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Sorghum germplasm from West and Central Africa maintained in the ICRISAT genebank: Status, gaps, and diversity

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ABSTRACT

The genebank at ICRISAT maintains 8020 accessions of sorghum from 16 West and Central African countries. Geographical gaps and diversity were assessed in the collection. Using the passport data of 3991 accessions for which georeferenced data were available, a total of 386 districts (gaps) located in 11 West and Central African countries were identified as geographical gaps. Burkina Faso with 140 and Nigeria with 118 districts were identified as countries with major geographical gaps. The collection of 43 accessions of wild species represented only three species belonging to *Sorghum bicolor* ssp. *drummondii* and ssp. *verticilliflorum*, *S. hevisonii*, and *S. macrochaeta*, highlighting the need for collection missions aimed exclusively at enriching the collection of wild relatives. Accessions having characterization data (7630) were used to assess diversity. The first three principal components contributed to >60% of variation. Maximum diversity was observed in the collection from Nigeria for both qualitative and quantitative traits. Mean values indicated significant differences between basic and intermediate races for the traits studied. Among the races, accessions of *guinea-caudatum* for qualitative traits and those of *caudatum* for quantitative traits were highly diverse. The low intensity of the sorghum collection and the many geographical gaps in the collection underline the importance of launching collection missions to fill the gaps, particularly in regions of predominantly *guinea* sorghums. Genotyping of possible duplicate accessions is needed to identify duplicates in the collection. It is suggested that all passport information including georeferenced data of collection sites should be collected when samples are collected in gaps.

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1. Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is the fifth most important cereal crop, grown mostly in both temperate and tropical regions of Africa, Asia, Europe, and the Americas. It is a major crop in Africa, with the growing area running across West Africa south of the Sahara through Sudan, Ethiopia, and Somalia. Although the crop is grown mainly for food, fodder, and feed in many countries, it has gained acceptability as a new-generation bioenergy crop owing to its multiple uses and high adaptability to varied agroclimatic conditions. Among biofuel feedstocks, sorghum is of particular interest because its grain and plant parts are used for the production of baked foodstuffs, alcohol, beer, fiber, starch, paper, and syrup. Sorghum grain is gluten-free and serves as an attractive alternative food for those with celiac disease [1]. During 2014, sorghum was grown on an estimated 44.80 million hectares (Mha) globally with a production of 70.83 Mt. [2]. Sudan (8.40 Mha), India (5.80 Mha), Nigeria (5.40 Mha), Niger (3.60 Mha), USA (2.60 Mha) and Mexico (2.00 Mha) were the major countries growing sorghum. In West and Central Africa (WCA), it was grown over an estimated 14.70 Mha, in Nigeria (5.40 Mha), Niger (3.60 Mha), Burkina Faso (1.50 Mha), Mali (1.20 Mha), Chad (1.10 Mha), Cameroon (0.80 Mha), Togo (0.30 Mha), Ghana (0.20 Mha), Mauritania (0.20 Mha), Senegal (0.20 Mha), Central African Republic (0.04 Mha), Gambia (0.03 Mha) and Sierra Leone (0.03 Mha) [2]. Sorghum cultivation in Cape Verde and Cote d'Ivoire was negligible.

Sorghum exhibits enormous phenotypic diversity and various taxonomic characteristics have been used to identify and assess patterns of this diversity. Landraces have been recognized as important sources of variation for agronomic, nutritional, and climate-related traits and stress tolerance [3]. Diversity loss is becoming more prominent as we face the need to adapt crops to climate change [4,5]. There is a need to conserve crop genetic resources before we lose them forever, owing mainly to the replacement of landraces with improved cultivars, concomitant natural catastrophes (droughts, floods, fires, etc.), human settlement, overgrazing, climate change, and the destruction of plant habitats for irrigation projects [5]. For a nearly complete assembly of species diversity, a critical assessment of existing collections for their status, duplicates, gaps, and genetic diversity is imperative. Geographic information systems (GISs) such as FloraMap [6], DIVAGIS [7], ARCGIS [8], Maxent [9], and Remote sensing [10] are very useful for a better understanding of species distributions, crop cultivation, and the representativeness of germplasm collections. Using FloraMap and other GIS software, spatial data, and remote sensing, geographical and taxonomic gaps have been identified in several crops including sorghum [11–16]. Phenotype-based diversity analysis has been considered [17] as a powerful tool for estimating genetic variation.

The genebank at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India maintains 39,923 sorghum germplasm accessions from 93 countries, including 8020 accessions from 16 WCA countries. The aims of the present study were to analyze the passport and characterization data of this collection, assess their status and diversity, and identify geographical and taxonomic gaps.

2. Materials and methods

2.1. Collection

Passport and characterization data of the sorghum germplasm collection maintained in the ICRISAT genebank were used. Data were retrieved for 8020 accessions originating in 16 WCA countries and summarized with respect to germplasm collection missions launched, germplasm collected, and biological status of accessions from each country. The cultivated sorghums were classified into five basic races (*bicolor*, *guinea*, *caudatum*, *kafir*, and *durra*) and 10 intermediate races (*guinea-bicolor*, *caudatum-bicolor*, *kafir-bicolor*, *durra-bicolor*, *guinea-caudatum*, *guinea-kafir*, *guinea-durra*, *kafir-caudatum*, *durra-caudatum*, and *kafir-durra*) based on spikelet and panicle morphology. The races are, for the most part, easily identifiable by spikelet morphology alone. Intermediate races involving *guinea*, for example, have glumes that open partially and seeds that twist noticeably, but not as much as in pure *guinea* [18]. The geographical distribution of basic races, intermediate races, and wild relatives was assessed.

2.2. Identification of gaps

A total of 3991 landraces originating in Benin (100), Burkina Faso (360), Cameroon (651), the Central African Republic (210), Gambia (55), Ghana (59), Mali (615), Niger (148), Nigeria (1206), Senegal (197), Sierra Leone (104), and Togo (286) and having georeferenced data were chosen to identify gaps in the collection. FloraMap, a Windows-based GIS software developed at the International Center for Tropical Agriculture (CIAT) in Cali, Columbia, was used to predict the probable sorghum distributions in individual countries [6]. The FloraMap system is based on calculating the probability that a climate record belongs to a multivariate normal distribution described by the climate at the collection points of a calibration set of organisms. With its user-friendly software linked to agroclimatic databases, maps can be created showing the most likely distribution of a species in nature. The basic input needed for the software is the coordinates (latitude and longitude) of collection sites with unique identifiers. Equal weights were allocated to the three climatic variables (rainfall, temperature and diurnal temperature) and an exponential transformation with a power of 0.3 was applied to the monthly rainfall data. Maps showing districts with high (>75%) probability of sorghum occurrence with few or no collection sites were considered as geographical gaps in the collection. Countries with few accessions having georeferenced data were excluded from the analysis and outliers with erroneous coordinates were validated using site-related information available in the passport database.

2.3. Assessment of diversity in the collection

Of the 8020 accessions from the WCA countries, 7630 accessions having characterization data were used to assess diversity. Accessions were characterized in batches of 500–1000 in the rainy (June to November) and post-rainy (October to March) seasons in vertisols at ICRISAT, Patancheru, India

(17°30′ N latitude, 78°16′ E longitude and 545 m.a.s.l.) during 1977–2014, when new germplasm was received in the ICRISAT genebank. Each accession was sown in a 4-m row with 75-cm row spacing. The crop was thinned two weeks after planting, leaving about 40 plants 10 cm apart. Fertilizers were applied at the rates of 80 kg ha^{-1} N and 40 kg ha^{-1} P_2O_5 before planting in both seasons. In every year, accessions were grown in an augmented design using systematic checks (IS 2205, an elite germplasm line; IS 18758 and IS 33844, released cultivars) repeated every 20 test accessions. To minimize the possible effects of the environment and other inputs, precision fields (well levelled fields with a uniform gradient and maintained with appropriate soil nutrients and proper irrigation and water drainage) were used for characterization, almost identical sowing dates were maintained, and crops were grown under no stress (spraying for diseases and insect pests, irrigating to mitigate drought, and maintaining weed-free conditions) across the years.

Observations of days to 50% flowering and plant height (cm) were recorded in both rainy and post-rainy seasons, while other traits such as number of basal tillers per plant, panicle exsertion (cm), panicle length (cm) and width (cm), seed width (mm), and 100-seed weight (g) were recorded during the post-rainy season. Qualitative traits such as plant pigmentation, nodal tillers, midrib color, panicle compactness and shape, glume color, glume covering, seed color, seed luster, seed subcoat, endosperm texture, and threshability were recorded following the descriptors for sorghum [19]. Using the qualitative traits, particularly spikelet and panicle morphology, accessions were classified into races and intermediate races [18]. Observations of days to 50% flowering were recorded on a plot basis, whereas the remaining quantitative traits were recorded using five representative plants. Seed width and 100-seed weight were recorded on random seed samples drawn from the accession's plot. Each accession was characterized once and the data obtained were maintained in a database. The characterization database was updated every year with data of new germplasm accessions. Photoperiod and temperature response data were collected as described by Upadhyaya et al. [20] and defined by the differences in flowering during rainy and post-rainy seasons. When an accession took more days to flower in a warm long-day rainy season, it was considered photoperiod-sensitive, requiring short days to flower. When days to 50% flowering were high in the relatively cool short-day post-rainy season, the accession was considered temperature-sensitive, requiring higher temperature for flowering. When there was no difference in days to 50% flowering during the rainy and post-rainy seasons (rainy – post-rainy flowering time = 0 days), the accession was considered insensitive to both temperature and photoperiod.

2.4. Data analysis

Frequencies were estimated for each class of 11 qualitative traits for each race and country. Range and means were calculated for all traits of all basic and intermediate races and countries of origin. The means for different traits were compared using the Newman–Keuls procedure [21,22]. Variances were estimated for all traits and tested using Levene's test [23]. Principal component analysis (PCA) of 10 quantitative traits was performed using GENSTAT 13.1 [24]. The Shannon–Weaver index (H') [25] is a commonly used diversity index that takes into account both abundance and evenness of species present in the population. H' was used to measure and compare phenotypic diversity for each of the 11 qualitative and 10 quantitative traits for each race and each country of origin. A low value of H' indicated lack of genetic diversity in the collection. Using the 'cluster' package of R [26], pairwise Gower's distance [27] between accessions from the countries was estimated using both qualitative and quantitative traits.

3. Results

3.1. Status of the collection

The sorghum germplasm from the WCA countries (8020 accessions) includes accessions from Benin (199), Burkina Faso (551), Cameroon (2569), Cape Verde (1), the Central African Republic (249), Chad (229), Cote d'Ivoire (7), Gambia (57), Ghana (149), Mali (694), Mauritania (62), Niger (895), Nigeria (1714), Senegal (242), Sierra Leone (108), and Togo (294) (Table 1). The collection represents landraces, breeding materials and wild relatives originating in different latitudes. Initially, the ICRISAT genebank assembled the germplasm by introducing already collected germplasm from various organizations located in different countries and then by launching systematic germplasm collection missions in WCA countries.

3.1.1. Germplasm introduced

Of the 8020 accessions from WCA countries, 6415 accessions represented introductions from 24 organizations located in 14 countries (Table 1). Rockefeller Foundation, New Delhi, India donated 3151 accessions originating in 13 countries. The other major donors include French Institute of Scientific Research for Development through Cooperation (ORSTOM), Montpellier, France (1873 accessions); ICRISAT Regional Center, Niamey, Niger (528 accessions); Mayaguez Institute of Tropical Agriculture, Mayaguez, United States of America (174 accessions); Ahmadu Bello University, Samaru, Nigeria (160 accessions) and the United States Department of Agriculture (USDA), Agriculture Research Station-Plant Genetic Resources, Griffin, GA, USA (130 accessions). All other donors donated fewer than 100 accessions. All accessions from Benin (199), Cape Verde (1), Chad (229), Cote d'Ivoire (7), Mauritania (62), and Senegal (242) were introductions in the total collection at the ICRISAT genebank.

3.1.2. Germplasm collected

ICRISAT and its partners in different countries launched 216 germplasm-collecting missions in 62 countries for its mandate crops during 1976–1993, including 14 missions in 10 WCA countries resulting in 1605 samples of sorghum (Table 1). Three collection missions launched in Cameroon resulted in collecting of 643 samples. In collaboration with Institut de la Recherche Agronomique (IRA), Maroua, Cameroon; United States Agency for International Development (USAID) and International Institute for Tropical Agriculture (IITA), 306 samples were collected in Cameroon during 1985. ICRISAT

Table 1 – Status of sorghum germplasm from West and Central African countries in the ICRISAT genebank, India.

Country	Collection			No. of accessions introduced	Total accessions	Biological status of collection			Landraces with latitude data
	Year of collection	Collection missions launched	No. of accessions collected			Breeding materials	Landraces	Wild accessions	
Benin				199	199		197	2	100
Burkina Faso	1976	1	39	512	551	3	545	3	360
Cameroon	1983	1	96	1926	2569	3	2559	7	651
	1985	1	306						
	1988	1	241						
Cape Verde				1	1		1		
Central African Republic	1988	1	210	39	249	35	214		210
Chad				229	229	28	190	11	
Cote d'Ivoire				7	7		1	6	
Gambia	1980	1	56	1	57	1	55	1	55
Ghana	1981	1	83	66	149	3	145	1	59
Mali	1993	1	20	674	694		694		615
Mauritania				62	62		62		
Niger	1976	1	32	863	895	10	881	4	148
Nigeria	1981	1	200	1330	1714	262	1447	5	1206
	1992	1	179						
	1993	1	5						
Senegal				242	242	2	238	2	197
Sierra Leone	1983	1	104	4	108		107	1	104
Togo	1989	1	34	260	294		294		286
Total		14	1605	6415	8020	347	7630	43	3991

collaborated with IRA to collect 96 and 241 samples in Cameroon during 1983 and 1988 respectively. ICRISAT also collaborated on collection missions with the Ministry of Rural Development in the Central African Republic during 1988; Department of Agriculture in Gambia during 1980 [28]; Crops Research Institute, Kumasi/German Agency for Technical Cooperation (GTZ), Tamale in Ghana during 1981; Ahmadu Bello University, Samaru during 1981 [29]; Ahmadu Bello University, Samaru and Lake Chad Research Institute (LCRI) during 1992 and with the West African Sorghum Improvement Project (WASIP), Samaru and University of Nigeria, in Nigeria during 1993 [30]; International Agriculture Development Project (IAD) in Sierra Leone during 1983; and Department of Agriculture Research in Togo during 1989, and collected mandate crop germplasm including that of sorghum.

3.1.3. Sources of germplasm

A summary of sources revealed that the majority of the samples (5848) were received from research institutes or experimental stations, while 2129 samples from farmer's fields and 43 samples were collected in wild habitats.

3.1.4. Biological status of the collection

The sorghum collection from WCA countries comprises 7630 landraces, 347 breeding materials, and 43 wild accessions (Table 1). All cultivated accessions from Benin, Cape Verde, Cote d'Ivoire, Mali, Mauritania, Sierra Leone, and Togo were landraces. All the five basic (5490) and ten intermediate races (2487) were represented in the collection of cultivated sorghum (Table 2). The race *guinea* was predominant in the total collection (34%) and in collections from Benin (93%), Burkina Faso (76%), Gambia (82%), Ghana (55%), Mali (68%), Nigeria (39%), Senegal (78%), Sierra Leone (100%), and Togo (83%). Race *caudatum* in Cameroon (52%), *durra* in Mauritania (52%), *guinea-caudatum* in Chad (22%), and *durra-caudatum* in the Central African Republic (29%) and Niger (22%) were in high proportion. Multiple races were observed in each country with a maximum of 14 races representing the collection from Nigeria, 12 races for the Central African Republic and Mali and 11 for Chad, Ghana and Niger. High racial diversity (H') was observed in the collection from Chad ($H' = 0.882$), Niger ($H' = 0.879$) and the Central African Republic ($H' = 0.801$) indicating their richness in sorghum races. Forty-three wild accessions originated in 11 countries, belonging to *Sorghum bicolor* ssp. *drummondii* (16) and ssp. *verticilliflorum* (22), *S. hewisonii* (1) and *S. macrochaeta* (1) and three unclassified accessions were found in the collection.

3.1.5. Geographical representation of the collection

A total of 819 geographical sites were represented in 3991 georeferenced accessions. The maximum geographical sites were observed in Nigeria (300), followed by 169 in Mali, 122 in Burkina Faso, 107 in Togo, and 104 in Senegal. Fewer than 100 sites were observed for the other 11 WCA countries. The intensity of collection was estimated by dividing the number of landraces by the number of geographical sites in each country. Intensity of collection was 6.9 samples per

Table 2 – Geographical distribution of races and wild relatives in the sorghum germplasm collection from West and Central African countries at the ICRISAT genebank, India.

Species	BJ	BF	CM	CV	CF	TD	CI	GM	GH	ML	MR	NE	NG	SN	SL	TG	Total
Cultivated species																	
Bicolor	1	7	13		3	11		2	6	13		73	36	3		3	171
Guinea	184	415	205	1	18	25		46	82	473	5	74	667	188	107	243	2733
Caudatum		6	1334		91	52		2	14	26	9	75	229	2		9	1849
Kafir						2			1	1			4	3			11
Durra	1	22	398		19	10		1	4	69	32	87	61	11		11	726
Guinea-bicolor	4	5	38		13	12		1	3	8		6	96	2		4	192
Caudatum-bicolor	2	10	48		4	18	1	2	5	12	5	183	85	6		4	385
Kafir-bicolor													3				3
Durra-bicolor		7	22		5	16			1	35	3	52	55	1		1	198
Guinea-caudatum	3	69	225		18	49		2	28	13	1	138	185	19		18	768
Guinea-kafir					1												1
Guinea-durra		1	3		2	2			2	1		3	16				30
Kafir-caudatum										1		2	5				8
Durra-caudatum	2	6	276		72	21			2	42	7	198	266	5		1	898
Kafir-durra					3								1				4
Cultivated total	197	548	2562	1	249	218	1	56	148	694	62	891	1709	240	107	294	7977
Wild species																	
S. bicolor																	
subsp. *drummondii*		3				2		1				4	3	2	1		16
subsp. *verticilliflorum*	2		7			5	6		1				1				22
S. hewisonii													1				1
S. macrochaeta						1											1
Not classified						3											3
Wild total	2	3	7			11	6	1	1			4	5	2	1		43
Grand total	199	551	2569	1	249	229	7	57	149	694	62	895	1714	242	108	294	8020

BJ, Benin; BF, Burkina Faso; CM, Cameroon; CV, Cape Verde; CF, Central African Republic; TD, Chad; CI, Cote d'Ivoire; GM, Gambia; GH, Ghana; ML, Mali; MR, Mauritania; NE, Niger; NG, Nigeria; SN, Senegal; SL, Sierra Leone; TG, Togo.

geographical site in Cameroon, 6.6 in Ghana, 4.2 in the Central African Republic, 4.0 in Nigeria, 3.9 in Sierra Leone, 3.6 in Mali, 3.0 in Burkina Faso, 2.7 in Togo, 2.6 in Gambia, 1.9 in Senegal, 1.5 in Niger, and 1.3 in Benin. The results revealed a collection of fewer than two samples per geographical site in Benin, Niger, and Senegal.

The collection is from a wide range of latitudes ranging from 4.33°N (Central African Republic) to 16.38°N (Senegal). Of the 3991 accessions, two were from latitudes ranging from 0°–5°N, 1077 from 5°–10°N, 2823 from 10°–15°N, and 89 from 15°–20°N. The collections from the Central African Republic (6.70°N), Sierra Leone (8.65°N) and Togo (9.40°N) were from mean latitudes lower than 10.00°N, while the collections from all other countries were from mean latitudes above 10.00°N.

3.2. Gaps in sorghum collection from WCA

3.2.1. Geographical gaps

Probability maps developed using FloraMap software indicated 386 districts in 11 WCA countries as geographical gaps (Fig. 1, Table S1). Burkina Faso with 140 gaps and Nigeria with 118 gaps were identified as countries with most geographical gaps and no gaps were found in the collection from Togo. All other countries accounted for fewer than 30 gaps. However, the size of a gap depends largely on the size of the district.

The geographical sites in each country revealed one geographical site per average area of 17,966 ha sorghum cultivation in WCA countries [2]. Similarly, one site represented 5789 ha in Chad, 4055 ha in Niger, 3758 ha in Nigeria, 2841 ha in Burkina Faso, 2742 ha in Mauritania, 1736 ha in Mali, 1566 ha in Ghana, 1065 ha in Togo, 525 ha in Senegal, 515 ha in Benin, 495 ha in Gambia, 320 ha in Cameroon, 294 ha in Sierra Leone, and 191 ha in the Central African Republic. Countries with large (>100 ha) areas under sorghum cultivation per geographical site may be considered as gaps and further explored to enrich the sorghum collection for diversity.

3.2.2. Taxonomic gaps

The genus *Sorghum*, comprising 22 species, offers wide variation for genetic crop improvement [18,31]. The WCA collection of wild relatives in the ICRISAT genebank consists of only three species: *S. bicolor* ssp. *drummondii* and ssp. *verticilliflorum*, *S. hewisonii*, and *S. macrochaeta*, with poor representation of wild species (Table 2). Among the countries, Chad and Nigeria were represented by two species each and all other countries by only one species. In contrast to collection of cultivated germplasm, problems during collection missions for wild species include a lack of information on species distribution, plant identification, and times of collection and maturity. In addition, almost all past collection missions launched by ICRISAT and its collaborators were targeted at cultivated sorghums, resulting in a poor representation of wild relatives in the world collection. This situation calls for the launching of germplasm collection missions aimed exclusively at sorghum wild relatives.

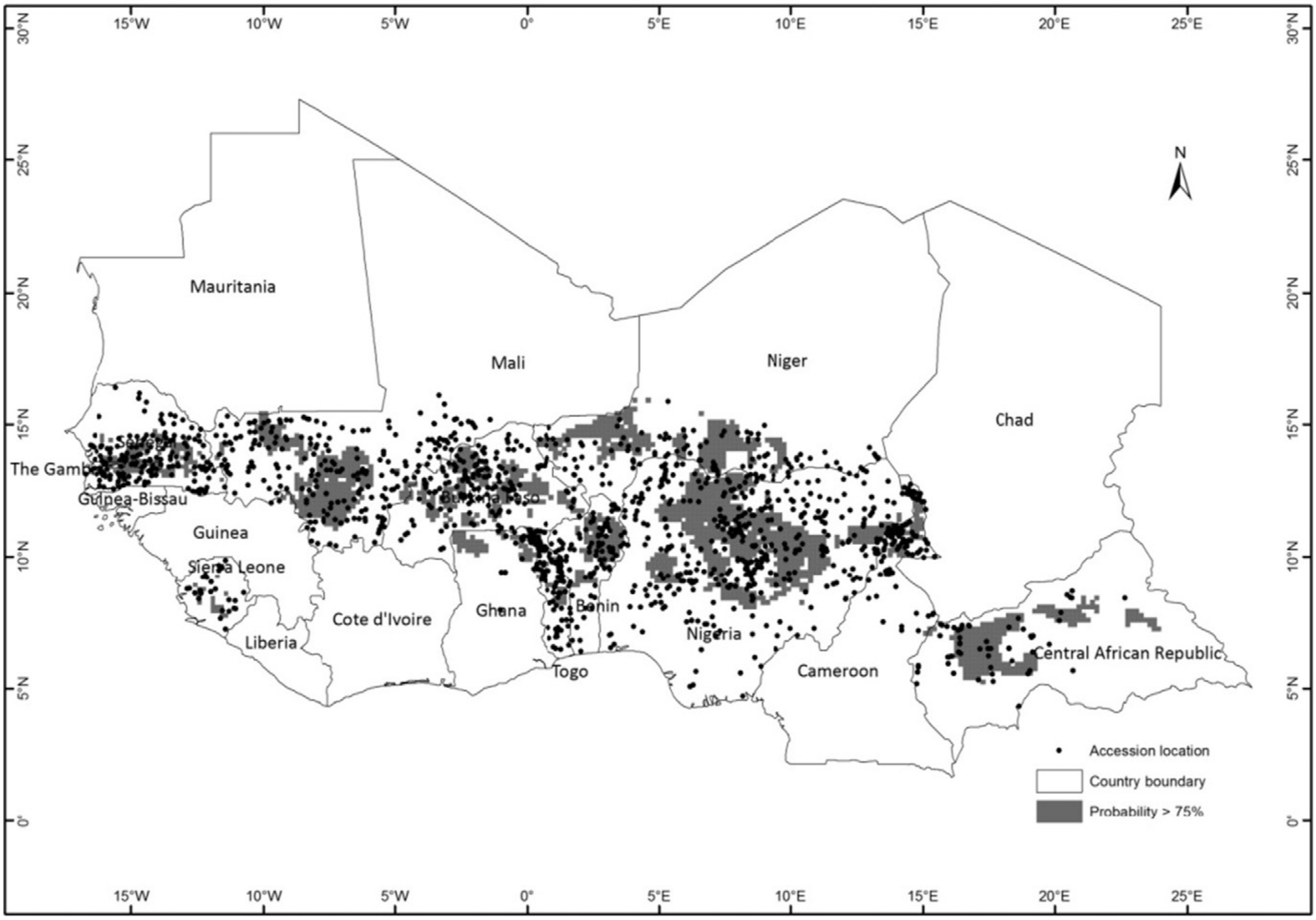

Fig. 1 – Geographical gaps (districts/provinces shaded) identified in the sorghum germplasm collected from West and Central African countries and collection sites (dots) of germplasm conserved at the ICRISAT genebank, India.

3.3. Diversity in the collection

3.3.1. Qualitative traits

3.3.1.1. Plant pigmentation. Over 95% of the accessions were pigmented, whereas tan plant color was found in 1.4% of the collection. A high proportion (14%) of accessions from Sierra Leone produced tan plants. Of the 130 tan accessions in the collection, 34 were from Nigeria, 22 from Niger, and 20 from Cameroon. Accessions of all races produced >90% pigmented plants, except *kafir*, in which 75% accessions had pigmented plants. *Guinea-caudatum* (7.6%), *guinea-durra* (4.8%), and *bicolor* (3.1%) were found to be good sources of tan plants.

3.3.1.2. Nodal tillering. In the entire collection from the WCA countries, 80% of the accessions produced basal tillers. All accessions from Mauritania and Sierra Leone and >60% of the accessions from all other countries, except, Benin, Mali and Togo, produced basal tillers. Over 65% of the accessions from Benin, Mali and Togo lacked basal tillers. High proportions of accessions belonging to race *bicolor* (80%), *guinea* (64%), *caudatum* (95%), *durra* (88%), *guinea-bicolor* (87%), *caudatum-bicolor* (85%), *durra-bicolor* (81%), *guinea-caudatum* (85%), *guinea-durra* (81%), and *durra-caudatum* (85%) produced basal tillers.

3.3.1.3. Midrib color. Three midrib colors (dull green, white and yellow) were found in the collection. White midrib was found in high proportion (93%), followed by dull green (6.6%) and yellow (0.4%). Accessions from Niger (15%), Nigeria (11%), Chad (10%), and Ghana (10%) with dull green midrib and those from Mauritania (1.6%), Senegal (1.3%), and Mali (1.2%) with yellow midrib were the most important sources. Over 80% of the accessions of all races produced white midribs. Among the races, dull green midrib was considerable in race *bicolor* (17%), *caudatum-bicolor* (14%), *guinea-caudatum* (13%), *durra* (11%), and *durra-bicolor* (10%) and 2% of *durra* accessions produced yellow midribs.

3.3.1.4. Panicle compactness and shape. Ten panicle types (compact elliptic, compact oval, loose-drooping branches, loose-stiff branches, semi-compact elliptic, semi-compact oval, semi-loose drooping branches, semi-loose stiff branches, very loose drooping branches, and very loose stiff branch type) were found in the collection with the predominance of semi-loose stiff branched type (32%) followed by semi-compact elliptic (28%). All other panicle types accounted for <10% of the collection. Collections from Benin, Gambia, Mali, Nigeria, and Sierra Leone for loose-stiff branches; Cameroon and Mauritania for semi-compact elliptic panicles and Burkina Faso, the Central African Republic, Chad, Ghana, Niger, Senegal, and Togo for semi-loose stiff branches were predominant. Accessions belonging to *guinea* and *guinea-bicolor* for loose-stiff branched panicles; *caudatum*, *kafir*, *durra* and *durra-caudatum* for semi-compact elliptic panicles and *bicolor*, *caudatum-bicolor*, *durra-bicolor*, *guinea-caudatum*, and *guinea-durra* for semi-loose stiff branched panicles were predominant. The *durra* race was an important source for compact-elliptic (25%) and compact-oval (4%) types of panicles.

3.3.1.5. Glume color. Twelve glume colors (black, brown, light brown, light red, partly straw and brown, partly straw and purple, purple, red, reddish brown, straw, white, and yellow) were observed in the collection. Black glume accessions were predominant (38%). In Sierra Leone, red glumes were in high proportion (30%). All races, except *durra-bicolor* and *guinea-durra* had black glumes, while *durra-bicolor* and *guinea-durra* were important sources of straw glumes.

3.3.1.6. Glume covering. Five types of glume covering (grain uncovered, one-fourth grain covered, half grain covered, three-fourth grain covered, and grain fully covered) were observed in the collection. One-fourth grain covering was predominant (53%) in the collection. The accessions from Gambia (51%), Senegal (42%), and Sierra Leone (97%) were good sources for uncovered grains. Among the races, *bicolor* for fully covered grains; *durra*, *guinea-caudatum*, *guinea-durra*, and *durra-caudatum* for half covered ones; *guinea*, *caudatum*, *guinea-caudatum*, and *durra-caudatum* for one-fourth covered ones; and *guinea-bicolor*, *caudatum-bicolor*, and *durra-bicolor* for three-fourth covered grains were predominant sources.

3.3.1.7. Seed color. Twelve seed colors (brown, chalk white, grey, light brown, light red, purple, red, reddish brown, straw, white, white and red mixed, and yellow) were observed in the sorghum collection. Twenty five percent of the total collection was white-seeded followed by straw (19%) and light red (16%) seeds. Among the countries, Benin for light red seeds, Burkina Faso, the Central African Republic and Mauritania for straw color seeds, and Cameroon, Gambia, Ghana, Mali, Niger, Nigeria, Senegal, Sierra Leone, and Togo for white seeds, were the important sources. Among the races, *bicolor* for brown seeds; *guinea*, *guinea-bicolor*, *guinea-caudatum* and *durra-bicolor* for white seeds; *caudatum* for reddish brown seeds; *kafir*, *durra*, and *guinea-durra* for straw color seeds; and *durra* and *durra-caudatum* for yellow seeds were important sources.

3.3.1.8. Seed subcoat. A high proportion of the collection (72%) lacked a seed subcoat. Over 50% of the accessions in all the countries were without subcoat and 50% of the accessions of all races except *caudatum*, lacked a subcoat. A high proportion (75%) of accessions in *caudatum* produced seeds with subcoat.

3.3.1.9. Seed luster. Over 65% of the accessions from each country, except Cameroon, produced lustrous seeds. Over 50% of the accessions belonging to all races, except *caudatum*, had lustrous seeds and 78% of the accessions of race *caudatum* had non-lustrous seeds.

3.3.1.10. Endosperm texture. Five types of endosperm texture (completely corneous, completely starchy, mostly corneous, mostly starchy, and partly corneous) were observed in the collection. Partly corneous endosperm type was in high proportion (33%) followed by mostly starchy endosperm (31%). Seeds with corneous endosperm are a rich source of protein. A majority of the accessions from Sierra Leone (99%) produced completely corneous seeds, followed by accessions from Mali (31%). A high proportion of accessions with corneous endosperm were from Burkina Faso (43%), Gambia (49%), Ghana (44%), Mali (32%), and Senegal (55%), while completely starchy seeds were mostly from Cameroon (20%) and Mauritania (19%). The highest proportion of *guinea* sorghums had completely corneous (20%) and mostly corneous (42%) endosperm texture, while *caudatum* had 28% completely starchy accessions.

3.3.1.11. Threshability. Threshability is an important post-harvest trait in sorghum. A majority (80%) of the accessions were freely threshable, 18% partly threshable, and 2% difficult to thresh. Over 65% of the accessions from all the countries except Chad were freely threshable. Most of the accessions from Chad were partly threshable (48%) and freely threshable (47%). Over 49% of the accessions of all races, except *bicolor*, were freely threshable. Fifty-six percent of accessions from *bicolor* were found difficult to thresh.

3.3.1.12. Phenotypic diversity. The Shannon-Weaver index (H') for each country and race is presented in Table 3. The H' values varied for traits among countries and races. Mean diversity over all countries varied from 0.029 ± 0.046 for plant pigmentation to 0.783 ± 0.112 for seed color. Mean diversity over traits ranged from 0.199 ± 0.251 in Sierra Leone to 0.419 ± 0.272 in Nigeria. Diversity was high for plant pigmentation in the collection from Sierra Leone, for nodal tillering in Ghana, for midrib color and glume covering in Niger, for panicle compactness and shape in Nigeria, for glume color in Togo, for seed color, seed luster, and seed subcoat in Cameroon, for endosperm texture in Burkina Faso, and for threshability in Chad. The lowest diversity for nodal tillering, midrib color, panicle type, glume covering, seed color, seed luster, seed subcoat, and endosperm texture was observed in the collection from Sierra Leone.

Mean diversity over the races ranged from 0.048 ± 0.072 for plant pigmentation to 0.719 ± 0.161 for seed color (Table 3). Mean diversity over traits varied from 0.208 ± 0.137 in *kafir-caudatum* to 0.409 ± 0.253 in *guinea-caudatum*. Among the basic races, diversity was high for plant pigmentation and midrib color in *kafir*, for panicle compactness and shape in *durra*, for seed color in *caudatum*, and for threshability in *bicolor*. Among intermediate races, *guinea-bicolor* for glume color and glume covering, *guinea-caudatum* for seed luster and seed subcoat, *guinea-durra* for endosperm texture, and *kafir-caudatum* for nodal tillering were highly diverse. Diversity was low in *kafir-caudatum* for plant pigmentation, midrib color, panicle compactness and shape, glume color, glume covering, seed color, and endosperm texture.

3.3.2. Quantitative traits

3.3.2.1. Range, means and variances. A high range of variation for days to 50% flowering and plant height in the post-rainy season, panicle length, and 100-seed weight was

Table 3 – Shannon-Weaver Index (H′) for several qualitative traits of sorghum races from West and Central African countries, evaluated at ICRISAT, India.

Country/race [a]	PP	NT	MC	PC	GC	GV	SC	SL	SS	ET	TR	Mean	SD±
Benin	0.001	0.277	0.014	0.479	0.780	0.157	0.625	0.122	0.122	0.487	0.111	0.289	0.251
Burkina Faso	0.011	0.165	0.066	0.572	0.644	0.485	0.740	0.251	0.195	0.621	0.208	0.360	0.245
Cameroon	0.020	0.041	0.082	0.604	0.845	0.343	0.964	0.301	0.301	0.536	0.172	0.383	0.305
Central African Republic	0.001	0.032	0.063	0.532	0.695	0.450	0.799	0.201	0.173	0.477	0.053	0.316	0.272
Chad	0.025	0.090	0.141	0.493	0.856	0.502	0.956	0.294	0.278	0.550	0.396	0.416	0.284
Gambia	0.040	0.166	0.068	0.576	0.637	0.492	0.767	0.285	0.285	0.536	0.040	0.354	0.248
Ghana	0.001	0.288	0.144	0.525	0.742	0.487	0.860	0.280	0.271	0.568	0.248	0.401	0.247
Mali	0.015	0.228	0.088	0.651	0.756	0.547	0.698	0.208	0.207	0.607	0.203	0.383	0.257
Mauritania	0.001	0.001	0.139	0.657	0.546	0.275	0.779	0.290	0.286	0.551	0.001	0.320	0.265
Niger	0.051	0.096	0.192	0.561	0.738	0.560	0.807	0.260	0.216	0.480	0.386	0.395	0.243
Nigeria	0.048	0.239	0.159	0.681	0.852	0.541	0.853	0.209	0.201	0.524	0.307	0.419	0.272
Senegal	0.021	0.130	0.126	0.613	0.726	0.490	0.683	0.230	0.223	0.508	0.087	0.349	0.247
Sierra Leone	0.176	0.001	0.001	0.311	0.781	0.056	0.581	0.023	0.023	0.023	0.209	0.199	0.251
Togo	0.001	0.162	0.049	0.498	0.875	0.303	0.848	0.220	0.207	0.561	0.133	0.350	0.290
Mean	0.029	0.137	0.095	0.554	0.748	0.406	0.783	0.227	0.213	0.502	0.182	0.352	0.263
SD±	0.046	0.098	0.057	0.094	0.095	0.156	0.112	0.076	0.075	0.144	0.123	0.059	0.019
Races [a]													
Bicolor	0.060	0.219	0.199	0.580	0.795	0.318	0.796	0.299	0.257	0.519	0.429	0.406	0.231
Guinea	0.020	0.284	0.038	0.529	0.834	0.361	0.714	0.151	0.131	0.538	0.185	0.344	0.263
Caudatum	0.024	0.089	0.114	0.544	0.810	0.285	0.947	0.231	0.245	0.443	0.182	0.356	0.286
Kafir	0.244	0.287	0.244	0.545	0.545	0.320	0.527	0.287	0.287	0.527	0.260	0.370	0.127
Durra	0.001	0.164	0.191	0.635	0.746	0.363	0.696	0.139	0.090	0.434	0.218	0.334	0.247
Guinea-bicolor	0.016	0.167	0.090	0.587	0.880	0.486	0.704	0.141	0.129	0.465	0.345	0.364	0.269
Caudatum-bicolor	0.008	0.184	0.182	0.561	0.759	0.347	0.925	0.276	0.254	0.473	0.393	0.397	0.256
Durra-bicolor	0.001	0.211	0.160	0.490	0.682	0.403	0.638	0.183	0.150	0.493	0.327	0.340	0.209
Guinea-caudatum	0.117	0.185	0.171	0.585	0.810	0.338	0.893	0.300	0.296	0.572	0.233	0.409	0.253
Guinea-durra	0.083	0.212	0.137	0.621	0.693	0.415	0.604	0.137	0.137	0.606	0.217	0.351	0.228
Kafir-caudatum	0.001	0.292	0.001	0.292	0.217	0.217	0.413	0.292	0.292	0.001	0.276	0.208	0.137
Durra-caudatum	0.001	0.186	0.131	0.611	0.815	0.379	0.770	0.214	0.159	0.438	0.240	0.358	0.258
Mean	0.048	0.207	0.138	0.548	0.715	0.353	0.719	0.221	0.202	0.459	0.276	0.353	0.230
SD±	0.072	0.059	0.070	0.091	0.180	0.068	0.161	0.069	0.076	0.154	0.081	0.052	0.050

PP, plant pigmentation; NT, nodal tillering; MC, midrib color; PC, panicle compactness and shape; GC, glume color; GV, glume covering; SC, seed color; SL, seed luster; SS, seed subcoat, ET, endosperm texture; TR, threshability.
[a] Countries and races having <5 accessions were excluded from the analysis.

observed in the Cameroon collection (Table 4). The collection varied widely: from Mali for days to 50% flowering in the rainy season; from Nigeria for plant height in the rainy season and seed width; from Senegal for panicle exsertion and panicle width; and from Sierra Leone for basal tillers per plant. Some accessions from Niger and Nigeria flowered early in both seasons (<50 days), those from Cameroon flowered late and grew tall in the post-rainy season with long panicles and large seeds. Important sources were the collection from Mali for very late flowering in the rainy season and broad-seeded accessions, Mauritania for short plant height in the post-rainy season, Nigeria for tall plant height in the rainy season (650 cm), Senegal for high panicle exsertion and stout panicles, and Sierra Leone for more basal tillers per plant and smaller seeds.

Accessions of race *durra* for larger seeds and *guinea* for all traits except 100-seed weight varied widely (Table 4). Low variation was observed in *kafir-caudatum* for all traits. Sources of early flowering (<50 days) during the post-rainy season were observed in *guinea*, *caudatum*, *durra*, *guinea-bicolor*, *caudatum-bicolor*, *durra-bicolor*, and *durra-caudatum*. Accessions of *guinea-caudatum*, *durra-caudatum*, and *caudatum-bicolor* were identified as good sources for early flowering (<50 days) during the rainy season. Accessions of *guinea* were late-flowering and tall in both seasons, and produced more basal tillers, high panicle exsertion, long and stout panicles, and larger seeds.

Mean values for different traits revealed that the collection from the Central African Republic and Niger flowered significantly early in the rainy season and that of Gambia and Niger in post-rainy seasons (Table 5). Accessions from Sierra Leone flowered significantly late in both seasons, and produced more basal tillers and longer panicles. The collection from the Central African Republic grew significantly shorter (323 cm) in the rainy season and taller in the post-rainy season (310 cm) when compared to the collections from other countries. The collection from Gambia for panicle exsertion and panicle width, Nigeria for seed width and Cameroon for 100-seed weight differed significantly from other collections.

Mean values for various traits of sorghum germplasm belonging to various races indicated that accessions of *kafir-caudatum* flowered significantly earlier than those of the other races and produced smaller seeds (Table 5). Race *guinea* flowered significantly late in the post-rainy season, grew tall in both seasons and produced long and stout panicles compared to other races. Among all races, accessions of *kafir* were short with low panicle exsertion and small panicles than other races. *Guinea-bicolor* flowered significantly late in the

Table 4 – Range of variation for different agronomic traits of sorghum races from West and Central African countries, evaluated at the ICRISAT, India.

Country/race [a]	ACC	FR	FP	HR	HP	BT	PE	PL	PW	SW	WT
Benin	197	60–156	61–114	150–500	100–360	1–3	0–42	6–54	6–19	2.0–3.5	2.0–5.4
Burkina Faso	545	56–158	47–135	115–560	110–395	1–3	0–55	4.4–62	4–28	1.5–5.0	1.2–6.5
Cameroon	2559	50–172	47–136	90–590	70–450	1–8	0–49	7–86	2–33	1.8–5.0	1.2–9.4
Central African Republic	214	67–99	54–96	280–360	120–370	1–3	0–37	8.5–50	4–22	2.0–4.5	2.2–7.1
Chad	190	46–161	52–110	105–550	85–370	1–5	0–41	11–58	3–22	0.8–4.5	0.9–7.6
Gambia	55	74–135	45–76	220–540	155–330	2–3	4–44	20–50	6–28	2.0–3.5	0.8–4.5
Ghana	145	58–154	52–113	110–525	120–350	1–6	0–42	10–49	4–18	2.5–4.5	1.8–4.9
Mali	694	53–199	49–119	90–580	105–375	1–4	0–50	7–51	4–27	1.0–5.0	0.8–6.4
Mauritania	62	52–152	53–79	230–465	160–270	1–3	0–31	8–35	4–17	1.8–4.0	1.4–5.9
Niger	881	45–159	40–101	130–510	55–285	1–7	0–39	7.8–53	4–27	1.8–4.0	1.3–6.4
Nigeria	1447	43–161	40–119	95–650	85–390	1–12	0–43	2.5–80	2–40	0.8–5.0	0.8–7.0
Senegal	238	63–154	49–117	140–525	120–335	1–5	0–60	13–55	4–80	1.8–4.5	1.1–5.4
Sierra Leone	107	125–164	56–120	225–450	160–275	2–14	0–30	11–59	6–16	1.5–4.0	0.7–2.5
Togo	294	68–155	51–117	230–510	145–380	1–3	0–46	12–50	5–30	2.0–4.0	1.6–6.6
Total collection	7628	43–199	40–136	90–650	55–450	1–14	0–60	2.5–86	2–80	0.8–5.0	0.7–9.4
Basic races	5302	50–199	40–136	90–650	55–450	1–14	0–60	2.5–86	2–80	0.8–5.0	0.72–9.4
Bicolor	163	50–159	44–124	110–550	85–370	1–5	0–44	13–48	3–33	0.8–4.0	0.75–5.7
Guinea	2702	52–199	45–136	90–650	95–450	1–14	0–60	2.5–86	2–80	0.8–5.0	0.72–6.8
Caudatum	1735	50–165	40–124	100–520	55–390	1–8	0–41	7–45	3–23	1.8–5.0	1.28–7.7
Kafir	8	56–140	61–90	110–460	105–275	1–3	7–37	21–37	6–11	2.5–4.5	1.58–4.0
Durra	694	50–170	44–116	140–560	87–380	1–5	0–46	7–41	4–19	2.2–5.0	1.24–9.4
Intermediate races	2319	43–172	40–127	90–595	70–410	1–2	0–55	3–65	2–30	1.8–5.0	1.01–7.9
Guinea-bicolor	171	61–159	49–116	255–595	130–390	1–12	0–44	7–65	3–35	1.8–5.0	1.68–5.2
Caudatum-bicolor	364	43–160	40–110	90–525	70–390	1–7	0–47	12–55	2–21	1.8–4.5	1.01–6.5
Durra-bicolor	174	50–156	44–124	125–540	125–380	1–5	0–44	6–49	4–30	2.5–4.5	1.89–6.2
Guinea-caudatum	726	45–172	43–127	130–565	75–410	1–5	0–55	8–60	3–24	2.0–5.0	1.46–5.6
guinea-durra	21	63–150	60–108	130–530	110–350	1–3	3–42	14–63	4–17	2.5–4.5	2.56–7.1
kafir-caudatum	5	66–84	52–90	320–390	190–260	2–3	7–32	20–30	5–8	3.0–3.5	2.02–3.1
durra-caudatum	858	46–159	44–121	90–535	100–400	1–5	0–49	3–58	3–26	1.8–5.0	1.47–8.0
Total collection	7621	43–199	40–136	90–650	55–450	1–14	0–60	2.5–86	2–80	0.8–5.0	0.72–9.4

ACC, no. of accessions; FR, days to 50% flowering-rainy; FP, days to 50% flowering-post-rainy; HR, plant height (cm)-rainy; HP, plant height (cm)-post-rainy; BT, basal tillers per plant, PE, panicle exsertion (cm); PL, panicle length (cm); PW, panicle width (cm); SW, seed width (mm); WT, 100-seed weight (g).

[a] Countries and races represented by <5 accessions were excluded from the analysis.

rainy season, grew tall in both seasons, and produced long panicles and broad seeds. No significant differences were observed among the races for basal tillers per plant and panicle exsertion.

Levene's test of significance revealed significant variances for all the traits under study, revealing high heterogeneity for all traits in the collection under study.

3.3.2.2. Principal component analysis (PCA). PCA was performed using standardized data of ten quantitative traits. The first three principal components (PCs) explained 67%, 69%, and 61% of the total variation in the entire collection, collection of basic races, and intermediate races, respectively. The first PC accounted for 33%, second 21%, and third 12.6% of variation in the entire collection; 34.8%, 21.9%, and 12.3% in basic races; and 26.6%, 19.8%, and 14.2% in intermediate races.

3.3.2.3. Gower's diversity. Gower's pairwise distance among the 7630 accessions from WCA showed an average of 0.209. Only two pairs of accessions (IS 30642 and IS 30643 both from Cameroon and IS 34974 from the Central African Republic and IS 27701 from Sierra Leone) showed a distance of 0.000, indicating them to be possible duplicates. Seven other pairs had distances of <0.005. However, their pedigrees and other passport data differed. Further studies are needed to identify duplicates in the collection by genotyping all possible duplicates identified in this study. The maximum distance of 0.697 was observed between IS 27701 of race *guinea* originating in Sierra Leone and IS 25641 of race *bicolor* originating in Mali. Besides this analysis, pairwise distances within each race and country of origin were estimated and accessions showing the maximum and minimum distances were identified (data not shown).

3.3.2.4. Phenotypic diversity. Mean diversity index (H') over all countries varied from 0.411 ± 0.115 for number of basal tillers per plant to 0.603 ± 0.021 for panicle length (Table 6). Mean H' over traits ranged from 0.524 ± 0.100 in Sierra Leone to 0.604 ± 0.052 in Nigeria. Diversity was high for days to 50% flowering in the rainy season in the collection from Burkina Faso, for days to 50% flowering and plant height in the post-rainy season in Nigeria, for plant height during the rainy season in Cameroon, for number of basal tillers per plant in Sierra Leone, for panicle exsertion and seed width in Niger, for panicle length in Mali, for panicle width in the Central African Republic, and for 100-seed weight in Chad.

Mean H' over races ranged from 0.430 ± 0.093 for number of basal tillers per plant to 0.587 ± 0.071 for 100 seed weight

Table 5 – Mean [a] values for different agronomic traits of sorghum races from West and Central African countries, evaluated at ICRISAT, India.

Country/race [**]	ACC	FR	FP	HR	HP	BT	PE	PL	PW	SW	WT
Benin	197	140.4 b	94.6 b	422.4 ab	273.3 c	2.0 cd	15.5 fg	34.5 c	9.9 efg	2.9 def	3.6 c
Burkina Faso	545	106.8 ef	85.5 d	380.6 cdef	271.1 c	2.0 cd	22.4 ab	29.3 e	12.7 c	3.1 bc	3.0 d
Cameroon	2559	110.2 ef	67.9 h	364.8 def	203.1 f	1.9 de	14.8 gh	18.9 g	6.8 j	3.0 bc	4.1a
Central African Republic	214	82.8 g	76.5 f	322.5 g	310.1 a	1.8 e	21.2 abc	27.4 e	11.3 d	2.9 cd	3.8 bc
Chad	190	116.7 de	71.5 g	364.4 def	222.1 e	2.1 cd	16.5 efg	24.3 f	9.1 gh	3.1 b	3.6 c
Gambia	55	111.0 ef	61.6 j	441.5 a	262.9 c	2.2 c	23.4 a	36.1 b	17.9 a	2.8 f	2.4 e
Ghana	145	108.3 ef	80.9 e	372.4 cdef	244.5 d	2.1 cd	19.4 cd	28.9 e	9.5 fg	3.1 b	3.1 d
Mali	694	109.0 ef	88.0 cd	389.0 bcde	237.8 de	2.1 cd	21.7 abc	29.0 e	10.6 e	2.8 def	2.6 e
Mauritania	62	98.1 f	64.4 i	353.5 efg	195.6 fg	1.5 f	11.7 i	16.7 h	7.9 i	3.0 bc	3.9 b
Niger	881	84.9 g	60.1 j	343.3 fg	186.1 g	2.2 c	20.5 bc	23.2 f	8.5 hi	2.8 ef	3.7 bc
Nigeria	1447	124.1 cd	73.8 fg	403.8 bcd	235.6 de	2.0 cd	17.4 def	31.7 d	10.3 ef	3.5 a	3.7 bc
Senegal	238	109.7 ef	76.7 f	403.1 bcd	239.7 de	3.0 b	21.1 abc	33.5c d	16.8 b	2.4 g	2.4 e
Sierra Leone	107	151.3 a	104.6 a	325.7 g	226.9 de	6.6 a	13.1 hi	39.6 a	9.3 fgh	1.7 h	1.0 f
Togo	294	129.8 c	89.8 c	407.9 bc	289.6 b	2.0 cd	18.2 de	32.1 d	10.2 ef	2.9 de	3.1 d
Grand mean		113	78.3	378.2	242.7	2.4	18.3	28.9	10.8	2.9	3.1
Races											
Bicolor	163	95.3 de	68.8 bcd	345.9 b	233.2 ab	2.2 a	20.0 a	27.8 b	10.3 abc	2.7 b	2.9 e
Guinea	2702	124.7 ab	83.5 a	419.9 a	268.3 a	2.3 a	19.9 a	34.1 a	11.6 a	3.0 ab	3.0 de
Caudatum	1735	96.9 de	65.2 cd	344.7 b	188.6 c	1.9 a	15.8 a	17.7 d	6.9 d	3.0 ab	3.8 bc
Kafir	8	89.7 e	77.8 ab	262.1 c	185.7 c	2.0 a	19.5 a	26.0 bc	8.6 bcd	3.0 ab	2.7 e
Durra	694	112.9 bcd	73.5 bc	348.2 b	207.9 bc	1.9 a	15.0 a	16.9 d	7.8 cd	3.2 a	4.4 ab
Guinea-bicolor	171	131.7a	73.4 bc	438.1 a	259.5 a	2.1 a	17.4 a	33.9 a	10.8 ab	3.3 a	3.5 cd
Caudatum-bicolor	364	97.5 de	64.8 cd	350.5 b	215.1 bc	2.0 a	19.2 a	25.3 bc	8.8 bcd	3.0 ab	3.6 c
Durra-bicolor	174	107.6 bcde	71.9 bcd	346.4 b	210.3 bc	2.2 a	16.9 a	26.5 bc	9.8 abc	3.1 ab	4.0 abc
Guinea-caudatum	726	102.7 cde	69.8 bcd	354.7 b	217.1 bc	2.2 a	17.3 a	24.6 bc	8.6 bcd	3.0 ab	3.4 cd
Guinea-durra	21	117.1 abc	74.4 bc	381.1 b	235.5 ab	1.8 a	17.2 a	28.0 b	10.1 abc	3.3 a	4.1 abc
Kafir-caudatum	5	74.2 f	61.8 d	344.0 b	216.7 bc	2.4 a	21.4 a	23.1 bc	6.1 d	3.2 a	2.7 e
Durra-caudatum	858	112.9 bcd	71.4 bcd	361.7 b	214.4 bc	1.8 a	17.0 a	22.3 c	8.6 bcd	3.3 a	4.5 a
Grand mean		108.1	71.36	359.39	221.43	2.03	17.73	25.73	9.26	3.08	3.62
Basic races	5302	113.4 a	75.8 a	384.9 a	233.8 a	2.1 a	17.9 a	26.3 a	9.5 a	3.0 a	3.4 a
Intermediate races	2319	108.0 a	70.1 b	362.1 a	219.4 b	2.0 b	17.5 b	24.7 b	8.9 b	3.2 a	3.9 a

ACC, no. of accessions; FR, days to 50% flowering-rainy; FP, days to 50% flowering-post-rainy; HR, plant height (cm)-rainy; HP, plant height (cm)-post-rainy; BT, basal tillers per plant; PE, panicle exsertion (cm); PL, panicle length (cm); PW, panicle width (cm); SW, seed width (mm); WT, 100-seed weight (g).

[a] Means were tested using Newman–Keuls Test, values followed by different letters differ significantly at $P = 0.05$.

[**] Countries and races represented by <5 accessions were excluded from the analysis.

(Table 6). H' over traits ranged from 0.336 ± 0.094 in *kafir-caudatum* to 0.596 ± 0.047 in *caudatum*. Race *bicolor* showed high diversity for plant height in the rainy season, basal tillers per plant, panicle exsertion and panicle length and those of *durra* for days to 50% flowering in the post-rainy season. Among the intermediate races, diversity was high for panicle width in *guinea-bicolor*, for days to 50% flowering during the rainy season in *durra-bicolor*, for plant height during the post-rainy season, for seed width, and 100-seed weight in *durra-caudatum*.

3.3.2.5. *Photoperiod and temperature sensitivity*. Accessions flowered early and grew short during short-day post-rainy season in comparison with the long-day rainy season. Data recorded for differences in days to flowering during the rainy and post-rainy seasons indicated 92.0% accessions as photoperiod-sensitive, 7.5% as temperature-sensitive, and only 0.5% as insensitive. Over 60% of the accessions from all the countries except Gambia and Sierra Leone exhibited photoperiod sensitivity. All the accessions from Gambia and Sierra Leone exhibited photoperiod sensitivity. Thirty four percent of the accessions from Burkina Faso were temperature-sensitive, followed by Ghana (17.9%) and Mali (17.3%). Eight countries had no representation for insensitivity. Eight accessions from Mali were found to be good sources of insensitivity to photoperiod and temperature. Among the races, 14 accessions of *guinea* showed insensitivity.

4. Discussion

4.1. *Data quality*

Ecogeographic studies are important for targeted and effective conservation strategies for plant genetic resources [32]. Globally, though many genebanks have large collections, sizeable gaps have been identified in the ex situ collections of many major crops including sorghum using GIS tools [11–16,33–35]. In the present study, 386 geographical gaps in 11 WCA countries were identified. In gap analysis, it is crucial that the coordinate data be of high quality for precise inference. There is no standard in terms of the minimum number of georeference points required, as this relates to the nature of the species. A 30% prediction success using Bioclim

Table 6 – Shannon–Weaver index (H′) for different quantitative traits of sorghum races from West and Central African countries, evaluated at ICRISAT, India.

Country/race [a]	FR	FP	HR	HP	BT	PE	PL	PW	SW	WT	Mean	SD±
Benin	0.402	0.565	0.523	0.594	0.317	0.584	0.596	0.554	0.463	0.588	0.532	0.086
Burkina Faso	0.627	0.601	0.621	0.627	0.331	0.606	0.604	0.620	0.410	0.593	0.557	0.102
Cameroon	0.536	0.617	0.634	0.614	0.483	0.593	0.570	0.541	0.602	0.612	0.585	0.045
Central African Republic	0.477	0.584	0.439	0.540	0.318	0.615	0.609	0.643	0.463	0.601	0.534	0.101
Chad	0.560	0.595	0.587	0.587	0.430	0.596	0.581	0.618	0.469	0.631	0.566	0.065
Gambia	0.622	0.547	0.628	0.561	0.238	0.575	0.586	0.588	0.569	0.579	0.541	0.109
Ghana	0.533	0.603	0.521	0.573	0.524	0.618	0.622	0.575	0.460	0.614	0.568	0.052
Mali	0.623	0.602	0.633	0.609	0.367	0.605	0.631	0.628	0.495	0.593	0.574	0.083
Mauritania	0.570	0.598	0.604	0.449	0.327	0.558	0.576	0.605	0.585	0.606	0.545	0.090
Niger	0.610	0.611	0.613	0.623	0.521	0.626	0.616	0.547	0.626	0.623	0.601	0.036
Nigeria	0.509	0.628	0.608	0.641	0.460	0.612	0.628	0.605	0.623	0.628	0.604	0.052
Senegal	0.604	0.589	0.588	0.616	0.547	0.612	0.621	0.531	0.495	0.586	0.576	0.041
Sierra Leone	0.485	0.548	0.576	0.588	0.614	0.596	0.580	0.509	0.296	0.406	0.524	0.100
Togo	0.506	0.545	0.589	0.595	0.278	0.606	0.618	0.587	0.543	0.617	0.553	0.101
Mean	0.547	0.588	0.583	0.587	0.411	0.600	0.603	0.582	0.507	0.591	0.561	0.076
SD±	0.067	0.027	0.055	0.048	0.115	0.018	0.021	0.041	0.092	0.056		
Races [a]												
Bicolor	0.593	0.548	0.639	0.599	0.562	0.622	0.622	0.516	0.528	0.613	0.583	0.043
Guinea	0.606	0.625	0.623	0.631	0.366	0.612	0.619	0.583	0.608	0.627	0.588	0.080
Caudatum	0.517	0.594	0.630	0.613	0.472	0.598	0.615	0.582	0.636	0.622	0.596	0.047
Kafir	0.415	0.452	0.415	0.469	0.452	0.545	0.320	0.470	0.320	0.423	0.429	0.068
Durra	0.613	0.638	0.622	0.610	0.470	0.568	0.593	0.586	0.497	0.618	0.578	0.055
Guinea-bicolor	0.541	0.619	0.617	0.609	0.241	0.609	0.613	0.588	0.556	0.613	0.563	0.115
Caudatum-bicolor	0.595	0.602	0.600	0.607	0.510	0.614	0.601	0.583	0.569	0.630	0.591	0.033
Durra-bicolor	0.615	0.598	0.604	0.578	0.481	0.591	0.594	0.509	0.518	0.616	0.566	0.046
Guinea-caudatum	0.595	0.606	0.607	0.632	0.495	0.619	0.615	0.546	0.463	0.623	0.578	0.058
Guinea-durra	0.536	0.395	0.568	0.595	0.382	0.565	0.501	0.553	0.594	0.565	0.524	0.077
Kafir-caudatum	0.458	0.217	0.413	0.276	0.292	0.413	0.217	0.458	0.276	0.458	0.336	0.094
Durra-caudatum	0.599	0.605	0.616	0.601	0.443	0.596	0.627	0.585	0.645	0.631	0.594	0.056
Mean	0.557	0.542	0.579	0.568	0.430	0.579	0.545	0.546	0.517	0.587	0.544	0.045
SD±	0.065	0.126	0.079	0.101	0.093	0.058	0.135	0.047	0.116	0.071		

FR, days to 50% flowering-rainy; FP, days to 50% flowering-post-rainy; HR, plant height (cm)-rainy; HP, plant height (cm)-post-rainy; BT, basal tillers per plant; PE, panicle exsertion (cm); PL, panicle length (cm); PW, panicle width (cm); SW, seed width (mm); WT, 100-seed weight (g).
[a] Races represented by <5 accessions were excluded.

[36], a GIS tool, with ten samples increased to over 80% when 75 samples were used [37]. In the present study, considerable number of accessions had coordinates and >25 geographical sites were observed in individual countries except Ghana, which was represented by 59 accessions collected at nine sites, facilitated the precise mapping of geographic distribution of accessions conserved at ICRISAT genebank and prediction of sorghum occurrence with high probability (>75%). Thus, exploring the geographical gaps (386 districts) by collecting germplasm would be very useful for filling gaps in the world collection of sorghum from WCA countries maintained in the ICRISAT genebank.

4.2. Representation of existing collection

A low intensity of sorghum collection was observed in most of the WCA countries. Actual geographical collection sites (819) and the area under sorghum cultivation (14.71 Mha) during 2014 indicated only one geographical site per average of 17,966 ha of sorghum cultivation in WCA countries [2]. One geographical site per >1000 ha of sorghum cultivation was observed in most of the individual WCA countries. Countries with larger areas under sorghum cultivation per geographical site and fewer samples collected per geographical site (<2 samples per site) may be further explored. Sorghum can be grown well under contrasting climatic conditions, up to 40° of latitude on either side of the equator [38,39]. The collection studied was from latitudes ranging from 4.33°N to 16.38°N and is expected to be adaptable to diverse climates. Out of 1077 accessions originating in the lower latitudes (5°–10°N), a high proportion (57%) of accessions belong to race *guinea*, and were identified as a good source of overall variation, as they flowered late, grew tall, and produced many basal tillers.

4.3. Diversity in the collection

Africa being the primary center of sorghum diversity, large variation was observed in the collection studied [40,41]. Variances for all traits indicated significant differences among the accessions. Mean diversity (H′) for qualitative traits ranged from 0.199 ± 0.251 in Sierra Leone to 0.419 ± 0.272 in Nigeria. Probably because of the extensive natural and human selection for adaptability to high rainfall conditions, sorghum collected from Sierra Leone may explain the lowest diversity for most of the qualitative traits. H′ was high for the collection from Chad (H' = 0.882) followed by Niger (H' = 0.879) and the Central African Republic (H' = 0.801) indicating the richness of sorghum races in these countries. High racial diversity in the sorghum collection from Niger and the predominance of race *guinea* in collections from other West African countries was observed [17,42,43]. Interestingly, all the accessions from Sierra Leone belong to race *guinea*, which has been reported to be a rich source of resistance to leaf diseases and grain weathering, high tillering, and small seed with protein-rich corneous endosperm [29,44,45]. Highly corneous seeds of *guinea* race have been reported in the sorghum collection from Nigeria [29]. Mostly, the large-seeded types are grown in the drier zone and the very small-seeded types in the wettest zones [18]. Thus, there is a need to evaluate systematically the entire collection from Sierra Leone and also that of race *guinea*, to identify promising sources for use in sorghum improvement.

Phenotypic diversity is the result of adaptive responses to the environment [46]. The distribution of traits is attributed to the specific climatic conditions in different regions, which may in turn lead to different evolutionary pathways [17]. The majority of traits are not conspicuously unique to any single region. This could be attributed to gene flow as farmers move seed from one place to another. The predominance of some phenotypic classes in an area may indicate the adaptive role of traits. Human intervention through selection for desired types is another reason for the diversity observed.

4.4. Importance of sorghum from WCA

Biotic stresses such as shoot fly, downy mildew, anthracnose, leaf blight, and rust are important diseases causing considerable losses in sorghum. Pathologists, entomologists, and biochemists at ICRISAT, Patancheru evaluated limited and varying numbers of accessions including those from WCA countries, during 1974–2012, for grain mold, anthracnose, downy mildew, rust, leaf blight, ergot [47], shoot fly, and seed protein using standard methods. Such evaluations revealed the importance of sorghum collections from WCA countries. Twenty nine per cent of the accessions for shoot fly, 6% for anthracnose, and 7.7% for leaf blight from Cameroon accessions have shown resistance. Similarly, 23% of accessions from Chad have shown resistance (<10% disease severity) for downy mildew, 42% from Ghana for grain mold, 15% from Nigeria for shoot fly during the post-rainy season, and 11% from Senegal for rust. Nutritionally, 31% of the 61 accessions from Senegal that were evaluated for seed protein content had >12% seed protein. Other important source countries for accessions with high seed protein content are Gambia (21%) and Mali (17%). A high proportion of accessions from Niger (25%), Nigeria (23%), and Cameroon (23%) were good sources for high seed lysine content.

Reports of past germplasm collections have revealed the cultivation pattern of sorghum and its importance in different WCA countries [28–30]. When the Urd, Mac Carthy Island division, North Bank division, Lower River division, and Western division in Gambia were explored, most of the sorghums from Gambia were of *guinea* type [28]. The collections RC 015 (IS 23626) and RC 073 (IS 23664) in Gambia are reported to be promising for drought tolerance and RC 093 (IS 23674) for high stalk sugar [28]. *Kaura*, *Fara-fara*, and *guinea* sorghums, which were considered as good sources of drought tolerance and yellow endosperm, were found predominantly in Sudan savanna, Northern Guinea savanna, and Jos Plateau [29]. The guinea sorghum, a West African race considered as an important source for corneous endosperm, resistance to insects (particularly stem borer), diseases, and grain weathering, and storage quality, was grown mostly in Sub-Sudan savanna [29]. Evaluation of the entire sorghum collection from Sudan savanna and Sub-Sudan savanna for drought tolerance may be very useful for identifying promising sources. It is reported that the Sahel region with low rainfall is dominated by drought-resistant millet and sorghum [48]. Some cultivars of race *guinea* are remarkably tolerant to flooding [49]. The predominance of *guinea-caudatum* in Nigeria, Chad, and Sudan and *conspicuums* in Sub-Sudan and Sudan-Savanna zone is also reported [18]. IS 3924 from Nigeria and IS 15401 and IS 15845 from Cameroon were directly released as cultivars in India and Mali respectively, indicating the superiority of the germplasm [41].

4.5. Taxonomic gaps

The genus sorghum comprises about 22 species including *S. bicolor*, a cultivated species, and most of them are useful sources of high levels of resistance to various stresses. For example, 36 potentially new sources of resistance for downy mildew were reported for wild and weedy sorghums [50,51]. *S. versicolor* and *S. purpureosereceum* were reported to be immune to shoot fly infestation [52,53]. It is important to fill taxonomic gaps in germplasm collections. The wild relatives collection from WCA countries in the ICRISAT genebank consists of only three species, *S. bicolor* ssp. *drummondii* and ssp. *verticilliflorum*, *S. hewisonii* and *S. macrochaeta*. Accessions of *S. hewisonii* (1 accession) and *S. macrochaeta* (1 accession) are in negligible numbers. Among the countries, Chad and Nigeria accounted for two species each and all other countries accounted for one species each. *S. bicolor* subsp. *drummondii* and subsp. *verticilliflorum* were collected in 11 countries, *S. hewisonii* in Nigeria and *S. macrochaeta* in Chad, indicating major taxonomic gaps in the collection. A wide distribution of subspecies *verticilliflorum* in Africa is reported [17].

4.6. Genetic erosion

Genetic erosion of traditional cultivars has been reported in rice [54], soybean [55], and cassava [56]. A drop in use of landraces over decades has been reported for many crops [4]. In contrast to these results, farmers in Niger clearly perceived an increase in the number of varieties managed per village between the 1970s and the 2000s [42]. An increased number of sorghum landrace names between 1960 and 2000 was noted in eastern Ethiopia [57]. These results show that farmers' management can preserve the diversity of sorghum varieties in Niger and in other countries despite recurrent and severe drought periods and major social changes.

5. Conclusions

In view of the rapid genetic erosion in sorghum, new landraces evolving over a period, and poor representation of wild relatives, and given the importance of races (*guinea*) and trait-specific sorghums in WCA countries, there is an urgent need to explore gaps identified in this study. The range of variation for different traits in the WCA collections suggests that the gaps identified in Niger and Nigeria for early flowering (<45 days), extreme height (650 cm), and high tillering (up to 12 tillers); in Cameroon for late flowering, tallness, long panicle, and large seed; in the Central African Republic for short stature; in Mali for late flowering during the rainy season; and in Senegal for highly exserted panicles, need to be explored for trait-specific germplasm. Collecting more sorghums belonging to race *caudatum* and *caudatum-bicolor* for early flowering, *durra* for larger seed, *durra-caudatum* for short height, *guinea* sorghums for late flowering, tallness, high tillering, and highly exserted panicles is needed for trait-specific diversity. ICRISAT has not launched any collection mission exclusively targeting wild sorghums and trait-specific germplasm. Photoperiod-insensitive late-maturing accessions are useful in developing fodder varieties of sorghum. Early-maturing insensitive accessions identified in this study need further testing before they are used in breeding photoperiod- and temperature-insensitive varieties for wider adaptation and for multiple cropping. Priority may be given to exploring Nigeria, a rich source of overall diversity for qualitative and quantitative traits, to enrich the world collection for diversity. Accessions IS 30642 and IS 30643 from Cameroon, IS 34974 from the Central African Republic, and IS 27701 from Sierra Leone showing Gower's distance of 0.000 indicating similarity, need further studies to identify duplicates by genotyping. The gaps identified in the current study may be prioritized for collection depending upon the threat to diversity, availability of resources, and accessibility to the target region, in consultation with local government officials, National Agricultural Research Systems (NARS) scientists, extension officers, and non-governmental organizations. It is important to collect information related to samples, including georeference data facilitating future mapping efforts. The collection described in this paper can be obtained following the Standard Material Transfer Agreement (SMTA) of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) and passport and characterization data can be accessed through http://genebank.icrisat.org/.

Supplementary data for this article can be found online at https://doi.org/10.1016/j.cj.2017.07.002.

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