bred pollinators, a series of hybrids have been developed starting in the 1970s. The increase in yield due to utilization of hybrids is estimated at 30–40% with the remaining improvement being due to better cultivation conditions (Zheng Yang 1997).

Breeding for multiple resistance to abiotic and biotic stresses

Low temperature**:** Low temperature is an important stress factor, especially for northeastern China in both the seedling and grain filling stages. Some cold-tolerant local varieties have been identified using low temperature seedling treatment. (Zheng Yang 1997).

Drought: Selection for rapid seedling emergence rates in water-limited areas was followed to develop cultivars resistant to drought at seedling stage. New male sterile lines and restorers with resistance to drought are being developed using this method of selection (Zheng Yang 1997).

Aphids: Most Chinese sorghum varieties lack genetic resistance to aphids. Several new male sterile lines with high degree of resistance have been developed by the Sorghum Research Institute (SRI), Liaoning Academy of Agricultural Sciences (LAAS) (Zheng Yang 1997).

Head smut: Sorghum head smut caused by the fungus, *Sphacelotheca reliana* is a serious disease. There are three different physiological races of the pathogen in China. Resistance to head smut is controlled by both major genes of 2 or 3 pairs and some minor genes (Yang Zhen and Yang Xiaoguang 1993). Among 10,083 germplasm accessions screened, 39 showed immunity to race 2, while 3 accessions have shown resistance to race 3 (Chen Yue and Shi Yuxue 1993). Based on these sources, resistance breeding is in progress (Zheng Yang 1997).

Breeding for quality

Chinese Kaolings are an excellent source of good grain quality types such as Xiang Yanai and Zhen Zhubai. However, they are not used directly in heterosis breeding due to low combining ability and poor restoration. Nutritive composition of hybrid sorghum grain is poor and the traditional fragrance of original local varieties needs to be recovered in high-yielding background (Zheng Yang 1997).

Grain for feed and forages for livestock

Since sorghum is the main raw material of compound feeds for livestock and poultry, breeding for feed quality has been one of the major objectives of sorghum breeding in China (Shi Yuxue et al. 1992). Most forage sorghums can be classified as dual purpose in China, with the grain for human consumption and stover for other purposes. At present, the focus is on breeding for high biomass coupled with good nutritional value and low Hydrocyanic acid (HCN) content (Zhen Yang 1997).

Breeding for sweet stalks

In China, sweet sorghum is primarily used for silage preparation. With the introduction of improved sweet sorghum varieties such as Rio, Roma, Ramada and Wray from several countries, a systematic sweet sorghum breeding program was initiated in LAAS in 1985. As a result, two sweet sorghum hybrids, Liaosiza No.1 and Liaosiza No.2 were developed and released during 1989 and 1995, respectively.

Sorghum breeding in Africa

The crop is grown as a rainfed crop in diverse environments across tropical and sub-tropical agroecologies in Africa; from extreme lowland arid and semi-arid zones (of Libya, Sahel of West Africa and Botswana) to the sub-humid and humid lowlands (of southern Guinea Savanna of West Africa) and the mid highlands (of Great Lakes Zone of East Africa). The semi-arid and sub-humid highlands are typified by highlands of Ethiopia, Eastern and Central Africa (ECA) and Lesotho (where sorghums are cultivated around Mokhotbug at an altitude of 2400 m). Sorghum breeding began in the late 1930s replacing traditional farmer selection activities. This led to the identification, selection and release of better landraces as "improved local selections". At the same time, exotic germplasm lines were introduced, adapted and tested. Between 1948 and 1960, useful cultivars, local varieties and exotic germplasm lines were used in hybridization program and initiated pedigree and bulk breeding programs. Population development and its improvement through recurrent selection were possible with availability of genetic male-sterility (ms_3 has been extensively used). Greater prominence was given to wide adaptation and increased productivity. Between 1930 and 1950, a multilateral collaboration in Eastern Africa involving Kenya, Uganda and Tanzania began (Doggett 1988). In the late 1970s, a regional approach to sorghum breeding was initiated as a result of such collaborations. The first of such regional approaches to sorghum breeding was the Organization of African Unity/Scientific Technical and Research Commission (OAU/STRC) Joint Project 31 on Semi-Arid Food Grain Research and Development in Africa (SAFGRAD), which was initiated in 1976. Subsequently, regional sorghum breeding approach began at different periods in three regions - East and Central Africa (ECA), South African Development Community (SADC) and West and Central Africa (WCA). These regional breeding programs were set up with the objective of tackling different production constraints specific to different regions.

East and Central Africa

Sorghum improvement research in eastern Africa began with the collection and screening of local germplasm in Kenya, Uganda and Tanzania (1930–50) (Obilana 2004). Useful local selections were identified; the popular ones are: Dobbs (from western Kenya) and L 28 (from Uganda) (Doggett 1988). With sorghum gaining significance in Uganda and Tanzania, a program to breed for early maturing, white and brown grain 'bird resistant' varieties was initiated in Tanzania during 1948. The outcome of this program was the development of brown grain variety, SERENA. The variety was derived from the cross Swazi P1207×Dobbs through pedigree breeding in 1956/57. The sorghum-breeding program in these three countries (Kenya, Uganda and Tanzania) progressed into an East African regional sorghum improvement program, which started in 1958 at Serere, Uganda. This regional program focused on managing the endemic weed, *Striga* in addition to bird damage in the next two decades (1958–1978). This phase resulted in the development of three varieties, two of which - SEREDO (Serena×CK60) with brown grains, and Lulu-D (SB77×Seredo) with white grain - are still popular in Kenya, Uganda and Tanzania.

Sorghum improvement research in Uganda is based at Serere Agricultural and Animal Production Research Institute (SAAPRI). In collaboration with ICRISAT and International Sorghum and Millet Collaborative Research Support Program (INTSORMIL), and a number of non-governmental organizations (NGOs) operating in the countries, several improved varieties have been released since 1969 such as Serena, Hijack, Himidi, Hibred, Lulu Tall, Lulu dwarf, Dobbs Bora, Seredo and 2Kx17/B/1.

ICRISAT came to the region in 1978 to assist in sorghum improvement; the focus was on the use of selected landraces as parents in hybridization to create variability, and adaptive testing of advanced lines derived from crosses. ICRISAT operated from India and Kenya under a project of the Tanzanian Government. This collaborative research expanded later into two successive regional networks during 1986–1993 - East Africa Regional Cereals and Legumes (EARCAL) network, and the East Africa Regional Sorghum and Millets (EARSAM) network. In 2002, the East and Central Africa Regional Sorghum and Millets (ECARSAM) network was set up. While EARCAL/EARSAM was funded by USAID through the SAFGRAD/ICRISAT collaboration, ECARSAM is funded by the European Union through ASARECA. Between 1993 and 1999, ICRISAT's involvement in East Africa was strengthened with inputs of improved varieties from the Southern Africa Development Community (SADC)/ICRISAT Sorghum and Millet Improvement Program (SMIP). Collaborative adaptive testing, both on-station and on-farm in Ethiopia during 1995–2000 has resulted in the release of five sorghum varieties for production in the western lowlands (ICSV 210, PP 290), central mid-highlands (IS 29415) and eastern lowland Wadi (89MW 5003, 89MW 5056). The varieties, Serena and Seredo are popularly used in mixtures with finger millet for making thin porridge, and with cassava flour for ugali, in the Great Lakes Region.

The two countries, Ethiopia and Sudan can be regarded as the strongest in the region for sorghum improvement. In line with the Ethiopian Government's policy guidelines, the Institute of Agricultural Research (IAR) organizes sorghum improvement research in a team approach in Ethiopia. For the purpose of sorghum improvement research in Ethiopia, four adaptation zones of sorghum are recognized. The zones are classified as: highlands (altitude of >1900 m) with about 800 mm rainfall; intermediate (altitude of 1600–1900 m), with more than 1000 mm rainfall; lowlands (altitude of <1600 m) with low rainfall, less than 600 mm; and low land (altitude of <1600 m) with high rainfall (Gebrekidan 1981). Each of the four distinct zones of adaptation requires specific type of sorghum to match with agro-ecological conditions and which cater to the needs of the farmers and the end users. However, due to the shortage of trained human resources and the inadequate research infrastructure, only one coordinated national breeding program operating from Nazret/Melkassa Research Center is responsible for the identification and development of improved varieties/hybrids resistant to anthracnose, ergot, grain mold stalk borer (*Buseola fusca*), shoot fly in late-planted sorghum, *Striga* and frost before grain filling and improved management practices suitable to all the four adaptation zones in order to increase the productivity levels. To assist the Nazret/Melkassa Research Center, several technology testing centers representing each of the four adaptation zones have been set up. In addition to the Research Center at Nazret, Werer Research Center, low land irrigated center, serves as an off-season program site. The primary objective of this center is to seed increase of breeding lines selections and promising varieties and hybrids for the ensuing rainy season. Over the years, this center developed sorghum lines from indigenous germplasm lines and from introduced advanced breeding lines and recommended/released several cultivars (Debelo et al. 1995). EARSAM, the Ethiopian national program took the lead in developing large-scale field screening techniques for resistance to the major diseases such as ergot, anthracnose and grain mold and several resistant genotypes have been identified. These screening techniques and resistance sources have enhanced the pace of developing varieties and hybrids resistant to the major diseases.

The Ethiopian Sorghum Improvement Program (ESIP) started in full-scale in 1973. The program also served as home for the popular *zerazera* (*caudatum* race) type sorghums, which were extensively used as parents in ICRISAT sorghum improvement programs until the 1990s. Nationally, the ESIP made good progress with release of the varieties, Awash 1050, the popular ETS series, and Gambella 1107 (E 35-1) that has been widely used in ICRISAT breeding programs (Reddy et al. 2004a).

The sorghum research in Sudan dates back to early 1940s. Initially, crop improvement through breeding and crop husbandry research was given greater emphasis but later focus was shifted to more adaptive on-farm research. Sorghum research included genetic improvement for yields and grain quality and resistance to major production constraints such as *Striga*, and post-harvest handling and utilization. During early 1940s, sorghum research concentrated on collection and evaluation of local and exotic germplasm. The full-fledged sorghum improvement program was initiated in 1952 in the central rainfed research station at Tozi in Sudan (Ibrahim et al. 1995). A program for hybrid breeding was started by the Arid Lands Agricultural Development (ALAD) Project in collaboration with the

Agricultural Research Corporation (ARC) of Sudan in the 1970s. In 1977, the ICRISAT/Sudan Cooperative Sorghum/Millet Improvement Program was initiated. The most significant outcome of these collaborative research activities is the release of a commercial hybrid, Hageen Durra 1 (Tx623A×karper 1597) by ICRISAT and Sudan Agricultural Research Corporation (ARC) in 1983 (Doggett 1988, Ejeta 1986). Between mid 1970s and early 1990s, ARC has released many improved cultivars with yield advantages of 10% to 70% for commercial production in both irrigated and rainfed systems (Babiker et al. 1995).

South African Development Community (SADC)

Sorghum research in the Southern Africa Development Community (SADC) region, mainly in South Africa and Botswana, began before the Second World War with emphasis on selections within landraces, bird resistance, and resistance to *Striga* and drought. These activities spilled over into Zimbabwe and Zambia with diversified focus on hybrid development and production. As early as 1940, converted sorghum genotypes, especially combined *kafirs* and the white grain male-sterile lines were introduced into South Africa. The entry of private seed companies led to the commercialization of sorghum for industrial use such as in 'opaque beer' and malting for foods and drinks. In South Africa, selections from landraces included the then well known Red Swazi, which is still one of the earliest maturing (90–95 days) variety in the region and Framida, selected for *Striga* resistance from an introduced Chadian/Nigerian landrace. The male parent (Red Nyoni) of the most popular hybrid, DC 75 known for its opaque beer brewing quality is a landrace selection, which is popular in Zimbabwe and Zambia. Red Nyoni was selected from the improved landrace, Red Swazi in Zimbabwe (Doggett 1988). One of the most popular and widely grown sorghum varieties in Botswana and the rest of the Southern Africa region, Segolane, was also selected from landraces. Among the other varieties released earlier in Botswana and derived from the introduced *kafirs* from USA are 8D and 65D (Saunders 1942).

The cyclic occurrences of severe droughts in the late 70s in the region, led to the heads of States of SADCC (Southern Africa Development Conference Community) to deliberate on interventions to minimize the effect of drought. This led to the establishment of SADC/ICRISAT Sorghum and Millet Improvement Program (SMIP) in 1983/84. Sorghum improvement in SMIP has used a regional, collaborative, and multidisciplinary approach since its inception. In the 15-year period from 1983/84 to 1997/98, improved varieties and hybrids were developed, tested on-station and on-farm and released by the national agricultural research system (NARS) of the eight countries in the SADC region. The major objectives of sorghum improvement research in the region include: development of high yielding and early maturing dual purpose varieties with resistance to drought, downy mildew, leaf blight, sooty stripe and *Striga*. Apart from these, the grains were also evaluated for food, malting and feed qualities.

More than 12,000 sorghum germplasm accessions were assembled from all over the world and made accessible to NARS for sorghum improvement. From these 10,075 improved breeding lines, 4634 improved varieties, 379 hybrid parents and 3436 experimental hybrids were developed and supplied to Angola (100), Botswana (2398), Lesotho (681), Malawi (1449), Mozambique (322), Namibia (139), South Africa (147), Swaziland (326), Tanzania (3702), Zambia (5330) and Zimbabwe (3930). A total of 27 varieties and hybrids were released in eight SADC countries: Botswana (three varieties and first white grain hybrid in the region), Malawi (two varieties), Mozambique (three varieties), Namibia (one variety), Swaziland (three varieties), Tanzania (two varieties), Zambia (three varieties and three hybrids), and Zimbabwe (five varieties and one hybrid). However, of these 27 released varieties and hybrids, only 9 (33%) are cultivated on about 20–30% of the sorghum area in six countries. Five sources of resistance to three *Striga* species were identified (Obilana et al. 1988, Obilana et al. 1991). Twenty-three drought-tolerant male parents (R-lines) and 36 female parents (A-lines) with their maintainer (B-lines) parents were developed and are presently being used by South Africa, Tanzania, Zambia and Zimbabwe in their hybrid development programs (Obilana 1998). The variety Macia proved most popular in the region, having been released in five SADC countries (latest was in Tanzania in 1999) and is increasing in hectarage.

West and Central Africa (WCA)

The West and Central Africa (WCA) region is the largest and most important sorghum production area in Africa. The sorghum crop in WCA is essentially rain-fed, and its cultivation extends from latitude 8°N to 14°N typified by varied agro-climatic zones of humid (Southern Guinea Savanna) and sub-humid (Northern Guinea Savanna) to semi-arid (Sudan Savanna) and arid (Sudano-Sahelian) conditions, from south to north. These agro-climatic zones are characterized by sharply varying rainfall, temperatures and soil conditions, ranging from high rainfall (600−1200 mm) in the Guinea Savannas to low rainfall (250–600 mm) and very high temperatures in the Sudan and Sudano-Sahelian zones. A combination of these with varying day length periods demands sorghum varieties with different maturity photoperiod sensitivities. Also, the production constraints and adaptations requirements vary with agro-climatic zone.

Before 1940, there was no account of sorghum breeding research work in WCA. However, by the early 1950s, local landraces were collected and selections were made in Burkina Faso, Cameroon, Mali, Niger and Nigeria. In Nigeria, the landraces were initially grouped into four main types-namely *Guinea*, Kaura (mostly yellow endosperm types of *durra-caudatum* hybrid race), Farafara (white grain type of the race *durra*), and *caudatum* types (Curtis 1967). Several selections were made, most popular of which were the Warsha type sorghums, short Kaura and Janjare from Niger and Nigeria, and Muskwaris/Masakwa (transplanted sorghums in vertisols and hydromorphic soils) sorghum from Lake Chad and the inland delta of the river Niger in Mali. By 1966, exotic materials were introduced and tested, and pedigree-breeding programs began from the derivatives of local×local, local×exotic and exotic×exotic crosses. In the next 10–15 years, ie, by 1971–84, several improved pure line varieties and hybrids were developed, tested and released.

In Nigeria, before 1970s, the hybrids directly introduced from USA and India failed to make a dent to boost sorghum productivity due to their poor adaptation. Therefore, the exotic seed parents were crossed with local breeding lines to develop male-sterile lines from 1970 onwards. From 1977, testing of large number of hybrids involving three (RCFA, ISNIA and Kurgi A) of the four locally developed male sterile lines and improved and released varieties was intensified (Obilana 1982b). Of these, five hybrids (SSH 1, SSH 2, SSH 3, SSH 4, SSH 5) were identified as promising (Obilana 1982a). Similar efforts in Niger resulted in the development and production of the hybrid, NAD-1 by 1989.

ICRISAT's involvement in sorghum breeding in West and Central Africa began in 1979 with the establishment of centers at Kamboinse and Ougadougou in Burkina Faso; later shifted to Niamey in Niger, and now operating from Samanko in Mali since 1985. ICRISAT's genetic enhancement work in West Africa was preceded by Institut de Recherche Agronomiques Tropicales (IRAT's) involvement in francophone territories from 1964. Selection from segregating materials (derived from exotic×local crosses) and exotic germplasm introduction were the focus of both programs. ICRISAT was also involved in population improvement for grain food quality among *guinea* sorghums in Sotuba and Samanko, Mali. Breeding for *Striga* resistance was also initiated in 1979 in Burkina Faso by ICRISAT. One of the achievements from the joint presence of ICRISAT and IRAT in West Africa is the development of the variety, IRAT 204, derived from a IRAT 11×IS 12610 cross. IRAT 11 is a derivative from Senegal local (Hadien-kori)×Niger local (Mourmoure) cross. IS 12610 is an Ethiopian germplasm accession from ICRISAT genebank.

Improved varieties with good malt and brewing clear lager beer qualities were developed and released in Nigeria, during 1980s (Obilana 1985). Collaborative grain quality testing including malting quality and proximate analysis, between Institute for Agricultural Research (IAR), Ahmadu Bello University (ABU), Samaru, Zaria, and the Federal Institute for Industrial Research (FIIRO), Oshodi, Lagos (Obilana and Olaniyi 1983, FIIRO 1986) led to the identification of SK 5912, the best malting sorghum. These were followed by a series of pilot brewing and test marketing of lager beer made of sorghum malt (barley malt was replaced in ratios of 25%, 50%, 75% and 100% by sorghum malt) in 1984 in collaboration with three breweries. Following positive outcomes from acceptability, quality testing and successful marketing of the 100% sorghum malt, the government of Nigeria banned import of barley malt in 1988, thus saving more than US$100 million foreign exchange. The federal Nigerian government installed a brewing industry with a production capacity of 18 million hectoliters of beer in 1988 (Bogunjoko 1992). A spillover effect of this impact is the establishment of intermediate malt industries. This led to quantum increase of sorghum malt and sorghum malt syrup production by beverage industries producing malt drinks (maltina, malta and Amstel) by major breweries and beverage companies in Nigeria (eg, Cadburry Ltd., Lagos). Another spillover impact of breeding and selection of varieties suitable for brewing malt is the use of sorghum malt in composite flour with wheat and maize, as weaning foods (Murty et al. 1997). A white-grain sorghum variety ICSV 400 with good brewing qualities was identified by Nigerian and ICRISAT scientists (Murty et al. 1997). Using ICRISAT material, a total of 112 varieties have been released in different countries in Africa.

INTSORMIL

The International Sorghum and Millet (INTSORMIL) Collaborative Research Support Program (CRSP, pronounced “crisp”) located at the University of Nebraska, began in 1979 and includes the participation of seven US universities (University of Illinois, Kansas State University, Mississippi State University, University of Nebraska, Purdue University, Texas A&M University and West Texas A&M University) and the USDA/ARS, as well as research institutions in the US and collaborating countries. The INTSORMIL CRSP, or simply INTSORMIL, is a research organization focused on education, mentoring and collaboration with host country scientists in developing new technologies to improve sorghum and pearl millet production and utilization worldwide. The results of the research are of benefit to both the United States and collaborating countries. Drought tolerance and disease tolerance bred into US lines of sorghum developed by INTSORMIL researchers have been incorporated into lines of these crops in Africa and Latin America, improving crop production and fighting hunger in those areas.

Researchers of the Sorghum/Millet (INTSORMIL) CRSP have developed a rapid non-destructive bioassay for assessing *Striga* resistance, and new genes found to have stable *Striga* resistance are being bred into improved sorghum varieties. More than nine *Striga*-resistant varieties of sorghum have been tested on farms throughout the African continent, and multiplication of well-adapted varieties is in progress. A new discovery from INTSORMIL funded research at Purdue University is a sorghum grain type with high protein digestibility. More easily digestible sorghum is expected to improve human nutrition, particularly in Africa and India, and has the potential to improve the nutrition of livestock, both in the US and elsewhere. Digestibility affects the value of sorghum as forage for livestock. The *brown-midrib* (*bmr*) trait in some lines of sorghum developed by INTSORMIL researchers provides greater digestibility than normal forage sorghums.

bmr Sorghum-Sudan grass forage: The first commercial production of NutriPlus *bmr* sorghum×Sudan grass forage hybrid, based on *bmr* sorghum mutants resulting from research by INTSORMIL scientists, was in 1996. This *bmr* hybrid has shown an 18.9% average increase in feed value, compared to normal sorghum×Sudan grass hybrids. Improved nutritional quality of sorghum for livestock forage is another benefit of INTSORMIL research, which through commercialization is providing value to the farmer.

bmr Sorghum forage: In Nebraska, research has shown that *bmr* forage sorghum outperformed standard sorghum hybrids and may be equal to some corn hybrids when used to feed dairy cows. *bmr* sorghum silage was shown to be 10% more digestible than regular sorghum silage. Palatability and feed intake of cows fed *bmr* silage were comparable to corn silage diets.

Latin America

In Latin America, sorghum is produced on intermediate to large farms except in some inland valleys and eroded mountain slopes of Central America utilizing hybrids imported from USA and cultivars developed in the regions. In Guatemala, El Salvador, Honduras, Nicaragua and Haiti, a large part of the production is on small subsistence holdings often less than one hectare size where farmers use photoperiod-sensitive landraces intercropped with maize and beans using traditional production practices. The damages due to downy mildew, anthracnose, grain mold, stem borer and midge among the biotic stresses and soil acidity and alkalinity, drought and cold temperature among the abiotic stresses are the major yield constraints apart from the lack of early-maturing, tropically adapted cultivars with high yield potential and tolerance to major stresses in the region. ICRISAT initiated the Latin America and Caribbean Program in 1976 by stationing its staff at International Wheat and Maize Improvement Center (CIMMYT), Mexico. The program was aimed at developing early, dwarf and bold grain varieties for fertile soils in both the highlands and lowlands of Central America. The program was later transformed as Latin American Sorghum Improvement Program (LASIP) in 1990. LASIP had a comparative advantage in the development of tropically adapted improved germplasm resistant/tolerant to major production constraints for food-grade cultivars in Latin America. Several varieties were released and adopted based on ICRISAT-bred improved germplasm. Due to funding constraints, LASIP was discontinued in 1993. However, considering the interest shown by Latin American NARS, a program for improving sorghum for acid soil tolerance was initiated in 1996 with funding support from Inter American Development Bank (IADB).

The INTSORMIL program identified 20 acid soil tolerant lines in the 1980s (Gourley 1991), but they were susceptible to leaf diseases. At its centers in India and Africa, ICRISAT has developed diverse sets of high-yielding sorghum breeding lines useful as base materials for testing in acid soils of Latin America. Since 1996, ICRISAT, International Center for Tropical Agricultural (CIAT) and the national programs of Brazil, Colombia, Honduras and Venezuela have jointly implemented an IADB-funded project on “A research and network strategy for sustainable sorghum production systems for Latin America”. The major objectives of this project include: (1) to assemble, multiply and evaluate grain and forage sorghum breeding lines for tolerance to acid soils and resistance to foliar diseases, (2) to develop a research network of scientists working on this crop in the region and train them in sorghum research, and (3) to test the most promising genotypes in the target production systems.

A diverse set of 378 pairs of grain sorghum A-/B-lines, 784 grain sorghum R-lines/varieties and 94 forage sorghum lines were introduced into Colombia in October 1995 from ICRISAT-Patancheru. In addition to these, male sterility inducing gene (ms_3)-based two-grain sorghum populations (ICSP LG-large grain and ICSP B-maintainer) and one forage sorghum population (ICSP HT-high tillering) developed at ICRISAT were introduced. These introductions were tested empirically for grain and forage under acid soil conditions and fifteen grain sorghum A-/B-lines were selected for high yield, resistance to leaf diseases and tolerance to acid soils and twenty-one R-lines (on A_1 cytoplasm) for high yield under acid soils (Reddy et al. 2004a). Besides these, four forage lines (IS 31496, IS 13868, ICSR 93024-1 and ICSR 93024-2) were selected for tolerance to acid soils.

In the back-up breeding program, ICSP LG-large grain and ICSP B-maintainer populations were merged and selected alternatively at CIAT farm under neutral pH, and at Matazul under acid soil conditions. Some of the selections (male-fertiles) were advanced through pedigree breeding. Several promising progenies were also selected from the segregating materials of the specific crosses made among the lines selected for acid-soil tolerance and less susceptible to foliar diseases. Nearly 200 hybrids involving selected A- and R-lines and INTSORMIL R-lines were evaluated at Matazul (60% Al^{3+} and 4.6% organic matter). These hybrids produced more than 5 t ha^{-1} grain yield while the Al^{3+} tolerant check Real 60 yielded 4 t ha^{-1}. These are less susceptible to leaf diseases, greener at maturity, and also taller than the check Real 60 (Reddy et al. 2004b).

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