Global Status of Sorghum Genetic Resources Conservation

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Abstract

Sorghum genetic resource conservations involve multiple strategies and collaboration to ensure the continued safeguarding of this valuable genetic resource. Curations of such worldwide collections require commitments to the acquisition, maintenance, distribution, evaluation, and utilization of such collections. In sorghum, a major challenge to its curation has been the standardization of protocols and techniques that each country deploys in evaluating their own collections. Information and documentation of these various collections has been a challenge; however, the two largest collections from the USA and ICRISAT have attempted to update their databases to reflect the rich sources of information available on their collections. In 2007, a panel of sorghum experts met to develop a "Strategy for the Global Ex Situ Conservation of Sorghum Genetic Diversity" and from this a review of the various collections is presented within this chapter. This review looked at various collections and evaluated the collections based on passport and characterization data. Collections reflected sorghum accessions from many different parts of the world and highlight some of the genetic stocks and phenotypic information available for utilization. As world populations increase and climate change challenges our ability to feed our population, the safety and curation of these types of collection allow us to respond to both biotic and abiotic stresses that will put pressure on the world's population to feed itself. These irreplaceable collections are in greater need of curation than ever before, but in order to understand the needs, one must first understand what is already present in these collections.

Keywords

Accessions · Curation · Genetic variation · Acquisition · Maintenance · Distribution · Utilization · Collections · Biotic · Abiotic · Food · Feed

1 Introduction

In its broadest sense, sorghum [*Sorghum bicolor* spp.] genetic resource conservation involves a series of strategies that help to acquire, maintain, distribute, and utilize global sorghum germplasm to preserve the integrity of the genetic variation that can be found within the sorghum species. This genetic variation can then be used to address biotic and/or abiotic stresses that confront sorghum as the crop and its farmers respond to new threats posed by climate change, insect and disease pressures and the continued need to produce more food to feed an ever-expanding world population. In 2016, sorghum was cultivated in 4477 mha worldwide with an average productivity of 14,279 kg ha^{-1} (FAOSTAT 2018). This has ranked sorghum as the fifth most important cereal crop in the world behind wheat [*Triticum* spp.], maize [*Zea mays* (L.)], rice [*Oryza sativa* (L.)], and barley [*Hordeum vulgar* (L.)]. Because of its wide adaptation, primarily driven by its course of domestication, it can be and is used in a wide arrangement of processes such as human food production systems, animal feed, either as a grain or forage source, building materials, converted to both high and low value alcohols, and as a biofeed stock for numerous renewable products (see Klein et al. 2015 for excellent review of dispersal and diversification).

In March of 2007, a panel of sorghum experts met in ICRISAT to develop a "Strategy for the Global *Ex Situ* Conservation of Sorghum Genetic Diversity" (https://www.croptrust.org/wp/wp-content/uploads/2015/05/Sorghum-Strategy-FINAL-19Sept07.pdf). This became one of the most comprehensive evaluations of worldwide sorghum collections. The stated purpose of the strategy was to "contribute to an efficient and effective conservation system for sorghum genetic resources" and articulated five major objectives:

1. Identification and assessment of the global, regional and national collections of sorghum genetic resources meeting the international standards for conservation and playing a key role in a global conservation system.
2. Identification of critical gaps in existing world collections of sorghum genetic resources and development of strategies to fill these gaps.
3. Development of a model for collaboration, cost sharing, and international responsibilities for the effective and efficient management of key sorghum genetic resource collections which will become the International Sorghum Germplasm Collection (ISGC).
4. Identification of information needs for a comprehensive integrated global database network that enhances the maintenance, sharing, and utilization of the ISGC.
5. Capacity building in order to upgrade and enhance various collection repositories to ensure the maintenance, regeneration, and sharing of the ISGC.

From their survey of genetic resources worldwide, the Global Crop Diversity Trust reviewed the Germplasm Holding Database maintained by Bioversity International and showed that 19 collections represented 86% of the total accessions known worldwide, with the USDA-ARS-PGRCU and ICRISAT accounting for 41.1% of the total (Table 1).

There was a wide range of information and documentation of these collections, with some institutes having excellent passport, characterization, evaluation, and availability records that could be easily accessed and utilized. The two best datasets were from the US and ICRISAT; however, documentation is somewhat variable, and most datasets are not accessible, and this remains true today. Because of the difficulty in collecting updates on these various collections, the three major collections, located at the ICRISAT, USDA-ARS-PGRCU and ICARNBPGR New Delhi India were detailed below.

2 The ICRISAT Collection

The ICRISAT genebank maintains 39,948 accessions originating from 93 countries and comprises 34,615 landraces, 4775 advanced breeding lines, 97 cultivars, and 461 wild and weedy relatives. The ICRISAT sorghum collection is the largest (about 17% of the total sorghum collections conserved globally) followed by the

Table 1 Collections of sorghum according to replies of the Sept 2006 survey (Atoyebi 2007)

Country	Institute	Number of accessions	% of total holdings (194,250 acc.)
USA	USDA-ARS-PGRCU	43,104	22.19
Global	ICRISAT	36,774	18.93
India	NBPGR	18,853	9.71
China	CAAS	18,250	9.40
Ethiopia	IBC	9772	5.03
Brazil	EMBRAPA	8017	4.13
Russia	VIR	7335	3.78
Zimbabwe	NPGRC	7009	3.61
Australia	DPI	5403	2.78
Sudan	PGRU-ARC	4191	2.16
Mali	IER	2975	1.53
France	CIRAD	2690	1.38
Kenya	NGBK	1320	0.68
Zambia	NPGRC	1005	0.52
South Africa	NPGRC	428	0.22
Malawi	NPGRC	401	0.21
Nigeria	NCGRB	159	0.08
Serbia	Inst. Field and Veg crops	152	0.08
Global	ILRI	52	0.03
	TOTAL 19 institutes	**167,890**	**86.43%**

USDA-ARS, Georgia, USA (~15%), while the ICS-CAAS, China and ICAR-NBPGR, New Delhi, India conserves about 7–8% each (Upadhyaya and Vetriventhan 2018). Germplasm accessions are conserved as active collection (medium-term storage) and base collection (long-term storage). The active collection is stored under medium-term storage condition at 4 °C and 20–30% relative humidity, which remains viable for 10–20 years with ≥85% viability, and are used for distribution, utilization, and multiplication purpose. Accessions in base collection are vacuum sealed in an aluminum foil pouch and stored at −20 °C and 5–7% moisture content after confirming initial germination (>90%). Seed viability of each germplasm is regularly monitored at 5–10-year intervals in the active collection and 10–20-year intervals in the base collection, and accessions are periodically regenerated when the seed quantity or viability goes below the standard limits, to maintain sufficient seed quantity and viability. The wild and weedy relatives of sorghum that are perennial types and vegetatively propagated are being maintained as live samples in the field genebank. About 91% of sorghum collection conserved in the ICRISAT genebank has been safely duplicated at Svalbard Global Seed Vault (SGSV), Norway, which guarantees the availability of a genetically identical sub-sample of the accession to mitigate the risk of its partial or total loss caused by natural or human caused catastrophes.

Table 2 Geographical and racial distribution of sorghum collection conserved at the ICRISAT genebank, India

Race/region	Africa	Asia	Americas	Europe	Oceania-Pacific	Unknown origin	Total
Bicolor	602	512	336	114	4	3	1571
Caudatum	6552	684	384	94	15	27	7756
Caudatum-bicolor	1145	570	211	75	5	33	2039
Durra	3660	4032	184	98	2	11	7987
Durra-bicolor	1447	843	62	83	2	3	2440
Durra-caudatum	2409	1987	322	85	7	9	4819
Guinea	4081	838	77	8		4	5008
Guinea-bicolor	281	39	21	4	1	2	348
Guinea-caudatum	3214	715	228	50	5	62	4274
Guinea-durra	128	79	18	7		2	234
Guinea-kafir	36	5	65				106
Kafir	925	71	306	11	1	1	1315
Kafir-bicolor	53	45	46	2	1		147
Kafir-caudatum	250	45	119	3		4	421
Kafir-durra	142	53	76		2		273
Wild	330	33	69	7	22		461
Un-classified	696	36	1	14		2	749
Total	**25,951**	**10,587**	**2525**	**655**	**67**	**163**	**39,948**

Geographical and racial distribution: The ICRISAT sorghum collection is largely from Africa (65.0%) and Asia (26.5%), and about 87% of the accessions were landraces. The cultivated sorghum is represented by five races and ten intermediate races, and all of these races were present in the ICRISAT sorghum collection, and the collection is dominated by accessions belonging to *durra* (accounted for 20.0%), *caudatum* (19.40%), *guinea* (12.5%), *durra-caudatum* (12.1%), and *guinea-caudatum* (10.7%), while the remaining races/intermediate races represent <6.1% of total collection (Table 2). Accessions belonging to the race *bicolor*, *durra*, and *durra-caudatum* were largely from Africa and Asia; *guinea-kafir* and *kafir* from Africa and the Americas; *kafir-bicolor* from Africa, Asia and the Americas; while other races were largely from Africa.

Distribution and impact: The ICRISAT genebank has been the major source of supplying sorghum germplasm accessions worldwide for use in crop improvement programs. Following the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), germplasm is supplied under the Standard Material Transfer Agreement (SMTA). Since 1974, the ICRISAT genebank has distributed 268,783 samples of sorghum germplasm accessions to 110 countries (Asia 55.0%, Africa 27.4%, the Americas 12.9%, Europe 4.3%, and Oceania 0.4%) with the majority of these samples distributed during the 1980s and 1990s. Twenty-one accessions have been distributed over 100 times, of which IS 18758 (a high yielding cultivar and released in Burkina Faso and Burundi) has been distributed about 250 times. The global collections held at the ICRISAT genebank also serve the purpose of restoration of germplasm to the source countries when national collections are lost due to natural calamities, civil strife, etc. The ICRISAT genebank has supplied >22,000 sorghum samples globally for the purpose of restoration of germplasm. It includes 14,615 accessions to India, 362 to Botswana, 1827 to Cameroon, 1723 to Ethiopia, 838 to Kenya, 1436 to Nigeria, 445 to Somalia, and 977 to Sudan. Thus the national programs of several countries have regained their precious plant germplasm heritage which could have been lost if this was not conserved in the ICRISAT genebank. Of the germplasm distributed from the ICRISAT genebank, 39 sorghum accessions originating from 14 countries have been released directly as 41 cultivars in 18 countries (Upadhyaya and Vetriventhan 2018).

Characterization and evaluation: The sorghum germplasm collections conserved at the ICRISAT genebank has been characterized for many morpho-agronomic descriptors, 42–44% of accessions screened for shoot fly, downy mildew and stem borer; 18–22% to grain mold, leaf blight, rust and striga, and 10% to anthracnose. For grain quality, approximately 26–29% of the accessions were evaluated for protein and lysine contents (Upadhyaya et al. 2014a). Photoperiod and temperature sensitivity, and latitudinal patterns of adaptation were assessed in the sorghum landraces (20,710 accessions). The results revealed that the lower latitudes (0.00–25.00°) were found to be important regions for sorghum collections. The differences in days to 50% flowering and cumulative growing degree days requirements during long-day rainy season and short-day post-rainy seasons were used and classified the landraces into three groups: (1) photoperiod and temperature insensitive (1697 accessions), (2) photoperiod sensitive and temperature insensitive (18,766 accessions), and (3) photoperiod- and temperature-sensitive (247 accessions). This study indicated the insensitive landraces were found in higher proportions at 0.00–25.00° N and 15.00–35.00° S, and the selective adaptation of photosensitive and temperature insensitive landraces either to rainy or post-rainy season, while those identified as insensitive to both photoperiod and temperature were adapted to both long-day rainy and short-day post-rainy seasons (Upadhyaya et al. 2018).

Core and Mini-Core Collections: Germplasm diversity representative sets of core collection (Prasada Rao and Ramanatha Rao 1995; Grenier et al. 2001) and mini-core collections (Upadhyaya et al. 2009) have been established to enhance the utilization of these accessions. The sorghum mini-core collection (Upadhyaya et al. 2009) has been extensively evaluated for agro-morphological and grain nutritional traits (Upadhyaya et al. 2016a), bioenergy traits (Upadhyaya et al. 2014b), disease resistance (grain mold, downy mildew, anthracnose, leaf blight, and rust diseases, Sharma et al. 2010, 2012), resistance to insect pests (Stem borer, shoot fly and aphids; ICRISAT, unpublished), low temperature stress tolerance (Upadhyaya et al. 2016b), and post-flowering drought tolerance (Upadhyaya et al. 2017) and identified germplasm sources for utilization in sorghum improvement. Several of the mini-core accessions were sources for multiple traits and these accessions have been utilized in hybridization programs for introducing novel diversity into sorghum cultivars.

3 USDA-ARS-PGRCU Sorghum Collection

In 1757, Benjamin Franklin mentioned sorghum in a letter to a Mr. Ward. He brought back seed from Europe because of its unique panicle formation, lending itself to broom manufacturing and began sharing the seed with friends. By 1810, The Philadelphia Agricultural Society mentioned Guinea Corn (Quinby 1974) and references to sorghums such as sorgo, Chinese amber cane, white and brown durras, milo, feterita, and hegari can be found in various publications between 1853 and 1908 (Doggett 1988). The United States Department of Agriculture began formal collections around 1905 and prior to the introductions of hybrids in the late 1950s, 13,611 accessions of sorghum had been introduced into the United States; however, serious curation of the crop did not take place until the early 1980s. Since then a total of 32,012 accessions have been added to the collection for a total of 45,623 accessions (Table 3; GRIN-Global, Germplasm Resources Information Network 2018). Several groups have reviewed the status of the U.S. collection (Duncan et al. 1991; Dahlberg and Spinks 1995). The collection is also broken down by species within the National Collection (Table 4; GRIN-Global, Germplasm Resources Information Network 2018).

Maintenance and Distribution: The working collection of sorghum is maintained at USDA-ARS Plant Genetic Resources Conservation Unit and S-009 Multi-State Project, in Griffin, Georgia, while the long-term backup collection is maintained at NCGRP at Fort Collins, Colorado. Accessions are maintained at −18 °C at both Griffin and NCGRP. Seed quantities and weights are recorded for each accession before entering long-term cold storage facilities. Priority for increase in the working collection is based on low seed numbers and low viability as determined by germination testing. The increases are primarily conducted at the Tropical Agriculture Research Station (USDA) in Mayagüez, Puerto Rico, and St. Croix.

The total number of accessions distributed from PGRCU to the United States and other countries from 1997 through 2017 has been 278,132 accessions of which 27,498 accessions have been to foreign scientists (Table 5). The sorghum collection continues to be one of the most active collections within the U.S. National Plant Germplasm System. Though the bulk of the seed has been distributed to U.S. scientists, some requests have been initiated from foreign scientists. Breeders from around the world can query the Germplasm Resources Information

Table 3 U.S. sorghum collection by country of origin (GRIN-Global, Germplasm Resources Information Network 2018)

Country	Number of accessions	Species
Afghanistan	9	2
Africa	1	1
Algeria	42	4
Ancient Palestine	1	1
Angola	3	1
Argentina	90	3
Armenia	1	1
Australia	111	16
Barbados	1	1
Belgium	1	1
Benin	417	1
Botswana	178	1
Brazil	3	2
Burkina Faso	355	2
Burundi	151	2
Cameroon	263	5
Central African Republic	12	1
Chad	120	4
Chile	2	2
China	1158	2
Colombia	3	1
Congo	1	1
Costa Rica	7	1
Cote D'Ivoire	1	1
Cuba	1	1
Cyprus	1	1
Denmark	1	1
Dominican Republic	2	1
Egypt	18	2
El Salvador	5	2
Eritrea	2	2
Ethiopia	7206	7
Former Serbia & Montenegro	2	1
France	15	1
French Equatorial Africa	5	1
French Guiana	1	1
Gambia	66	3
Georgia	6	1
Germany	7	1
Ghana	52	2
Greece	4	1
Guadeloupe	11	1

(continued)

Table 3 (continued)

Country	Number of accessions	Species
Guatemala	14	1
Guinea	1	1
Honduras	70	1
Hungary	43	2
India	2178	5
Indonesia	24	3
Iran	12	2
Iraq	6	2
Israel	24	2
Italy	147	3
Jamaica	28	1
Japan	72	1
Jordan	3	1
Kazakhstan	3	1
Kenya	903	5
Korea	15	1
Korea, North	5	2
Korea, South	22	1
Lebanon	32	1
Lesotho	18	1
Liberia	3	2
Libya	22	2
Madagascar	10	1
Malawi	548	1
Maldives	6	1
Mali	2416	3
Mauritania	17	1
Mexico	386	3
Morocco	1	1
Mozambique	22	1
Myanmar	8	3
Nepal	9	1
New Zealand	2	1
Nicaragua	2	1
Niger	520	1
Nigeria	584	3
Oman	54	1
Pakistan	33	2
Papua New Guinea	1	1
Paraguay	1	1
Peru	2	1
Philippines	6	1
Portugal	21	2

(continued)

Table 3 (continued)

Country	Number of accessions	Species
Puerto Rico	7	1
Rhodesia	5	1
Romania	2	2
Russian Federation	51	1
Rwanda	86	1
Saudi Arabia	21	1
Senegal	356	2
Sierra Leone	27	1
Somalia	107	1
South Africa	1101	5
Soviet Union	133	3
Spain	14	1
Sri Lanka	2	1
Sudan	3998	5
Swaziland	17	1
Syria	6	1
Taiwan	20	1
Tanzania	345	4
Thailand	6	2
Togo	564	3
Turkey	107	3
Uganda	1421	3
Ukraine	3	1
United Kingdom	12	1
United States	4825	6
Unknown	32	4
Uruguay	1	1
Venezuela	16	1
Yemen	4642	2
Zaire	54	3
Zambia	577	3
Zimbabwe	1227	5
No data available	7207	7
Total	**45,623**	**N.A.**

N.A. not appropriate for summation since accessions for the same species may come from different countries

Network-Global (GRIN-Global) for information on any of the 45,623 accessions in the system and can place orders for germplasm through GRIN-Global. Internet access to GRIN is available through the World Wide Web at http://www.ars-grin.gov/npgs.

Characterization and evaluation: The U.S. sorghum collection has been screened for many abiotic and biotic stresses over the years. The evaluation of sorghum

Table 4 U.S. sorghum collection by species (GRIN-Global, Germplasm Resources Information Network 2018)

Sorghum species	Number of accessions
Sorghum angustum	8
Sorghum bicolor	495
Sorghum bicolor nothosubsp. *Drummondii*	88
Sorghum bicolor subsp. *Bicolor*	44,661
Sorghum bicolor subsp. *Verticilliflorum*	60
Sorghum brachypodum	2
Sorghum bulbosum	7
Sorghum ecarinatum	1
Sorghum exstans	3
Sorghum halepense	72
Sorghum hybr.	36
Sorghum interjectum	2
Sorghum intrans	5
Sorghum laxiflorum	2
Sorghum plumosum	9
Sorghum propinquum	1
Sorghum purpureosericeum	3
Sorghum spp.	127
Sorghum stipoideum	3
Sorghum timorense	4
Sorghum versicolor	4
Sorghum × *almum*	30
Total	**45,623**

collections for major pest, diseases, and nutrient evaluations is outlined in Table 6. As with most of the sorghum collections worldwide, the collection is roughly XX% photoperiod sensitive which makes it difficult to screen in temperate regions of the world.

Unique Collection: The USDA has put together for maintenance and curration of series of sorghum collection special groups, work groups, and genetic stocks. These are available by request from the GRIN database.

4 Collections by ICAR-NBPGR-New Delhi, India

The first major effort in the assembly of a World Collection of sorghum germplasm was in the 1960s by the ICAR-Rockefeller Foundation's Agricultural Research Programme in India. A total of 22,701 exotic germplasm have been introduced in India from different countries of the world for various sources of important traits. The major contribution is from Ethiopia, Sudan, Nigeria, Uganda, Zimbabwe, Cameroon, and the USA, Ethiopia, Uganda, and Sudan in East Africa, Nigeria,

Table 5 Distribution of sorghum accessions 1997–2017 (GRIN-Global, Germplasm Resources Information Network 2018)

Year	U.S. distributions (no. of accessions)	Foreign distributions (no. of accessions)
1997	729	57
1998	1749	581
1999	716	462
2000	26,611	203
2001	7364	1254
2002	17,123	141
2003	33,227	1887
2004	3318	151
2005	1843	203
2006	1980	211
2007	9284	213
2008	13,801	2199
2009	17,054	2330
2010	11,954	1922
2011	11,514	1514
2012	15,997	4690
2013	13,561	1540
2014	14,835	2563
2015	13,242	1368
2016	21,984	2669
2017	12,748	1340
Total	**250,634**	**27,498**

Mali, and Burkina Faso. Resistance to several diseases is found in the c*onspicuum* of Nigeria. Alleles for high productivity with prospects for increased yield due to nodal tillering appear to be in combinations of *caudatum*, *durra,* and *caffrorums* from both West and East African regions. The Ethiopian *durras* are an excellent source for the stay-green (non-senescence) trait related to post-flowering drought-tolerance trait.

In addition, 14,475 accessions of exotic germplasm received from 45 countries viz. Algeria, Angola, Australia, Botswana, Brazil, Burkina Faso, Barundi, Cameroon, Canada, Central African Republic, Chad, China, Cuba, Israel, Italy, Japan, Kenya, Korea, Lesotho, Madagascar, Malawi, Mali, Mexico, Morocco, Nepal, Nicaragua, Niger, Nigeria, Russia, Rwanda, Senegal, Somalia, South Africa, Sri Lanka, Sudan, Swaziland, Syria Arab Republic, Tanzania, Thailand, Uganda, United States of America, Venezuela, Yemen, Zambia, Zimbabwe are conserved in the National Genebank, NBPGR, New Delhi.

Germplasm experts attempted thorough explorations several times in different Indian states and made substantial collections. At present, National Genebank of ICAR-NBPGR holds and preserved 11,646 accessions of indigenous sorghum collections from collected from all the Indian states (Table 7). Out of these preserved accessions, substantial part (18.1%) is of unknown origin for which passport data on their origin is not available. Out of remaining 71.9%, the majority part of accessions

Table 6 Partial list of pest or disease resistance, nutrient toxicity, and nutritional values (additional phenotypic data can be found at: https://www.ars-grin.gov/npgs/descriptors/sorghum)

Evaluation	Number of accessions
Acid detergent fiber %	2510
Aluminum toxicity	10,384
Anthracnose	16,399
Crude protein %	2914
Sorghum downy mildew (P1)	4186
Sorghum downy mildew (P3)	5966
Ergot	2022
% Fat	2910
Fall army worm	8942
Grain weathering	15,126
Gray leafspot	306
Greenbug biotype E	14,580
Greenbug biotype I	1455
Ladder spot	1470
Leafblight	340
Manganese toxicity	7334
Metabolizable energy for swine (Mcal/cwt)	2914
Net energy gain for cattle (Mcal/cwt)	2914
Net energy gain for lactating cattle (Mcal/cwt)	2914
Phosphorous %	2914
Photoperiod sensitivity	18,571
Restorer A_1 cytoplasm	656
Restorer A_2 cytoplasm	585
Restorer A_3 cytoplasm	585
Race designation	23,011
Rust	17,402
Sorghum yellow banding virus	210
Sugarcane mosaic virus	427
Total digestible nutrients %	2914
Working group designation	15,262
Yellow sugarcane aphid	5564
Zonate leaf spot	1470

(~50%), majority part of accessions was collected from the four major sorghum growing states i.e. Maharashtra (19.9%), Karnataka (9.9%), Andhra Pradesh (10.2%) and Madhya Pradesh (9.7%).

In addition, trait-specific sorghum germplasm lines introduced from other countries in India are conserved at National Genebank, NBPGR, New Delhi. Majority of these germplasm lines were having desirable traits like male sterility and, resistant to biotic and abiotic stress (Table 8).

Table 7 State-wise Indian sorghum collections conserved at National Genebank, ICAR-NBPGR, New Delhi

S. No.	Indian state	Number of collections	% of total holdings (11,646 acc.)
1	Andaman & Nicobar Islands	3	0.0
2	Andhra Pradesh	1188	10.2
3	Arunachal Pradesh	19	0.2
4	Assam	5	0.0
5	Bihar	254	2.2
6	Chhattisgarh	143	1.2
7	Delhi	78	0.7
8	Gujarat	499	4.3
9	Haryana	45	0.4
10	Himachal Pradesh	6	0.1
11	Jammu and Kashmir	12	0.1
12	Jharkhand	80	0.7
13	Karnataka	1150	9.9
14	Kerala	17	0.1
15	Madhya Pradesh	1129	9.7
16	Maharashtra	2320	19.9
17	Manipur	3	0.0
18	Meghalaya	2	0.0
19	Mizoram	2	0.0
20	Odisha	239	2.1
21	Punjab	127	1.1
22	Rajasthan	458	3.9
23	Tamil Nadu	569	4.9
24	Telangana	566	4.9
25	Tripura	16	0.1
26	Uttar Pradesh	499	4.3
27	Uttarakhand	73	0.6
28	West Bengal	35	0.3
29	Unknown origin	2109	18.1
	Total	**11,646**	

4.1 Characterization of Sorghum Germplasm at ICAR-Indian Institute of Millets Institute Hyderabad

A total of 12,345 accessions were characterized at ICAR-IIMR (ICAR-Directorate of sorghum research) Hyderabad. Data on 8 quantitative and 15 qualitative traits were collected. The plant height was the most variable character followed by grain yield, days to 50% flowering, leaf length, etc., 573 potential trait-specific germplasms are identified for early maturing, high biomass, high fodder yield and grain yield viz., 17 acc. Are identified as early flowering (<57 days), 13 acc. With

Table 8 Trait-specific introduction of sorghum germplasm lines from other countries in India by ICAR-NBPGR

EC No.	Country	Trait
EC242786-91	Sudan	Drought hardy
ECI91789	Australia	High lysine content
EC315823-52	USA	Acid soil tolerant
EC 331138-48	USA	Resistance to army worm and anthracnose
EC 428874	Nigeria	Disease-tolerant lines
EC 466525-526	USA	Tx2911. TAMBPK-59, varieties resistant to green mold, downy mildew & head smut
EC4826705-97	USA	Male sterility & fertility restorer lines for immediate application for basic research
EC496845-854	Canada	Multi cutting purpose type fodder
EC538941-46	USA	Maintainers of the Al cytoplasmic genetic male sterility system
EC558947-55	USA	Restorers of the Al cytoplasm genetic male sterility system
EC587422-509	USA	Striga-resistant
EC568885-86 EC562509-I3	USA	Male sterile line
EC568887	USA	Maintainer line
EC582502-508	USA	Isogenic lines for brown mid rib genes
EC 416988	Nigeria	Early open pollinated variety

Source: Plant Germplasm Reporter (1975–2006)

more number of leaves (>20), 40 acc. With longer leaves (>90 cm), 27 acc. With wider leaves (>10 cm), 42 acc. With taller height (>300 cm), 48 acc. With longer ear head (>45 cm), 60 acc. With wider ear head (>8 cm), 305 acc. With higher grain yield (>100 g/plant), and 21 acc. With more 100-seed weight (>5 g).

4.2 Potential Sorghum Genetic Resources for Biotic and Abiotic Stress

Among 3585 sorghum genetic resources evaluated at ICAR-Indian Institute of Millets Research (IIMR), 63 accessions were reported as the potential sources of resistance for different biotic stresses. This includes genetic resources for combine resistance to stem borer + shoot bug shoot fly + stem borer, grain mold, and leaf diseases (Table 9). Similarly, genetic resources with improved tolerance to various

Table 9 Potential genetic resources identified for multiple biotic and abiotic stresses

Traits	No. of accessions
Biotic stresses	
Shoot fly and stem borer	12
Shoot fly, stem borer, and head bug	3
Shoot fly, stem borer, and midge	1
Shoot fly, stem borer, and shoot bug	1
Stem borer and shoot bug	18
Shoot bug and aphids	2
Aphid and shoot bug	1
Shoot fly and charcoal rot	3
Shoot fly and stripe disease	4
Grain mold and leaf diseases	1
Grain mold and downy mildew	15
Stripe disease and charcoal rot	1
Charcoal rot	1
Abiotic stresses	
Post-flowering drought tolerance	26
Resistance to post flowering drought and lodging	1
High relative water content (RWC) and low leaf senescence	5
Mid-season drought tolerance	3
Herbicide tolerance	9
Salinity tolerance	10
Stay green trait	8

abiotic stresses like drought, high temperature, frost, cold, salinity, and other edaphic factors have been identified. The accessions identified for the multiple resistance to grain mold and leaf diseases are originated from India except one from Nigeria. The accessions identified for the rust resistance originated from India except one from Nigeria. Some of these sources of resistance for biotic and abiotic stresses are registered with ICAR-NBPGR (Table 10) and involved in the breeding programs at ICAR-Indian Institute of Millets Research (IIMR).

5 Special Groups

Core Collection: The core collection consists of 2438 accessions. The core collection was formed by Jeff Dahlberg and John Erpelding.

Sorghum Association Panel: There are 406 accessions in the Sorghum Association Panel (SAP). The description of the SAP available on GRIN-Global is the following: The Sorghum Association Panel is a set of diverse and historically important sorghum lines characterized for genotypic and phenotypic diversity and suitable for association mapping studies. The accessions in the panel represent all

Table 10 Sorghum germplasm registered for potential valuable traits at ICAR-NBPGR

Accessions	Novel unique features
IC 345715, IC 569675, NRCSFR 07-5	Shoot fly resistance with other desirable traits
EC 434430	Sugarcane aphid *Melanapsis sacchari*, resistance
IC 570245, IC 570246, IC 570247, IC 570248, IC 570249, IC 570250, IC 570251, IC 570252, IC 584513, IC 584514, IC 584515, IC 584516, IC 0584517, IC 584518	Grain mold resistance with desirable specific traits on plant height, duration, grain color, shape, and size
IC 345703, IC 345733, IC 345734, IC 345772	Multiple foliar diseases-rust, anthracnose, zonate leaf spot, sooty stripe, and downy mildew
IC 567687, IC 567688, IC 567689, IC 567690, IC 567691, IC 567692, IC 567693, IC 567694, IC 567695, IC 567696, IC 572931, IC 572932, IC 572933, IC 572934, IC 572930, IC 584519, IC 584520, IC 584521, IC 584522, IC 584523, IC 584524, IC 584525, IC 584526, IC 584527, IC 584528, IC 584529, IC 584530, IC 584531, IC 584532, IC 584533, IC 584534. IC 584535, IC 584536, IC 612149, IC 612150, IC 612157, IC 612158, IC 594687	Male sterility lines in different types of sorghum (rainy, post rainy, sweat sorghums) with desirable traits required in each type
IC 584056, IC 595529, IC 597771, SPV 2018, IC 632083, IC 471842, IC 565017, IC 585921	Improved quality traits
IC 549901, IC 392140	Improved drought adaptation
IC 432861, IC 432862)	CMS, Thermos-insensitive with high yield and long panicle
IC 568489	Basmati Jowar (scented sorghum)
IC 560414, IC 561243	Converted male & female parents of dual-purpose sorghum hybrids, SPH 1148 with high yield
IC 585920	Somaclonal mutant in postrainy sorghum
IC 632070	Sorghum forage line derived from intergeneric cross between sorghum × maize, low HCN and high IVDMD

Source: Elangovan (2020)

major cultivated races (tropical lines from diverse geographic and climatic regions), and important U.S. breeding lines and their progenitors.

6 Work Groups

Sorghum Converted: There are 422 accessions in the group. Converted lines developed in the Sorghum Conversion Program conducted cooperatively by USDA/ARS at Mayaguez, Puerto Rico and the Texas Agricultural Experiment Station.

Researcher of Project: Rosenow, Darrell T, Texas A&M University.

Other Work Groups: Which includes various evaluations performed on selected germplasm accessions at a defined location including Ethiopian (1998 and 2000), Honduran (1989), Isabela (1993 and 1994), Mali, Mayaguez (1993 and 1994), St. Croix\Virgin Islands (1992–1997, 1993 with Sudan).

7 Sorghum Genetic Stocks

Cold Tolerant Subset: This collection contains 171 accessions. Description of methods and environmental conditions for screening of cold tolerant mapping population available on GRIN-Global is the following: For the cold-tolerant population RTx430/PI610727 (Gaigaoliang), both cold and optimal germinability were assessed under laboratory conditions. Briefly, 25 seeds were sown in polystyrene Petri dishes lined with filter paper moistened with sterile distilled water. Seeds were allowed to incubate/germinate at a constant 12 °C (cold germination) or at 30 °C (optimal germination) for 8 h in the light, in separate controlled temperature chambers and then both treatments were exposed to 20 °C for 16 h in the dark. Germination under laboratory conditions was determined visually based on protrusion of radicle to approximately 1 mm length. Final germination was counted at 4 or 7 days after sowing for optimal and cold temperature test. To determine variation in field emergence, the RILs and parents were sown in 5 × 1 m plots at the USDA-ARS farm in Lubbock, TX (101° 90′ west longitude; 33° 59′ north latitude) and at Texas Agrilife farm at New Deal, TX (101° 82′ west longitude; 33° 69′ north latitude). A total of 50 manually selected high-quality seeds were sown on top of well-prepared beds on April 1, 2009 for both locations. Plots were uniformly irrigated using a drip system after sowing. Seed emergence was measured based on the number of seedlings per plot at 14, 21, and 30 days after sowing. The mean field soil and air temperature during the experimental period was 14.9 °C and 16.6 °C, respectively.

Researchers on Project: Franks, Cleve, DuPont Pioneer; Burow, Gloria B., CSRL, USDA-ARS; Burke, John, USDA, ARS; Xin, Zhanguo, USDA-ARS, PSGD.

RIL BTX623 X PI567946 (HKZ) Subset: These collections contain 226 accessions. A description of this subset available on GRIN-Global is the following: In early spring of 2011, the BTx623HKZ_recombinant inbred mapping population including the two parents and eight commercial checks were planted in replicated plots in three locations representing the US sorghum belt temperate region, USDA zones 4b to 6b between April 1 and 18 (differing due to latitudes of location and precipitation) to evaluate variation for early season field traits for cold tolerance based on field emergence and seedling vigor, biomass. The locations used for field testing were: Lubbock, Texas (33.6°N-101.88°W, 2381 ft. elevation), Manhattan, Kansas (39.21°N-96.51°W, 1053 ft. elevation) and Wall, South Dakota (43.99°N-102.24°W, 2208 ft. elevation). The mean ambient and soil temperatures for all three locations at the time of planting were: Lubbock, TX—18.3; 17.7 °C; Manhattan, KS—12.2; 14.4 °C; Wall, SD—12.6; 12.5 °C. Each entry was planted in 10 m long plots with 100 cm spacing between plots and equal number of seeds were planted per plot. Field emergence was evaluated on a weekly basis and at 30 days after planting as % field emergence. Seedling vigor was rated on a 1–5 scale, with rating of 1 as robust vigor and 5 as poor vigor. Subsequently, five seedlings in the inner section of each plot were harvested for above-ground biomass to determine dry weight.

RIL BTX623 X PI568016 (NSZ) Subset: This collection contains 292 accessions. A description of this subset available on GRIN-Global is as follows: The parents of the population are BTx623, which is a combine type elite line that germinates poorly during the early cool season of the year crossed to Niu Sheng Zui (PI 568016) which is a Chinese landrace that exhibit >70% germination under cool conditions in temperate regions of the U.S. sorghum belt (USDA hardiness zones 4b to 6b). The BTx623NSZ_Recombinant Inbred Mapping Population (RIMP) was developed by hand emasculation of the female parent BTx623 and pollination with pollen from. The resulting F1 hybrid was intermediate in height, with brown seed color. A total of 300 F2 plants were planted, but only 292 lines were advanced single seed descent breeding technique in Lubbock, Texas from F3 to F4 generations. From F5 to F7, seeds were produced alternately between Lubbock, Texas, and Puerto Rico. At the F6:7 stage of development, ten representative uniform plants were tagged and seeds were bulked from the 10 tagged plants to compose each line. A total of 292 RILs were generated and are used to represent the BTx623NSZ_RIMP. In spring of 2015 through 2017, the BTx623NSZ_RIMP including the two parents and eight commercial checks were planted in replicated plots in three locations representing the U.S. sorghum belt temperate region, USDA zones 4b to 6b between April 1 and 18 (differing due to latitudes of location and precipitation) to evaluate variation for early season field traits for cold tolerance based on field emergence and seedling vigor, biomass. The locations used for field testing were; Lubbock, Texas (33.6°N-101.88°W, 2381 ft. elevation and Manhattan, Kansas (39.21°N-96.51°W, 1053 ft. elevation). The mean ambient and soil temperatures for all three locations at the time of planting were: Lubbock, TX—18.3; 17.7 °C; Manhattan, KS—12.2; 14.4 °C; Wall, SD—12.6; 12.5 °C. Each entry was planted in 10 m long plots with 100 cm spacing between plots and equal number of seeds were planted per plot. Field emergence was evaluated on a weekly basis and at 30 days after planting as % field emergence. Seedling vigor was rated on a 1–5 scale, with rating of 1 as robust vigor and 5 as poor vigor. Subsequently, five seedlings in the inner section of each plot were harvested for above ground biomass to determine dry weight.

Schertz Mutants Subset: This collection contains 455 accessions. A description of this subset available on GRIN-Global is as follows: The late Keith Schertz, USDA, ARS collected 536 sorghum lines consisting of natural and induced mutants, linkage analysis lines, and chromosome translocation lines from various sources around the world. In order to make this mutant collection available for sorghum genetic and genomic studies, the seed inventories were categorized, replanted, and phenotypes confirmed based on Dr. Schertz's original notes. Seeds were replanted at Halfway, Texas in 2004, and at Lubbock, Texas in 2006 and 2009. Standard cultivation practices were followed and irrigation was applied as needed. Phenotyping was conducted several times during the growing season at seedling, vegetative, reproductive, and maturity stages. Days to flowering, plant height, and exertion were recorded.

RIL BTX623 X IS3620C: This subset contains 431 accessions. A description of this subset available on GRIN-Global is as follows: Phenotypic evaluation of the original 137 F2-derived F6–8 generation inbred lines from the BTx623/IS3620C population was conducted as early as 1994. The population was planted in a randomized complete block design with two replications in College Station, Texas (30.5°N, 96°W) and Lubbock, Texas (33.6°N, 101.9°W). The population was evaluated for 28 traits in both locations and QTL analyses for these traits were performed (Hart et al. 2001; Feltus et al. 2006). In 2004, 119 of the F7 to F9 RILs were cultivated and phenotyped at College Station, Texas (30.5°N, 96°W), Halfway, Texas (34°N, 101.5°W), and Weslaco, Texas (26°N, 98°W). Utilizing these 119 F7 to F9 RILs, 15 agronomic traits including primary, secondary, and tertiary branching were measured and QTL analyses for these traits were performed by Brown et al. (2006). Laboratory studies were also conducted on a subset of the population at the USDA-ARS Plant Stress & Germplasm Development Unit in Lubbock, TX in 2004 and 2005 for seedling tolerance to chilling and high temperatures.

8 Conclusions

The ICRISAT and U.S. collections remain the largest and most active international collections of sorghum germplasm. These are followed by the collection by ICAR-National Bureau of Plant Genetic Resources (NBPGR) which is the nodal agency for plant genetic resources management in India. All the three collections continue to enhance their collections through further evaluations and characterizations of their respective collections and will continue to explore genetic variation utilizing new genomic and high-throughput evaluation technologies. Smaller collections still face many obstacles that were identified in the "Strategy for the Global *Ex Situ* Conservation of Sorghum Genetic Diversity" in 2007. These include lack of funding for germplasm maintenance, inadequate storage facilities for maintaining long-term viability of collections, lack of descriptor and evaluation data, and lack of personnel. These continue to be long-term issues that plague the international efforts to preserve these important collections.

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