# Global millets improvement and its relevance to India and developing world

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## Introduction

Sorghum and millets are the important food and fodder crops predominantly in semi-arid regions are gaining importance in a world that is increasingly becoming populous, malnourished and facing large climatic uncertainties. These crops are adapted to range of temperatures, moisture-regimes and input conditions supplying food and feed to millions of dryland farmers, particularly in the developing world. Besides they also form important raw material for potable alcohol and starch production in industrialized countries. Among these crops, sorghum is the world's fifth most important cereal, in terms of both production and area planted. Millet, a general category for several species of small-grained cereal crops, is the world's seventh most important cereal grain (FAO, 1995). Roughly 90 percent of the world's sorghum area and 95 percent of the world's millet area lie in the developing countries, mainly in Africa and Asia (Table 1). These crops are primarily grown in agro-ecologies subjected to low rainfall and drought. Most such areas are unsuitable for the production of other grains unless irrigation is available. Sorghum is widely grown both for food and as a feed grain, while millet is produced almost entirely for food. These crops are also moving to new niches like rice-fallow sorghums in India.

***Table 1. Production (in million tons) and value of production (VOP in USD billions) for millets and sorghum worldwide and in low-income food deficit countries (LIFDC)1***

| Crop | Production (MT) | | VOP (USD billion) | |
|---|---|---|---|---|
| | LIFDC | World | LIFDC | World |
| Millets (finger and pearl) | 26.5 | 29.9 | 4.9 | 5.4 |
| Sorghum | 31.6 | 61.5 | 4.6 | 8.8 |
| Total | 58.1 | 91.4 | 9.5 | 14.2 |

*[1] FAOSTAT 2014. FAO's classification and criteria for low-income food-deficit countries (LIFDC) can be found at http://www.fao.org/countryprofiles/lifdc.asp?lang=en*

The economic importance of the millets is increasing in terms of feed value, particularly that of sorghum (Blummel and Rao 2006) though it is grown in contrasting situations in different parts of the world. The world sorghum economy can be broadly categorized under two production and utilization systems. Intensive, commercialized production, mainly for livestock feed, characterize the developed world and parts of Latin America and the Caribbean. Hybrid seed, fertilizer and improved water management technologies are used fairly widely, and yields average 3-5 t/ha. Such commercialized production systems cover less than 15 percent of the world's sorghum area, but produce over 40 percent of global output. Roughly 40 percent of this grain is traded on international stock feed markets. In sharp contrast are the low-input, extensive production systems in most of the developing world, where sorghum is grown mainly for food. While improved varieties are being adopted in such systems, particularly in Asia, management practices generally remain less intensive than in the commercialized systems. Fertilizer rates are low and the adoption of improved moisture conservation technologies is limited (FAO, 1995). As a result, average yields remained low between 0.5 and 1.0 t/ha in many areas but gradually increasing in spite of area decline in some regions (Table 2).

Millets are grown in the harshest environments where there is limited scope for growing other crops. Millet production systems in Africa and Asia are generally characterized by extensive production practices and limited adoption of improved varieties. Yields still average only 0.3 to 1.0 t/ha. While hybrids are being adopted in parts of Asia, most of the world's millet area remains under traditional varieties. Few farmers apply fertilizer or use improved moisture conservation practices. Therefore the yield levels remained low for long but increasing wherever improved hybrids and management practices are increasingly adopted like in India.

The sorghum and millets are crucial to the world food economy because they contribute to household food security in many of the world's poorest, most food-insecure regions. In the main production regions in Africa and Asia, more than 70 percent of the sorghum crop and over 95 percent of the millet crop are consumed as food. A large proportion of farm households aim simply to produce enough grain to meet household requirements - and many often fail to meet even this limited goal. Only a small proportion of the harvest is traded, mostly on local food markets. In some countries like India, sorghum contributes to 1% of the total agricultural GDP while it goes up to

*Table 2. Annual compound growth rates in sorghum and millet area and yield*

| | Area | | | | Yield | | | |
|---|---|---|---|---|---|---|---|---|
| Crop/Region | 1981-90 | 1991-00 | 2001-10 | 1981-10 | 1981-90 | 1991-00 | 2001-10 | 1981-10 |
| **Sorghum** | | | | | | | | |
| WCA | 5% | 1% | 0% | 9% | -¬3% | 1% | 0% | -¬1% |
| SA | -¬1% | -¬2% | -¬2% | -¬7% | 1% | 2% | 2% | 2% |
| ESA | -¬1% | 2% | 2% | 3% | 0% | 0% | 2% | 1% |
| **Millet** | | | | | | | | |
| WCA | 5% | 1% | 1% | 7% | -¬-1% | 1% | 0% | 0% |
| SA | -2% | -1% | -¬1% | -¬4% | 2% | 3% | 1% | 5% |
| ESA | 1% | 1% | 2% | 5% | -¬1% | -¬1% | 1% | 0% |

7% in Maharashtra and 5% in Karnataka the two major sorghum growing provinces in India.

Most sorghum and millet growing areas are characterized by high population, poverty and malnutrition with limited access and affordability to buy better food (Table 3) and low agricultural productivity is one the major reasons contributing to these problems. Growing environments and technology adoption play key role in enhancing millet productivity. In Africa, the agro-climatic factors most responsible for food insecurity also constrain the adoption of improved technology. Farmers at the margins of subsistence find it risky to invest in new technology. A growing proportion of farmers are beginning to adopt new varieties because only a small investment is required to change seed. However, they are less willing to allocate scarce cash resources to purchase chemical fertilizer or manure. Allocations of capital and family labor required to improve water and nutrient availability to the crop are limited because of the perception of higher returns from alternative farm and non-farm enterprises. In recent years, sorghum and millet production in Africa has expanded mainly due to increases in cropped area. Yields have failed to increase or have even declined because production is being pushed into more marginal areas and poorer soils, even in areas that are already drought-prone. Nonetheless, farmers are expected to begin intensifying production practices as land constraints become binding and the costs of food production shortfalls mount. There are some investments being made under the Harnessing Opportunities for Productivity Enhancement (HOPE) project and CGIAR Research Program on Dryland Cereals jointly by the NARS, CGIAR centers, Govt. departments, Famers Associations and Community Based Organizations (CBOs) to enhance the productivity of sorghum and millets across Africa and Asia.

While continuing the thrust on productivity enhancement it is important to increase the profitability of sorghum and millets to farmers. End-product specific cultivar use, value-addition and market linkages are critical to make these crops more profitable to farmers. Market infrastructure in Asia is relatively well developed, especially in areas with high population density. As a result, adoption of improved technology has been earlier and more widespread than in Africa, resulting in significant yield growth over the past

***Table 3. Population, poverty and malnutrition indicators, by region***

| Location (village) | Affected households (No./ No. investigated) | Affected population |
|---|---|---|
| Atkur Thanda | 33/34 (97%) | 278 (91.7%) |
| Atkhur | 57/80 (72%) | 320 (73%) |
| Kalkonda | 39/50 (78%) | 234 (81.5%) |
| Noorlapur | 32/38 (84%) | 229 (91.9%) |
| Thatepally thanda | 39/39 (100%) | 241 (100%) |
| Yacharam | 23/52 (44%) | 122 (34.3%) |
| Total | 223/293 (76%) | 1424 (76%) |

[1] *Rural and urban population estimates for 2011 were obtained from the United Nations, Department of Economic and Social Affairs, Population Division (http://www.un.org/esa/population/). Statistics for the number of stunted children, prevalence of stunting, and number of poor were extracted from datasets from the Generation Challenge Program's framework for priority setting (https://sites.google.com/site/gcpprioritysetting/Home).*

[2] *SA – South Asia, WCA – Western and Central Africa, ESA – Eastern and Southern Africa*

three decades. Production systems in the drier and less populated regions are more similar to those in Africa, with unimproved production and management practices, low adoption of improved technology and food insecurity.

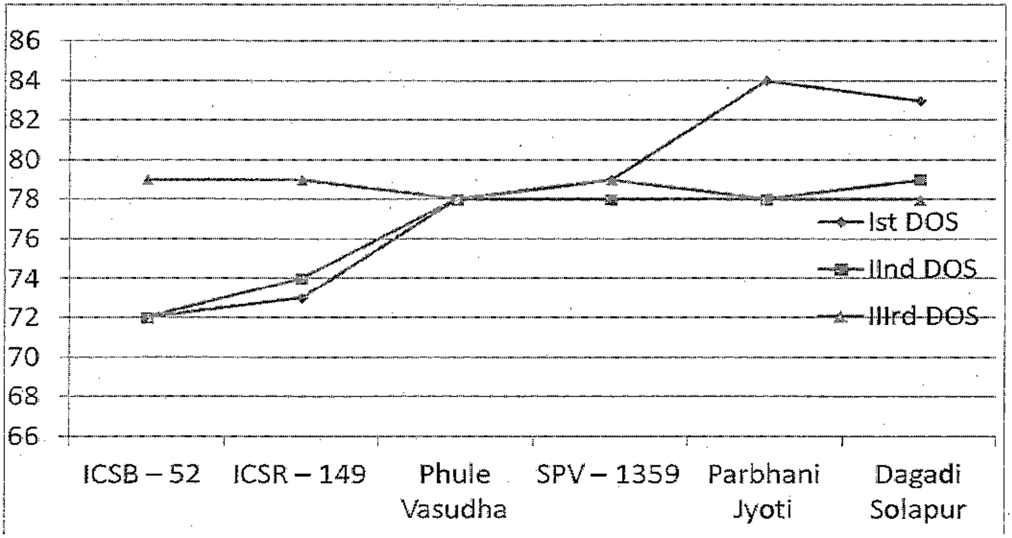
Overall, the area planted to sorghum and millet has been declining in Asia. Slow productivity growth and low producer prices have reduced the competitiveness of these cereals, resulting in crop substitution in many areas. In some cases, sorghum and millet have shifted into more marginal lands, where their adaptation to drier, less fertile conditions gives them a comparative advantage over other cereals. To change this situation it is increasingly important to make more investments in R & D of sorghum and millets towards sustainable intensification of production and in value-addition to make them more remunerative for the farmers. Further the nutritional benefits of these crops should be highlighted in a big way to generate large consumer demand. Some of the recent progress made in this direction is briefly discussed hereunder.

## II. Recent advances in increasing sorghum and millets yield potential, addressing production constraints and value addition

***Exploiting the photoperiod sensitivity and temperature insensitivity:*** Photoperiod plays a major role in sorghum and millets production. Photoperiod sensitivity basically allows for the length of the vegetative phase to vary with planting date, such that flowering occurs around the same time each season (Vaksmann *et al* 1996). In West Africa and also in postrainy season in India this mechanism works particularly well as the end of the season is far more predictable (and less variable) than the start (Craufurd *et al* 2011). In studies at ICRISAT Patancheru involving diverse sorghum genotypes in postrainy season it was established that M35-1, the postrainy season ruling variety has a distinct feature of photoperiod sensitivity and thermo-insensitivity that offers the ability to flower in more or less same time even in delayed sowings (Reddy *et al* 1987). Further breeding work involving M 35-1 as parent, several improved progenies were developed for postrainy season adaptation (Reddy *et al* 2009). Further studies at ICRISAT-Patancheru on the flowering response of various postrainy sorghum genotypes under different dates of sowings showed that in December, the critical photoperiod decreases to 10.5 hrs from 12 hrs and temperature to 15$^0$C from 24$^0$C. The rainy season adapted genotypes like ICSB 52 and ICSR 149 being photoperiod insensitive takes more time to mature in later dates of sowing and are not suitable for postrainy cultivation. Postrainy sorghum cultivars like Phule Vasudha and SPV 1359 did not respond for photoperiod but Parbhani Jyoti and Dagadi Solapur showed photoperiod sensitivity and temperature insensitivity by taking less time for flowering in third date of sowing compared to the first date of sowing (Fig. 1). This clearly indicated the need for season specific selection while breeding for postrainy season. However, the material can be advanced in rainy season without selection, to speed up the breeding program. Photoperiod sensitivity is exploited well in pearl millet and sorghum improvement particularly in WCA region. High yielding photoperiod-sensitive cultivars have been developed and commercialized. In future, identification of molecular markers linked to photoperiod sensitivity QTLs and cloning and transformation of other maturity genes may help in transferring photoperiod sensitivity to elite cultivars for better adaptation to tropical and sub-tropical environments.

In addition to photoperiod-sensitivity, tolerance to early and mid-season cold temperature is needed for increasing the production in temperate and tropical sorghum production areas around the world where the plants experience cold stress during emergence and/or at anthesis. Tolerant genotypes show increase in seedling vigor, resulting in greater biomass and grain yield in cold and dry environments.

*Figure 1. Flowering behavior of selected sorghum genotypes in different dates of sowing at ICRISAT, Patancheru, postrainy season 2010*



At ICRISAT- Patancheru, the simple and cost effective screening methodologies were developed to screen genotypes for cold tolerance in the same field trials that are intended for grain yield selections. It involves adjusting the planting date of test material in such a way that the flowering coincides with the period of lowest minimum temperatures in the year. Among various traits, the seed set percentage and panicle harvest index in the material flowered under low temperature conditions give an indication of cold tolerance of the material (Krishnamurthy *et al. in press*). Further a field and growth chamber based testing has been standardized for cold tolerance screening (Ashok Kumar – manuscript under development).

## Genotypes

***Yield potential:*** Among various millets, sorghum has a high yield potential, comparable to those of rice, wheat, and maize. On a field basis, yields have exceeded 11 000 kg/ha, with above average yields ranging from 7000 to 9000 kg/ha where moisture is not a limiting factor. In those areas where sorghum is commonly grown, yields of 3000 to 4000 kg/ha are obtained under better conditions, dropping to 300 to 1000 kg/ha as moisture becomes limiting (House 1985). Grain yield is the most important trait in millets breeding as in other crops; however stover yield is equally important in sorghum and pearl millet particularly in countries like India with large deficits on dry and green fodder supply. Breeding for grain yield improvement is carried out by selecting genotypes directly for grain yield and for component traits. Heterosis for grain and stover yield is high in sorghum and pearl millet and therefore hybrids development should be targeted in dual purpose back ground. A heterosis of 30-40% for grain yield is reported in hybrids compared to the best varieties (Ashok Kumar *et al* 2011b). Hybrids are the cultivar options and hybrid parents' development is critical for exploiting heterosis in these crops.

In addition to dual-purpose types, hybrid parents improvement to develop dwarf hybrids for mechanized harvesting and fodder purpose hybrids with high recovery ability (for multi-cut forage purpose) in a range of maturity (70 to 85 days to 50% flowering) should be the major focus. Additionally, forage varieties amenable for both single- and multi-cuts to meet the needs of farmers and dairy industry should be given high thrust. For e.g. a multi-cut forage sorghum variety CSH 24F is becoming highly popular with farmers in India where the demand is green forage is fast increasing. The newly developed pearl millet varieties recorded 50-60 tons/ha of green fodder and 12-15 tons /ha of dry fodder at 80-day cut (AICPMIP, 2013). Some of the recently developed pearl millet experimental hybrids have shown 5-6 tons of dry biomass in single-cut and 12-15 tons / ha of cumulative dry biomass in two cuts (Rai *et al*, 2012). Also, a highly efficient A5 CMS system discovered at ICRISAT can enhance the pace of breeding forage type male sterile lines for use in breeding high-yielding forage hybrids. In case of finger millet and small millets being highly self-pollinated, OPVs are the cultivar choice with main focus on the grain and dual-purpose nature.

Genetic and cytoplasmic diversification of hybrid parents needs to be given high thrust in developing improved male and female parents in sorghum and pearl millet. In sorghum the *caudatums* and *durras* are mostly exploited in breeding programs but bringing *guinea* race in to breeding programs brings next level diversification and yield advantage (Reddy *et al* 2011). Use of *iniadi* germplasm lines contributed to significant yield improvement in pearl millet and there is large scope for increasing the yields by exploitation of new CMS sources in parental line development. Population improvement is a good option in long-term for improving the grain and stover yields in both maintainer and restorer back grounds in sorghum and millets.

Availability of cytoplasmic-nuclear male sterility (CMS) system, higher heterosis % in the improved hybrids, and strong private sector presence facilitated the development of improved sorghum hybrids in large part of the globe. In addition to the widely used Milo-cytoplasm ($A_1$), cytoplasmic male-sterile lines are also available in $A_2$, $A_3$, $A_4$, $A_{4M}$, $A_{4VZM}$, $A_{4G1}$, $A_5$, $A_6$, 9E and KS cytoplasms in sorghum (Ashok Kumar *et al* 2011b). Considering the restoration frequency, hybrid performance and comparable $A_1$ and $A_2$ CMS effects for grain yield and resistance to shoot fly and grain mold, it is advantageous to use $A_2$ CMS system for developing hybrid parents, among the alternate cytoplasms available. This not only increases the cytoplasmic diversity but reduces the possibility of epidemics occurrence when a single source of cytoplasm is used. Pearl millet hybrid development programs globally have been based on A1 CMS system, hence at ICRISAT more emphasis is given on diversification of the CMS systems. Among the various alternative CMS systems evaluated (A2 and A3 from India, A4 from USA, Av from France, and Aegp and A5 identified at ICRISAT), it was found that A4 and A5 CMS systems to be distinctly different from others. (Rai *et al.*, 2005).

***Insect pests management:*** Sorghum and millets are affected by a large number of insect pests. On sorghum itself nearly 150 insect species have been reported as pests, of which sorghum shoot fly (*Atherigona soccata*), stem borers (*Chilo partellus* and *Busseola fusca*), sugarcane aphid (*Melanaphis sacchari*), sorghum midge (*Stenodiplosis sorghicola*), and head bugs (*Calocoris angustatus* and *Eurystuylus oldi*) are the major pests worldwide (Sharma 1993).

Infester row, artificial infestation, and no-choice-cage screening techniques have been standardized to evaluate sorghum germplasm, breeding material, and mapping populations for resistance to insect pests (Sharma *et al* 1992). Large-scale screening of the sorghum germplasm at ICRISAT has resulted in identification of several lines with reasonable levels of resistance to shoot fly, stem borer, midge, and head bugs (Sharma *et al* 2003). Sources of resistance to insects in sorghum have been used in the breeding program, and many varieties with resistance to insect pests have been developed (Sharma *et al* 2005). Cultivars with resistance to midge have been released in India and Myanmar, but are cultivated on a limited area due to non-availability of seed. However, these lines have been used by the seed industry to develop midge- resistant hybrids in Australia and USA. Resistance to midge and shoot fly has been transferred into maintainer lines, which have been supplied to, and used by the NARS partners and the industry in developing improved varieties in different regions (Ashok Kumar *et al.* 2011b).

Wild relatives of sorghum belonging to *Parasorghum*, and *Stiposorghum* have shown high levels of resistance to shoot fly, stem borer, and sorghum midge (Sharma and Franzmann 2001; Kamaia *et al* 2008 and 2012), and have diverse mechanisms of resistance to insects. These can be used to transfer resistance genes into the cultigen. The presence of trichomes has been found to contribute to oviposition nonpreference and the trichomes controlled by a single recessive gene (House 1985). Polymorphic simple sequence repeat (SSR) loci associated with resistance to shoot fly and the traits associated with resistance to this insect have been identified (Folkertsma *et al.* 2003), and are now being transferred into the locally adapted hybrid parental lines via SSR based MAS. The QTLs associated with antibiosis and antixenosis mechanisms of resistance to sorghum midge (Tao *et al* 2003), and tolerance to green bug (Nagaraj *et al* 2005) have also been identified. MAS will allow for rapid introgression of the resistance genes, and ultimately gene pyramiding, into the high yielding varieties and hybrids. At ICRISAT-Patancheru, three shoot fly resistant QTLs are being introgressed in to four elite backgrounds that include two B-lines and two varieties. Sorghum plants having *cry1Ac* gene have been developed (Girijashankar *et al* 2005). Combining transgenic resistance to insects with the conventional plant resistance will make plant resistance an effective component for insect pest management in sorghum. In pearl millet and other millets, insect problem is manageable under field conditions.

***Diseases management:*** In most semi-arid tropical environments, economically important diseases are grain mold in sorghum and downy mildew in pearl millet. While anthracnose, leaf blight, downy mildew, charcoal rot, rust, ergot and smuts are other important diseases in sorghum blast is emerging a major production constraint in millet. These diseases, either alone or in combinations, cause substantial damage to crops resulting in heavy economic losses every year (Thakur *et al* 2007). Grain mold is a major disease of improved white-grained, short to medium duration sorghum cultivars that mature during rainy season. The disease affects both grain production and quality and can cause 30-100% losses depending on cultivar, time of flowering and weather conditions during flowering to harvest (Singh and Bandyopadhyay 2000). Several toxigenic *Fusarium* spp. associated with grain mold complex that produce mycotoxins, such as fumonisins and trichothecenes have been characterized (Sharma *et al* 2011). Anthracnose, leaf blight and rust are the important foliar diseases and under favorable conditions up to 50% losses have been reported (Thakur *et al* 2007). Downy mildew is another destructive due to its systemic nature of infection resulting in the death of plants or lack of panicle initiation. Charcoal rot is the most important disease of post-rainy (*rabi*) season sorghum that is generally grown on residual soil moisture in India. The disease is more severe and destructive on high yielding sorghum cultivars when grain filling coincides with low soil moisture in hot dry weather. Management strategy for these diseases has been mainly through host plant resistance (HPR), which is economical, environment friendly and technically feasible at farmers' level. Disease management through HPR involves development of a simple and effective screening technique to identify genetic resistance that could be appropriately utilized in breeding programs to develop disease resistant cultivars. Over the years, screening techniques have been developed and refined for major sorghum diseases, such as grain mold, anthracnose, leaf blight, downy mildew, ergot, rust and charcoal rot. Although high level of mold resistance is not available in white-grained sorghum, several tolerant lines have been identified and utilized in breeding program. Efforts are also being made to map QTLs for grain mold resistance for their introgression into elite backgrounds. In addition, efforts are also required to identify resistance against toxigenic Fusaria associated with grain mold complex. Several sorghum germplasm and/or breeding lines with moderate to high levels of resistance to anthracnose, downy mildew, rust and leaf blight have been identified and used .in trait-specific breeding program at ICRISAT (Thakur *et al* 2007). Recently grain mold resistance hybrids in white grain backgrounds were developed at ICRISAT (Ashok kumar *et al.* 2008 and 2011a). High level of charcoal rot resistance is not available; moreover, abiotic factors such as soil moisture stress and high temperature predispose plants to charcoal rot infection and disease development. Therefore, there is need to explore other methods of disease control in addition to host plant resistance for the management of charcoal rot.

Downy mildew (DM) caused by *Sclerospora graminicola* is a widespread and economically most important disease of pearl millet causing substantial annual yield losses, particularly in single-cross F1 hybrids. With increasing area under hybrid cultivation since the 1970s the disease has become more severe due to evolution of new virulent pathotypes in response to new hybrid genotypes. At ICRISAT, breeding for DM resistance using conventional breeding and more recently marker-assisted backcross breeding has been successful, and a large number of disease resistant hybrids have been developed and deployed. This has, to a large extent, helped in arresting the occurrence of widespread DM epidemics since the 1990s. In view of the increasing severity of the disease and evolution of new more virulent pathotypes, a long-term DM resistance breeding strategy was proposed that involves conducting on-farm surveys, development of DM nurseries in different adaptation zones, development greenhouse screening facilities, designate hybrid parental lines for resistance to specific DM pathotypes (Thakur *et al.*, 2008). Recently sequence data of isolate Sg 445 of *S. graminicola* with over 100 X coverage has been generated at UC Davis. At ICRISAT 14 isolates of *S. graminicola* have been re-sequenced through MiSeq platform to generate normal paired end data with 20X coverage for each isolate (R Sharma personal communication).

***Managing weeds:*** Striga is the most important weed affecting sorghum and millets production, predominantly in sub-saharan Africa where in limited fertilizers are used on these crops. *Striga* is a genus of obligate, root – parasitic flowering plant, with most of the species is occurring in Africa. These include *Striga hermonthica, S. asiatica, S. aspera and S. forbesii.* Of these, *S. asiatica* used to be a major constraint limiting yield in sorghum in Asia.

During 1972 to 1985, ICRISAT- Patancheru concentrated its major efforts in developing a three stage screening technique for identifying resistant sources and improving them for high yield under adaption to rainy season conditions in India. The SAR 1 to SAR 36 refers to improved restorer lines and varieties developed at ICRISAT- Patancheru. Work was also directed at identification of resistant mechanisms (mechanical, strigol negative and antibiosis). Also several improved *Striga* resistant improved male sterile lines were developed at ICRISAT- Patancheru during 1985 to 2003 (Reddy *et al.* 2004). These include ICSB 567, ICSB 568, ICSB 569, ICSB 571, ICSB 572, ICSB 584, ICSB 594, ICSB 598, and ICSB 599 (Reddy *et al* 2007). The improved management practices (better tillage, fertilizer application and intercultivation) are by and large keeping the striga under control in most parts of Asia.

In Africa, much of the research work on *Striga* control was carried out initially in the national programs of Nigeria, Sudan, Uganda and Kenya before 1970 and of late in Bamako-Mali. Efforts were carried out to develop resistant varieties (Obilana and Reddy 1996), and also various other control measures such as cultural management (Hess and Dembele 1996), chemical control (Hess and Grard 1996) and biological control

(Abbasher *et al* 1996). Obilana (2004) indicated that the future research includes adopting new breeding strategies adopting marker technology, identifying the physiological basis of *Striga* pathogen variability, adopting non-conventional approach to *Striga* control including transposon-based mutation and integrated *Striga* control technology exchange and up scaling.

The networking efforts of ICRISAT in use and adoption of biotechnology tools- developing RIL populations of 296 B × Framida (SRN 4841) (stimulant negative), and N 13 (mechanical resistant) × E 36-1, at ICRISAT- Patancheru, phenotyping in pot and field conditions in Western Central Africa (WCA) and Eastern and Southern Africa (ESA) thru networking with national programs, genotyping and identification of markers and QTLs in Germany and at ICRISAT-Patancheru (Haussmann *et al* 2000) and adoption of marker assisted back cross breeding paid rich dividends in developing and release of four *Striga* resistant varieties in Sudan in the genetic backgrounds of popular, but *Striga* susceptible improved sorghum varieties, Tabat, Wad Ahmed and AG 8. These four released varieties are Asareca.T1, Asareca.W2, Asareca.AG3 and Asareca.AG4 (Reddy *et al.* 2012).

***High temperature tolerance:*** Sorghum and millets are known for their adaptation to a range of temperatures. Sorghum grows well in a temperature range of 15-40$^0$C but temperatures below and above this may have a bearing on crop germination, establishment, flowering and seed setting. Sorghum flowers and set seed under high temperatures (up to 43$^0$C) provided soil moisture is available (House 1985). In many regions of the world, sorghum production encounters heat and drought stress concurrently but heat and drought tolerances are unique and independent traits (Jordan and Sullivan 1982). Despite the level of adaptation of sorghum in the semi-arid tropics, seedling establishment is still a major problem. Failure of seedling establishment due to heat stress is one of the key factors that limits yields and affect stability of production (Peacock 1982). Thomas and Miller (1979) reported that sorghum seedlings respond differently when exposed to varying temperatures, and genetic variation for thermal tolerance in sorghum has been shown to exist in certain lines that are capable of emerging at soil temperature of about 55°C. Peacock *et al* (1993) and Howarth (1989) have discussed the need for greater diversity in sorghum seedling tolerance to heat in superior genotypes, as this will improve the crop establishment in the semi-arid tropics. Genetic variability for heat tolerance among the genotypes at seedling stage was demonstrated by Wilson *et al* (1982). Using screening techniques such as leaf disc method (Jordan and Sullivan (1982) and leaf firing ratings by ICRISAT breeders, genetic variability past the seedling stage was demonstrated and positive correlation found between grain yield and heat tolerance thus making breeding for heat tolerance a viable option. Genetic variability for heat tolerance in sorghum was also reported by other researchers (Sullivan and Blum 1970; Seetharama *et al.* 1982; Jordan and Sullivan 1982).

Khizzah *et al* (1993) reported that two loci were responsible for expression of heat tolerance, and complete dominance at both gene pairs, but one gene when dominant is epistatic to the other. The importance of additive gene effects over dominance effects for heat tolerance index was reported by Setimela *et al* (2007). However, selection for heat tolerance has limited success as (i) laboratory techniques to screen for heat tolerance have not been effective in improving heat tolerance in field studies; (ii) field screening for heat tolerance is difficult to manage and is often confounded with drought tolerance (Rooney 2004). Due to the confounding effects, though the heat and drought tolerance are independent traits, the selection for drought tolerance traditionally has been assumed to improve heat tolerance.

ICRISAT's experimentation during 2013 and 2014 identified some promising sorghum lines (B-lines, R-lines and varieties) which flowered normally and showed 100% seed set under temperatures above $40^{0}$C. However not all sorghums show heat tolerance. The 1000 test genotypes (600 B- lines, 300 R-lines and 100 varieties) at ICRISAT showed lot of differences for growth and flowering. Some of the genotypes flowered early, some flowered normally, some flowered late while some of them did not flower at all. Genotypes like ICSR 14001, ICSR 8, ICSR 21, ICSB 55, ICSB 84, ICSB 603, ICSV 162, ICSV 376 flowered normally, similar to their flowering time in the rainy season with a seed set percentage of 100% indicating the heat tolerance of these lines. These studies also showed that planting the material in first week of March gives best results for field screening for heat tolerance and the traits flowering time, seed set % and panicle harvest index serves as good proxies for selecting for heat tolerance. In pearl millet based on multilocation testing in India, improved genotypes that can flower and set seeds when temperatures are above $42^{0}$c identified. They can be exploited in developing improved cultivars for expanding summer pearl millet.

***Drought management:*** Millets and sorghum show high degree of drought tolerance though there are large genotypic differences. Sorghum has the capacity to survive some dry periods and resume growth upon receipt of rain. Sorghum also withstands wet extremes better than do many other cereal crops especially maize. Sorghum continues to grow, though not well, in flooded conditions; maize by contrast will die.

In sorghum four specific droughts were recognized. These are: 1. Seedling emergence under deep planting and high temperature, 2. Early seedling drought, 3. Mid-season drought or pre-flowering drought and 4. Post flowering/terminal drought. Among these, the two distinct drought-stress responses, a pre-flowering drought tolerance that occurs prior to anthesis and a post-flowering drought-stress that is observed when water-limitation occurs during grain-filling stage as in post rainy season adaptation have been considered as the most important in sorghum (Rosenow and Clarke 1981; Rosenow *et al* 1983).

At ICRISAT, growth-stage-specific breeding for drought tolerance, which involves alternate seasons of screening in specific drought and well-watered environments, has been used to breed sorghum that can yield well in both high-yield-potential environments as well as in drought-prone environments (Reddy *et al* 2009 and 2011). Since hybrids have exhibited relatively better performance than open pollinated (OP) cultivars for grain yield under water-limited environments, hybrid cultivar development (including their parents) should be given strategic importance for enhancing sorghum production in water-scarce environments (Reddy *et al* 2009).
Some of the drought tolerant sources identified in

***Table 4: Sorghum germplasm and breeding lines tolerant to drought at specific growth stages, ICRISAT-Patancheru, India***

| Growth stage | Tolerant sources/ improved lines |
|---|---|
| Seedling emergence | IS 4405, IS 4663, IS 17595 and IS 1037, VZM1-B and 2077 B, IS 2877, IS 1045, D 38061, D 38093, D 38060, ICSV 88050, ICSV 88065 and SPV 354 |
| Early seedling | ICSB 3, ICSB 6, ICSB 11 and ICSB 37, ICSB 54 and ICSB 88001 |
| Mid-season | DKV 1, DKV 3, DKV 7, DJ 1195, ICSV 272, ICSV 273, ICSV 295, ICSV 378, ICSV 572, ICSB 58 and ICSB 196 |
| Terminal drought | E 36-1, DJ 1195, DKV 3, DKV 4, DKV 17, DKV 18, ICSB 17 |

*Source: ICRISAT 1982; Reddy et al 2004* sorghum in early work at ICRISAT include Ajabsido, B35, BTx623, BTx642, BTx3197, El Mota, E36Xr16 8/1, Gadambalia, IS12568, IS22380, IS12543C, IS2403C, IS3462C, CSM-63, IS11549C, IS12553C, IS12555C, IS12558C, IS17459C, IS3071C, IS6705C, IS8263C, ICSV 272, Koro Kollo, KS19, P898012, P954035, QL10, QL27, QL36, QL41, SC414-12E, Segaolane, TAM422, Tx430, Tx432, Tx2536, Tx2737, Tx2908, Tx7000 and Tx7078 (www.icrisat.org). ICRISAT has identified lines that are tolerant to drought at various growth stages (Table 4). Drought tolerance of M 35-1, a highly popular post rainy season adapted landrace in India, has been amply demonstrated (Seetharama *et al* 1982).

In another study, the results for the measured variables [carbon exchange rate, (CER), transpiration, transpiration ratio (CER/transpiration), leaf diffusive resistance, leaf water potential and osmotic adjustment] showed a general trend for greater drought resistance in sorghum than in millet, indicating that the commonly observed adaptation of the millets to dry environments may be due to other factors, such as drought escape or heat tolerance (Blum and Sullivan 1985).

Among several drought tolerant traits, stay green trait in sorghum (the capacity of certain genotypes to maintain their leaves green during the grain-filling period) is the well characterized and exploited as a post-flowering drought tolerant trait (Reddy *et al* 2009; Haryarimana *et al* 2010). It's well documented to be polygenic and heritable, and is used extensively in breeding programs for developing drought tolerant cultivars (Harris *et al* 2007; Jordan *et al* 2012). This phenotype is also reported to be associated with reduced stalk lodging, reduced susceptibility to charcoal rot and maintenance of seed size (Borrell *et al* 1999 and 2000). Several studies had identified genomic regions/Quantitative Trait Loci (QTLs) underlying stay green expression (Tuinstra *et al* 1997a, Crasta *et al* 1999; Subudhi *et al* 2000a and 2000b; Tao *et al* 2000; Xu *et al* 2000; Kebede *et al* 2001 and Sabadin *et al* 2012). Physiological mechanisms such as improved capacity and WUE for water extraction, response to Vapor Pressure Deficit (VPD), transpiration efficiency (TE), leaf conductance and kinetics, specific leaf area and canopy development have been associated with stay green QTLs (Vadez *et al* 2011). These QTLs are been used for developing drought tolerant cultivars through marker-assisted backcrossing (Kassahun *et al* 2010; Jordan *et al* 2012) and effects of each QTL on stay green expression, grain and fodder yield had been reported. This needs to be further validated across several genetic backgrounds and different target regions. Similarly modeling efforts to characterize soil and agro-climatic parameters for production areas where post rainy sorghum is grown had been reported (Hammer *et al* 2010).

Drought scenarios in postrainy sorghum have been classified and quantified using crop simulation at ICRiSAT. Variation in traits that hypothetically contribute to drought adaptation (plant growth dynamics, canopy and root water conducting capacity, drought stress responses) were virtually introgressed into the most common post-rainy sorghum genotype, and the influence of these traits on plant growth, development, and grain and stover yield were simulated across different scenarios. Limited transpiration rates under high vapour pressure deficit had the highest positive effect on production, especially combined with enhanced water extraction capacity at the root level. Variability in leaf development (smaller canopy size, later plant vigor or increased leaf appearance rate) also increased grain yield under severe drought, although it caused a stover yield trade-off under milder stress. Although the leaf development response to soil drying varied, this trait had only a modest benefit on crop production across all stress scenarios. Closer dissection of the model outputs showed that under water limitation, grain yield was largely determined by the amount of water availability after anthesis, and this relationship became closer with stress severity. All traits investigated increased water availability after anthesis and caused a delay in leaf senescence and led to a 'stay-green' phenotype. These studies concluded that breeding success remained highly probabilistic; maximum resilience and economic benefits depended on drought frequency and maximum potential could be explored by specific combinations of traits (Kholova *et al.*, 2013 and 2014).

***Nutritional value:*** Sorghum and millets have predominant role in meeting the dietary energy and micronutrient requirements particularly in the low income group populations in Africa and south Asia. Efforts were made to understand the genetic control of nutritional quality in sorghum and millets. Protein content is relatively more studied in sorghum where in high genetic variability reported. Gains in protein content were also reported by various authors. The best method for phenotyping for protein content is through using Microkjeldahl method or Technicon autoanalyser (TAA) method. A study on limited number of germplasm lines, hybrid parents in sorghum did not show appreciable variability for β-carotene content in sorghum (Reddy *et al* 2005). Similar is the case with yellow endosperm lines where in the β-carotene did not exceed 1.1 ppm. For phenotyping for this trait, spectrophotometry can be followed but estimation using High-Performance Liquid Chromatography (HPLC) gives more accurate information.

Grain Fe and Zn enhancement is one of the major breeding objectives at ICRISAT and elsewhere. Large scale screening of sorghum core germplasm accessions, hybrid parents and commercial hybrids showed high genetic variability for grain Fe and Zn contents and most of this variation is heritable (Reddy *et al* 2005 and Ashok Kumar *et al* 2012). Significant positive association exists between grain Fe and Zn contents ($r^2$=0.6-0.8) and it is possible to simultaneously improve both the traits (Ashok Kumar 2009 and Reddy *et al* 2011). Additive gene action plays significant role in conditioning the grain Zn content while non-additive gene action is predominant for grain Fe content (Ashok Kumar *et al.* 2013a). Identification of QTL controlling grain Fe and Zn in sorghum is underway. Improved high Fe and Zn sorghum varieties and hybrids are being field tested in multilocation trials (Ashok Kumar *et al.* 2013b). The X-ray Fluorescence Spectrometry (XRF) can be used for rapid phenotyping of large number of breeding products to select the high Fe and Zn lines and the final validation can be done using the Inductively Coupled Plasma – Emission Spectrometry (ICP-ES) (Ashok Kumar *et al.* 2013b).

Excellent progress has been made in biofortifying the pearl millet. Large genetic variability for Fe and Zn, quantitative inheritance, predominance of additive gene action, strong positive correlation between Fe and Zn were reported (Rai *et al.* 2012 and Velu *et al.* 2011). An improved high Fe pearl millet cultivar 'Dhanashakti' was released for commercial cultivation in India. It has 10% high Fe and 5% high yield than the 'ICTP 8203' from which it was developed. In a study to assess the bioavailability of Fe from the high Fe cultivar, iron-deficient Indian children under the age of three who ate traditionally-prepared porridges (sheera, uppama) and flat bread (roti) made from iron-rich pearl millet flour absorbed substantially more iron than from ordinary pearl millet flour, enough to meet their physiological requirements. As an added bonus, this iron-rich pearl millet also contained more zinc, which was similarly absorbed in sufficient amounts meet the children's full daily zinc needs. This vindicates biofortified products can potentially increase Fe absorption (www.harvestplus.org).

***Bio-energy:*** Energy security is a critical concern in India and other developing countries and there is large Sorghum has distinct advantage as energy sorghum because of its high biomass production and adaptation across semi-arid tropical environments. Hence, this crop is widely believed as a model biofuel feedstock owing to its adaptation and ease of handling segregating generations. Sorghum biomass yields vary between 15 and 25 t ha$^{-1}$, but have been reported to be as high as 40 t ha$^{-1}$ (Rooney *et al* 2007). It is a very robust plant that not only produces high biomass but also accumulates large quantities of sugars in the stalks that can be used for biofueis production without scarifying the grains. Sweet sorghum or high energy sorghum can also thrive under moderate water stress conditions on marginal lands, and with little external inputs (Reddy *et al* 2004, Reddy *et al* 2008, Srinivasarao *et al* 2009). It also can be grown successfully in degraded and marginal lands contaminated with heavy metals (Zhuang *et al* 2007). Thus, energy sorghum (both biomass and sweet sorghum) is well suited for land of low productivity or at higher risk for drought or water logging stress and is unlikely to replace food crops from higher-quality land (Srinivasarao *et al* 2010). Specific traits of interest are stalk sugars accumulation, biomass yield, post-flowering drought adaptation, water-use efficiency, non-lodging, and cell wall composition. Elucidating the genetic basis of stem sugar and stem juice accumulation, modifying cell wall composition through *bmr* alleles introgression so that sorghum biomass can be processed more efficiently, maximizing biomass yield for a given geographic area and production system, and understanding the different mechanisms underlying drought tolerance are the main focus areas among sorghum researchers that target bioenergy traits. As mapping populations and collections of mutants increase, it will become easier to identify genes of interest, and it will ultimately become possible to identify all the genes involved in a particular process or pathway, and know how they interact. Efforts are underway in combining this information to generate germplasm that will enable sustainable bioenergy production using sorghum and pearl millet.

***Fodder quality:*** The stover of sorghum and millets is an important animal feed particularly in dry areas. Extensive market survey of fodder trading in India has shown that the ratio of stover to grain price is narrowing with stover: grain price ratio approaching now 0.5 (Sharma *et al* 2010). Additionally price premiums are paid for higher quality stover and a difference of about 1 percentage unit in stover digestibility was associated with a price premium of about 5% (Blümmel and Rao 2006).

Phenotyping for stover fodder quality of pipelined and release tested hybrids and OPVs has shown that about 5 units difference in stover digestibility exists that can be exploited without detriment to grain and stover yield (Blümmel *et al* 2010). Price premiums for such stover are 25 to 30%. Near infrared Spectroscopy (NIRS) platforms were developed and validated to phenotype for stover quality in multidimensional crop improvement programs (Sharma *et al* 2010). The dry stalks are controlled by a simple dominant gene, D; juiciness is recessive (House 1985). High yielding dual-purpose and forage sorghum and millet cultivars were developed with high *invitro* drymatter digestibility. Stay green QTL introgression can improve stover digestibility by 3 to 5 percentage units without detriment to grain and stover yields, in addition to improving drought resistance of sorghum cultivars and their water use efficiency. Brown mid rib introgressions improved stover quality similarly, but had a depressing effect on grain and stover yields.

Fortification and densification works has shown that sorghum stover based feed blocks, feed mash and feed pellets have the potential to increase average milk yields (currently < 4 kg/day) by three to 4 folds (12 to 16 kg/day, Anandan *et al* 2010).The effect of such intensification on natural resource usage and greenhouse gas emission is dramatic. For example an increase in average daily milk yield from 4 to 6 kg would reduce methane emission from Indian dairy by more than 1 million tons per year (Blümmel *et al* 2010).

***Alternative uses:*** Sorghum and millets are predominantly used as food by making various products out of them which are country/region specific. For e.g., sorghum is consumed in the form of *roti, bhakri or chapathi* in India *and ugali, kisra, injera, To, etc.,* in Africa. Similarly millets in the form of *bhakri or porridge or gruel*. The possible promising alternative food products from sorghum and millets are bakery products, maltodextrins as fat replacers in cookies, liquids or powder glucose, high fructose syrup and sorbitol. Malted sorghum and millets can be a good alternative for baby weaning foods. Popped sorghum and sorghum noodles, also as breakfast or snack foods form good alternative uses.

The industrial products made from sorghum grain include alcohol (potable grade) and lager beer. Other technologies such as production of glucose, maltodextrins, high fructose syrup and cakes from sorghum are yet to be scaled up. The juice from sweet sorghum stalks is fermented to produce ethanol (Biofuel) and other sweet sorghum products like syrup and *jaggery* have received good attention in production of food products like sweets and ready to serve foods.

Recently the NutriPlus Knowledge (NPK) program of the Agribusiness Business and Innovation Platform (AIP) at ICRISAT has demonstrated that sweet sorghum juice and syrup can be used as sugar alternative for meeting certain requirements of the beverage industry (Datta Mazumdar *et. al* 2012). Value addition, through conversion of the juice to syrup and beverages, offers farmers an excellent opportunity to improve farm income and productivity in semi-arid regions. In this study a new method to produce clarified sweet sorghum juice was demonstrated. Further, flavoured nutritious beverage formulations, with acceptable sensory properties were successfully developed using the clarified juice and syrup. Further the efforts are underway to increase the shelf-life of pearl millet using genetic and mechanical approaches.

## Relevance to India and developing world

Sorghum and millets continue to be important food and feed crops in developing world. Their versatility in multi-purpose use, stress adaptation and nutritive value makes them even more important crops in the era of extreme climate variability and high incidence of dietary induced malnutrition. Recent advances in sorghum and millets research and development in enhancing their yields, adaptation, stress resistance, nutritional value and processed products development discussed above contributes to increased economic value of these crops to the producers. The biofortified pearl millet and sorghum, sweet sorghum for bioenergy are some of the examples showcasing the potential of these crops in providing nutritional and energy security in developing world. Sorghum genome sequence is available and put to use for improving various traits. An ICRISAT-led consortium is sequencing the pearl millet genome and the draft genome sequence is expected by end of 2014. Efforts are underway to sequence the finger millet genome also. The challenge will be to make use of the genome information and developing customized research products and technologies to suit various climatic, food, nutritional and product quality requirements. Besides productivity enhancement the whole value chain should be looked in to make these crops more remunerative to farmers and processors. This calls for increased interest and investment from national governments and private sector for developing thriving integrated value chains for sorghum and millets.

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