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Variation for qualitative and quantitative traits and identification of trait-specific sources in new sorghum germplasm

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Abstract. Assembling, collecting and characterising the unique germplasm accessions for morphological and agronomic characteristics are essential activities of a dynamic genebank. The phenotypic diversity and agronomic performance of 667 newly acquired sorghum germplasm accessions, representing five basic races, eight intermediate races and two wild species, originating from 34 countries were assessed for seven qualitative and eight quantitative traits. Large variability was observed among these accessions for various qualitative and quantitative traits. Trait-specific accessions for early flowering (108), short plant height (8), medium panicle exsertion (34), and medium-sized seeds (78) have been identified. The diverse trait-specific promising accessions have the potential for their utilisation in future breeding programs for developing improved sorghum cultivars with a broad genetic base. The hierarchical cluster analysis grouped five races, six intermediate races, and two wild species into three clusters. The present study has played a significant role in filling up the gaps and has also identified region(s) to carry out future explorations, and in providing the trait-specific germplasm for use by the breeders.

Additional keywords: agronomic, diversity, morphological, principal component analysis, sorghum, trait-specific accessions.

Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is the fifth most important cereal in the world after rice, wheat, maize and barley. It is cultivated in 104 countries on an estimated area of 43.79 million ha with 64.6 million metric tonnes of annual production (FAO 2007) spread over Africa, Asia, Oceania and the Americas. In the world, the major sorghum-producing countries are India (8.45 million ha with 7.40 million tonnes of production), Nigeria (7.40 million ha with 10.5 million tonnes of production), Sudan (6.7 million ha with 5.05 million metric tonnes of production) and the USA (2.75 million ha with 12.83 million metric tonnes of production) (FAO 2007). Sorghum is a staple food crop for millions of poor farmers particularly in rain-fed areas of Asia and Africa.

S. bicolor comprises of weedy and cultivated annual forms that are fully inter-fertile. The cultivated sorghum belongs to *S. bicolor* subspecies *bicolor* and is classified into five basic races (*bicolor*, *caudatum*, *durra*, *guinea* and *kafir*) and 10 intermediate- or hybrid- or half-races (*caudatum-bicolor*, *durra-bicolor*, *guinea-bicolor*, *kafir-bicolor*, *durra-caudatum*, *guinea-caudatum*, *kafir-caudatum*, *guinea-durra*, *durra-kafir* and *guinea-kafir*) (Harlan and de Wet 1972; de Wet 1978) on the basis of spikelet morphology and panicle shape. These races and intermediate races are distributed in several geographic regions and differ considerably in their ecological adaptation.

Genebank at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, India has the global responsibility of collection, conservation, characterisation, evaluation, distribution and documentation of sorghum genetic resources. Germplasm collection at ICRISAT is dynamic, and the genebank acquires and characterises new germplasm as and when they become available through collection expeditions or donations from other institutes to bridge the gaps in germplasm collections and databases. Recently, the ICRISAT genebank has acquired 667 unique germplasm accessions of sorghum, including 619 accessions from the genebank at Griffin, Georgia, USA, and 48 accessions from Mauritania. Currently, 37 943 sorghum germplasm accessions from 92 countries are conserved in the ICRISAT genebank. The value of germplasm is realised only when characterised for morpho-agronomic traits to unearth new gene combinations for use in crop improvement programs. Hence, the present investigation was undertaken to identify and fill up the gaps in sorghum germplasm conservation at ICRISAT, to characterise the new germplasm accessions from 34 countries for various morphological and agronomic traits and identify diverse trait-specific accessions.

Materials and methods

The experimental material for the present study comprised 667 newly assembled sorghum accessions consisting of 659 cultivated types belonging to subspecies *bicolor* (328 accessions belonged to five basic races and 331 accessions to eight intermediate races) and eight wild species accessions

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(six accessions belonging to subspecies *drummondii*, one to *S. halepense* and one with unknown identity). These accessions have originated from 34 countries representing five continents, namely Africa (507 accessions from 17 countries), Asia (50 accessions from 9 countries), America (88 accessions from 4 countries), Europe (4 accessions from 3 countries) and Australia (5 accessions from 1 country). The country of origin for 13 accessions was not known (Table 1). These 667 accessions along with the control cultivar, Parbhani Moti (IS 33844; a released cultivar belonging to race *durra*) were evaluated in an augmented design during 2004–05 after the rainy season at ICRISAT, Patancheru in the vertisol (Kasireddypally series-Isohyperthermic Type Pellustert) field. The control cultivar was repeated after every 50 test entries. Each plot consisted of a single 4-m-long row on a ridge, in a ridge and furrow system. The distance between rows was 75 cm and between plants was 10 cm. The experiment received 42 kg N and 42 kg P ha^{-1} as basal fertiliser and 46 kg N ha^{-1} as top-dressing along with full irrigation (five irrigations, each with 7 cm of water) and protection from diseases, insect-pests and weeds.

Data were recorded on a plot basis for seven qualitative characters. Data on midrib colour was recorded as dull/white/yellow; plant pigmentation as pigmented/tan; nodal tillers as absent/present; panicle compactness and shape as compact elliptical/compact oval/loose drooping branches/loose stiff branches/semi-compact elliptical/semi-compact oval/semi-

Table 1. Geographic distribution of newly acquired sorghum germplasm accessions

Continents/	Races[A]					Intermediate races[B]								Wilds[C]		Unknown	Total
countries	B	C	D	G	K	CB	DB	DC	GB	GC	GD	KB	KC	s.d.	SH		
Africa	5	68	129	25	41	86	32	41	1	61	1	8	1	6	1	1	507
Burkina Faso	–	1	–	1	–	–	–	–	–	1	–	–	–	–	–	–	3
Cameroon	–	22	37	3	–	13	1	2	–	6	1	–	–	–	–	–	85
Chad	–	2	–	–	–	3	1	1	–	1	–	–	–	–	–	–	8
Congo	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1
Ethiopia	2	14	66	1	–	19	27	23	–	13	–	–	–	–	–	–	168
Kenya	–	2	–	–	–	1	–	–	–	3	–	–	–	–	–	–	6
Malawi	–	–	–	1	–	–	–	–	–	1	–	–	–	–	–	–	2
Mauritania	–	9	23	3	–	5	1	6	–	1	–	–	–	–	–	–	48
Nigeria	2	3	–	11	–	9	1	5	–	1	–	–	–	–	–	–	32
S. Africa	–	2	–	–	40	10	–	–	–	2	–	7	–	–	–	–	61
Senegal	–		–	–	1	–	–	–	–	–	–	–	–	–	–	–	1
Somalia	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1
Sudan	–	1	2	–	–	2	–	3	–	8	–	–	–	3	–	–	19
Tanzania	–	–	1	1	–	1	–	–	–	–	–	–	–	–	–	–	3
Uganda	–	10	–	3	–	16	1	1	1	18	–	–	1	–	1	1	53
Zambia	–	–	–	1	–	1	–	–	–	1	–	–	–	–	–	–	3
Zimbabwe	–	1	–	–	–	6	–	–	–	5	–	1	–	–	–	–	13
Asia	5	6	13	5	1	10	4	1	–	5	–	–	–	–	–	–	50
India	2	4	7	5	–	3	4	1	–	3	–	–	–	–	–	–	29
China	–	–	–	–	–	2	–	–	–	–	–	–	–	–	–	–	2
Pakistan	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2
Japan	1	2	4	–	–	–	–	–	–	–	–	–	–	–	–	–	7
Indonesia	–	–	–	–	1	1	–	–	–	1	–	–	–	–	–	–	3
Russia and CIS	–	–	–	–	–	3	–	–	–	–	–	–	–	–	–	–	3
Syria	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–	1
Taiwan	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	1
Yemen	–	–	1	–	–	–	–	–	–	1	–	–	–	–	–	–	2
Americas	4	6	9	3	1	26	2	10	3	24		–	–	–	–	–	88
Argentina	3	1	–	2	1	5	1	1	–	7	–	–	–	–	–	–	21
Guatemala	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1
Mexico	–	1	1	–	–	1	1	–	–	3	–	–	–	–	–	–	7
USA	1	3	8	1		20	–	9	3	14	–	–	–	–	–	–	59
Europe	2	1	–	–	–	–	–	1	–	–	–	–	–	–	–	–	4
Portugal	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2
Spain	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	1
Turkey	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1
Australia	–	1	–	–	–	1	1	1	–	1	–	–	–	–	–	–	5
Unknown	–	2	1	–	–	3	–	1	–	6	–	–	–	–	–	–	13
Total	16	84	152	33	43	126	39	55	4	97	1	8	1	6	1	1	667

[A]B = *Bicolor*; C = *Caudatum*; D = *Durra*; G = *Guinea*; K = *Kafir*.
[B]CB = *Caudatum-bicolor*; DB = *Durra-bicolor*; DC = *Durra-caudatum*; GB = *Guinea-bicolor*; GC = *Guinea-caudatum*; GD = *Guinea-durra*; KB = *Kafir-bicolor*; KC = *Kafir-caudatum*.
[C]s.d. = subspecies *drummondii*; SH = *S. halepense*.

loose drooping branches/semi-loose stiff branches; glume colour as black/brown/light brown/light red/partly straw and brown/partly straw and purple/purple/red/reddish-brown/straw; glume covering as grain fully covered/half grain covered/one-fourth grain covered/three-fourth grain covered; and seed colour as brown/chalky white/grey/light brown/light red/purple/red/reddish-brown/straw/white/yellow. Phenotypic proportion of classes of qualitative characters was calculated in the entire set of 667 germplasm accessions and in different basic and intermediate races and in the wild species. For the five basic races, eight intermediate races and wilds (consisting of subspecies *drummondii* and *S. halepense*), the phenotypic proportions were calculated based on the total of each of the classes of qualitative characters. Of the eight quantitative characters, data on days to 50% flowering, number of basal tillers, and 100-seed weight (g), were recorded on a plot basis according to the descriptor for sorghum (ICRISAT/IBPGR 1993). Data on the remaining five traits, namely plant height (cm), panicle exsertion (cm), ear head length (cm), ear head width (cm), and panicle weight (g) were recorded on five randomly selected representative plants. One-hundred representative mature and disease-free seeds were used to record 100-seed weight (g). The data on quantitative characters were analysed using Residual Maximum Likelihood (REML) in Genstat 10.0 (Payne 2009) and best linear unbiased predictors (BLUP) were obtained. The components of variance due to genotypes and their standard errors were calculated for the entire set and each of the three groups (basic races, intermediate races and wilds), separately.

Mean, range, and variance were calculated for the entire set and three different groups. The means were tested using the Newman–Keuls test (Newman 1939; Keuls 1952) and variances using the Levene (1960) test. Genotypes were classified into different groups for days to 50% flowering, plant height, panicle exsertion and 100-seed weight (Table 2).

Correlations were calculated on BLUP for each race and intermediate race separately and the number of significant correlations were identified. The Shannon–Weaver diversity index (H′) (Shannon and Weaver 1949) was calculated for the entire set, three groups, individual race/intermediate race within a group and wild species for all the qualitative and quantitative traits. Phenotypic diversity was calculated following Johns *et al*. (1997) for three different groups, for each of five basic and six intermediate races, separately and for trait-specific accessions identified for four traits in the entire set. Mean and range of diversity were calculated, and the most and least diverse genotypes were identified. Principal component analysis (PCA) on agronomic (quantitative) traits was performed to determine traits contributing to the polymorphism in the material. Data on quantitative traits was standardised with mean 0 and standard deviation of 1 and was used to perform PCA using Genstat 10.0. Cluster analysis of five races, six intermediate races, and two wild species was performed using scores of the first three principal components (PC) following Ward (1963).

Table 2. Grouping of the newly acquired sorghum germplasm accessions for important agronomic traits

Traits	Groups
Days to 50% flowering	Early (≤60 days)
	Medium (61–110 days)
	Late (>110 days)
Plant height	Dwarf (≤100 cm)
	Medium (101–300 cm)
	Tall (>300 cm)
Panicle exsertion	Low (≤30 cm)
	Medium (31–50 cm)
	High (>50 cm)
100-seed weight	Low (≤3.0 g)
	Medium (3.01–6.0 g)
	High (>6.0 g)

Results

The highest number of acquired accessions were from Ethiopia (168) followed by Cameroon (85), South Africa (61), USA (59), Uganda (53) and Mauritania (48) (Table 1). All the accessions showed variability with respect to the various qualitative and quantitative characters studied.

Qualitative characters

The frequency distribution of different phenotypic classes (expressed in percent) of the qualitative characters was calculated (data not given).

Midrib colour

Observation on midrib colour was recorded at flag-leaf stage on the main stem. The white midrib colour was most prevalent (49.2%) followed by dull colour (47.8%) in the entire set. The yellow midrib colour was rare, present only in 3% accessions in the entire set, and in races *caudatum* (1.2%), *durra* (9.9%) and *durra-caudatum* (7.3%), mostly from Ethiopia. The wild accessions did not have yellow midrib colour. Among races, dull colour was prevalent while white colour was most common among intermediate races and wilds. All the accessions of *guinea-bicolor*, *guinea-durra*, *kafir-caudatum* and most of the accessions of races *bicolor*, *caudatum* and *guinea*, intermediate races *caudatum-bicolor*, *durra-bicolor* and *kafir-bicolor*, and wild accessions of *S. drummondii* showed white midrib colour. *S. halepense* accessions exhibited dull midrib colour.

Plant pigmentation

Plant pigmentation is an important seedling character, which is associated with grain quality and reaction to pests and diseases (Axtell *et al*. 1982). This trait was recorded in two classes: tan or presence of pigmentation on main stem. Pigmented stem dominated the entire set, races, intermediate races and wilds representing 98.2, 99.1, 97.3 and 100% of the accessions, respectively. Tan-coloured accessions were absent in wild species accessions, while it was present in 0.9% of accessions in *bicolor* and *guinea* and 2.7% among intermediate races *caudatum-bicolor*, *durra-caudatum* and *guinea-caudatum*, mainly of Ugandan origin. All the accessions belonging to races *caudatum, durra*, and *kafir* and that from intermediate races, *durra-bicolor, guinea-bicolor*, *guinea-durra*, *kafir-bicolor*, *kafir-caudatum* and all the wild accessions had pigmented plants.

Nodal tillers

Nodal tillers were present in most of the accessions (84.4%) of the entire set, 88.1% accessions in basic races, 80.4% in intermediate races and 100% in wild species. More than 80% accessions belonging to each of the five basic races and the intermediate races, *caudatum*-*bicolor*, *durra*-*caudatum* and *guinea*-*caudatum* exhibited nodal tillers. Nodal tillers were present in all the accessions belonging to the intermediate races, *guinea*-*bicolor*, *guinea*-*durra*, *kafir*-*bicolor* and *kafir*-*caudatum* and all the wild species. In the entire set, of the 16% accessions which had no nodal tillers, ~50% of the accessions were from Ethiopia.

Panicle compactness and shape

This trait mainly depends on the number, length and strength of primary and secondary branches of rachilla, which is related to the taxonomic races. The trait was recorded into eight classes and the pattern of distribution of these classes was different in the entire set, basic races, intermediate races and wilds. Semi-loose stiff branches were prevalent in the entire set (32.5%), basic races (28.7%, represented mainly by *kafir*) and the intermediate races (37.2%, represented mainly by *kafir*-*bicolor*, *kafir*-*caudatum*, *caudatum*-*bicolor* and *durra*-*caudatum*). The race *bicolor* exhibited mainly loose drooping branches (31.3% accessions) and loose stiff branches (31.3%) type, the race *caudatum* had semi-compact elliptical type, race *durra* compact elliptical type and race *guinea* had loose stiff branches type panicles. Loose drooping branches were dominant in intermediate races *durra*-*bicolor* and *guinea*-*bicolor*; compact elliptical in *guinea*-*durra* and semi compact elliptical in *guinea*-*caudatum*. The other prominent class for panicle compactness was semi-compact elliptical type. The least prominent class in the entire set was semi-compact oval (0.6% represented by race *caudatum* and *durra*) and semi-loose drooping branches (0.7% represented by races *bicolor*, *caudatum, guinea* and intermediate races *caudatum*-*bicolor* and *guinea*-*caudatum*). The wild accessions had mostly loose stiff branches type of panicles.

Glume colour

This trait was recorded in 10 classes of which black (38.1%) and straw (28.6%) colour were the most dominant in the entire set as well as among races, intermediate races and wilds. A large proportion of the accessions of races *bicolor* (50%), *caudatum* (60.7%), *durra* (35.5%), and *guinea* (36.4%) and intermediate races *durra*-*caudatum* (30.9%) and *guinea*-*caudatum* (48.5%) and subspecies *drummondii* (66.7%) had black-coloured glumes. In the entire set, the accessions with straw-coloured glumes belonged to the race *kafir* and intermediate races *caudatum*-*bicolor*, *durra*-*bicolor*, *guinea*-*bicolor*, *kafir*-*bicolor* and *S. halepense*. Only 0.4% accessions in the entire set had purple glumes and belonged to *durra*, *caudatum*-*bicolor* and *durra*-*caudatum*. All the accessions of *guinea*-*durra* and *kafir*-*caudatum* had light red-coloured glumes. A large percentage (62.5%) of the accessions belonging to Ethiopia had partly straw (41.5%) and straw-coloured (21%) glumes.

Glume covering

Glume covering indicates the amount of grain covered by the glumes at maturity and the accessions were classified into four classes. In the entire set, a large proportion of the accessions (57.1%) had grains that were half covered followed by three-fourths (19.9%), one-fourths (17.5%) and fully covered (5.4%) grains. The pattern was different in races and intermediate races. Among races, most of the accessions (78.4%) belonging to races *caudatum*, *durra* and *kafir* had half-covered grains. About 40% accessions belonging mainly to *caudatum*-*bicolor*, *durra*-*bicolor*, *guinea*-*bicolor* and *kafir*-*bicolor* had three-fourths grain covered. The grains of all the wild accessions and most of the race *bicolor* accessions were fully covered with glumes. The accessions belonging to *guinea*, and *guinea*-*caudatum* had one-fourth of the grains covered with glumes, while all the accessions of *guinea*-*durra* and *kafir*-*caudatum* had half grain-covered glumes.

Seed colour

Seed colour was classified into 11 classes of which the light red (18.4%) and the straw colour (18.3%) were the most dominant in the entire set followed by reddish-brown (16.5%), white (10.3%) and yellow (10%). Light red (25.9%) and straw colour (19.2%) were prevalent in basic races; reddish-brown in intermediate races (25.4%) and wild accessions (62.5%). Very few accessions (0.4%) in the entire set had grey-coloured grains represented by the accessions of *durra*-*caudatum* (1.8%) and *guinea*-*caudatum* (2.1%). Among the races, brown was most common in *bicolor*; reddish-brown in *caudatum*; yellow in *durra*; white in *guinea* and light red in *kafir*. Among the intermediate races, reddish-brown colour was common in *caudatum*-*bicolor*, *durra*-*bicolor*, *durra*-*caudatum* and *guinea*-*caudatum* and in two wild species (*S. drummondii* and *S. halepense*), straw colour in *guinea*-*bicolor*, *guinea*-*durra* and *kafir*-*bicolor* and light red in *kafir*-*caudatum*. Light red seed colour was prevalent in the accessions from South Africa.

Quantitative characters

REML analysis of the entire set of newly acquired germplasm indicated that the variance component due to genotypes was significant for all the characters except basal tillers. Similarly, the genotypic variance of all five basic races together was significant for all the traits except basal tillers and 100-seed weight, whereas in the eight intermediate races, the variance was significant for all the traits except basal tillers. The genotypic variance component was significant for all the traits in all the five basic races, except for 100-seed weight in *caudatum*, and basal tillers in *kafir* (data not shown). Among intermediate races, the genotypic variance was significant for all the traits in *guinea*-*caudatum*, all traits except 100-seed weight in *caudatum*-*bicolor*, except basal tillers and panicle weight in *durra*-*bicolor* and all except plant height in *durra*-*caudatum*. In two intermediate races, *guinea*-*bicolor* and *kafir*-*bicolor*, and in subspecies *drummondii*, genotypic variance was non-significant for all the traits. This may be due to low number of accessions (4, 8 and 6, respectively), available in this material. The Wald statistics for different subgroups i.e. basic and intermediate races and wilds was significant for all the characters except days to 50% flowering (data not shown) indicating that the three groups differed significantly from each other and exhibited significant variability for most of the traits.

Means

Mean values were calculated for each character in five basic races, eight intermediate races and wild types, and tested using the Newman–Keuls procedure. The means of basic and intermediate races were similar for all the traits; however, they were significantly different from the wild species group for all traits except ear head width and panicle exsertion (Table 3). The earliest flowering accessions with shorter plant height were among the wild accessions but with small seed size and low panicle weight. The means of basic races differed significantly from each other for all the traits (data not given). The tall and late flowering accessions were from race *guinea* (262.7 cm height, 71.7 days). The accessions from this race were characterised by high value of ear head length (34.57 cm), width (11.84 cm) and panicle exsertion (22.53 cm). The accessions of *durra* had the shortest ear head length (17.23 cm) and width (8.20 cm). The accessions of *bicolor* were earliest in flowering, short height, the lowest 100-seed weight, and panicle weight and the highest number of basal tillers (data not given). There were no significant differences in the mean performance of the eight intermediate races for any of the quantitative traits except for number of basal tillers (data not shown). The accessions of *guinea-bicolor* had the highest number of basal tillers (1.74 per plant). Similarly, there was no significant difference in the mean performance among the wild species except for days to flowering, ear head length, ear head width and number of basal tillers (data not shown). Accessions of subspecies *drummondii* were earliest to flower (60 days) with long ear head (30.54 cm) but with less number of basal tillers (1.49 per plant). Accessions belonging to *S. halepense* had the largest number of basal tillers (4.95) and the widest ear heads (10.95 cm). The average 100-seed weight in the entire set was 3.4 g and the accessions from subspecies *drummondii* had the smallest seeds (2.1 g) and *guinea-bicolor* the largest seeds (3.74 g) (data not shown).

Variance

Variances were calculated for five basic races, eight intermediate races and wild types as groups as well as individually within the groups, separately. The homogeneity of variances of three groups and races/intermediate races within the group was tested using Levene's test. Variances were homogenous for four traits, days to 50% flowering, ear head width, exsertion, and panicle weight ($P = 0.126$–0.808) (Table 3). Wild species group had highest variances for four traits (days to flower, ear head length, ear head width, and basal tillers) followed by basic races for three traits (panicle exsertion, 100-seed weight, and panicle weight) and intermediate races (plant height) (Table 3). Variances of five basic races were significantly different for all the characters except plant height and panicle weight (data not given). Among the basic races *bicolor* had the highest variances for plant height, ear head length, exsertion, basal tillers, *guinea* for days to flowering, ear head width, *caudatum* for 100-seed weight and *durra* for panicle weight (data not given). *Kafir* had lowest variances for all the traits except plant height and panicle weight for which *guinea* showed the lowest variances (data not given). The variance of intermediate races was significant for ear head width (highest in *durra-bicolor* and lowest in *guinea-bicolor*) and 100-seed weight (highest in *caudatum-bicolor* and lowest in *kafir-bicolor*). Variance was not calculated for the wild species since there was only one accession sampled in *S. halepense*. Overall, the results indicated the presence of large genotypic variability in the newly acquired sorghum germplasm for quantitative traits and thus there is a considerable scope of identifying useful germplasm in this material.

Correlations

Phenotypic correlations were calculated between all the eight agronomic characters in the entire set of newly acquired germplasm, basic races as a group and individually, intermediate races as a group and individually and in wild types as a group. Correlation among the traits was not studied in four intermediate races viz., *guinea-bicolor*, *guinea-durra, kafir-bicolor* and *kafir-caudatum* and the wild species as a group as they were represented by very few accessions (less than 10) in each group. Any correlation with 665 degrees of freedom (in the entire set) with a value more than 0.064 will be significant at $P = 0.05$ and greater than 0.090 will be significant at $P = 0.01$. Of the 28 correlations, 22 were significant at $P = 0.05$ and 21 at $P = 0.01$ in the entire set. Similarly in the basic races and intermediate races as groups, 20 and 17 correlations, respectively, were significant at $P = 0.05$ and 19 and 15 at $P = 0.01$. Only two correlations were significant at $P = 0.05$ for wild species as a group and none at $P = 0.01$. A large number of

Table 3. Mean and variance components for various traits in the basic races, intermediate races and wilds of newly acquired sorghum accessions
Means were tested following the Newman–Keuls test and variances using Levene's test. Means followed by the same letters are not significant at $P = 0.05$. $^{*}P \le 0.05$; $^{**}P \le 0.01$

Characters	Mean			Variance			F-value	$P > F$
	Basic race (328)	Intermediate race (331)	Wild (8)	Basic race (328)	Intermediate race (331)	Wild (8)		
Days to 50% flowering	69.01a	67.42a	61.10b	66.65	66.49	144.77	0.21	0.808
Plant height (cm)	238.43a	230.90a	210.17b	756.98	1149.77	286.03	7.11	0.0009**
Ear head length (cm)	21.37b	21.14b	29.51a	60.80	35.82	88.93	6.95	0.001**
Ear head width (cm)	8.85a	9.31a	9.36a	4.63	5.90	7.37	0.68	0.506
Exsertion (cm)	20.20a	17.84a	21.03a	44.77	42.69	32.42	0.42	0.659
Basal tillers (number)	1.09a	1.09b	1.99a	0.16	0.1	2.27	13.89	<0.0001**
100-seed weight (g)	3.48a	3.23a	2.13b	0.38	0.27	0.05	3.80	0.0229*
Panicle weight (g)	43.06a	42.81a	41.74b	0.93	0.48	0.87	2.08	0.126

correlations were significant in individual races and intermediate races (data not given). The number of significant correlation coefficients (at $P = 0.05$) was maximum in *guinea-caudatum* (15) followed by *durra* (13), *guinea* (11), *caudatum-bicolor* (11), *durra-bicolor* (10), *caudatum* (10) and *guinea-bicolor* (10).

The proportion of variance in one trait can be attributed to its linear relationship with a second trait and is indicated by the squares of the correlation coefficient (coefficient of determination) (Snedecor and Cochran 1980). In the present study, we have considered only those correlations, which are greater than 0.500 or smaller than –0.500 (Table 4), as meaningful as at least 25% of the variation in one trait is predicted by the other. Days to flowering and plant height consistently showed >0.500 correlation in seven [entire set (0.500), race *bicolor* (0.673), *durra* (0.662), intermediate races as a group (0.526), *durra-bicolor* (0.656), *durra-caudatum* (0.690) and *guinea-caudatum* (0.550)] out of a total 12 (entire, all race, all intermediate races, five races and four intermediate races) groups. Some other traits also showed such correlations in the entire set, in basic and intermediate races as a group and individually (Table 4).

This information would help in selecting the useful traits and thus optimise the data recording by taking observations on a few related traits in the preliminary trials involving a large number of germplasm accessions.

Diversity analysis

Diversity

The H′ was calculated to compare phenotypic diversity for all characters among the races, intermediate races and for entire set (data not given). Two intermediate races, viz. *guinea-durra* and *kafir-caudatum*, and the wild species *S. halepense* were not included in the analysis as they were represented by only one accession in each group. A low H′ indicates an extremely unbalanced frequency classes for an individual trait and a lack of genetic diversity. Estimates were made for each trait in the entire set, each race, intermediate race and wild species and pooled across the traits, basic races and intermediate races for both qualitative and quantitative traits (data not given). The highest H′ in the entire set was 0.636 for plant height and least for basal tiller (0.143) among quantitative traits, while it ranged between 0.935 for seed colour and 0.039 for plant pigmentation among qualitative traits. The mean H′ in the entire set was 0.503 ± 0.062 while that in basic races, intermediate races and wild type (*S. drummondii*) was 0.438 ± 0.054, 0.458 ± 0.048 and 0.338 ± 0.011, respectively. The accessions from *caudatum* had the highest (0.495 ± 0.059) pooled H′ across the traits and the *guinea* accessions had the lowest pooled H′ (0.396 ± 0.052) among basic races. Among intermediate races, the maximum H′ was 0.525 ± 0.037 for *durra-bicolor* and the least was 0.327 ± 0.034 for *guinea-bicolor*. The accessions from subspecies *drummondii* had 0.374 ± 0.021 pooled H′ across the traits.

Phenotypic distance matrix was created by calculating differences between each pair of accessions for each of the seven qualitative and eight quantitative traits. The diversity index was calculated by averaging all the differences in the phenotypic values for each trait divided by their respective range (Johns *et al*. 1997). In the entire set of newly acquired germplasm accessions, the mean diversity was 0.275. The maximum diversity (0.626) was observed between IS 13335 of *caudatum* race and IS 2895 of *bicolor* race, both from Ethiopia and least (0.001) between IS 15416 of *durra* race and IS 15790 of *caudatum* race, both from Cameroon (Table 5). *Bicolor* is a primitive race and it would be interesting to involve the most diverse lines IS 2895 and IS 13335 in the hybridisation program to see the extent of segregation for different traits. Among intermediate races, the mean diversity was 0.288 and the accessions IS 12263 of race *guinea-caudatum* from Ethiopia and IS 8592 of race *guinea-caudatum* from Aden were highly diverse (0.545). Similarly, diverse lines were identified individually in each of the five basic races, six intermediate races and in wild types (Table 5). In the entire set and basic races as a group, a pair of highly diverse accessions belonged to two basic races (*caudatum* and *bicolor*), both from Ethiopia, whereas in intermediate races group, two highly diverse accessions belonged to *guinea-caudatum* but were from two different countries (IS 12263 from Ethiopia, and IS 8592 from Aden). This shows that highly diverse accessions should be selected on the basis of diversity and not on the basis of geographic origin or races. The use of these diverse accessions in the sorghum improvement programs would help the breeders to develop cultivars with a broad genetic base.

Principal component analysis

The PCA on the mean values of the races provides a reduced dimension model that would indicate measured differences among the races. The results revealed the importance of the first three PC in discriminating in the entire set, five basic races as a group and individually, and six intermediate races as a group and individually except *guinea-bicolor* where the first two PC were found important in explaining variability. Similarly, in wild species as a group, the first three PC were important. The percentage of total variation explained by these PC was 63.1,

Table 4. Frequency of correlation coefficients more than 0.500 or less than –0.500 among different traits in the different races/intermediate races of newly acquired sorghum germplasm

	Days to 50% flowering	Ear head length	Ear head width	Basal tillers	100-seed weight	Panicle weight	Exsertion
Plant height	7 (0.500 to –0.690)	–	1 (0.520)	–	1 (0.555)	–	–
Days to 50% flowering	–	–	–	–	–	1 (0.511)	1 (–0.679)
Ear head length	–	–	4 (0.517 to 0.574)	–	–	–	–
Ear head width	–	–	–	–	2 (–0.530 to –0.548)	–	–
Basal tillers	–	–	–	–	2 (–0.533 to –0.700)	–	–
100-seed weight	–	–	–	–	–	1 (0.600)	–
Panicle weight	–	–	–	–	–	–	–

Table 5. Estimates of phenotypic diversity and the pair of accessions showing minimum and maximum diversity with their racial classification and centre of origin among different groups of newly acquired sorghum germplasm accessions

	Mean diversity	Minimum diversity	Pair of accessions showing minimum diversity		Maximum diversity	Pair of accessions showing maximum diversity	
Entire set	0.275	0.001	IS 15416 (D; Cameroon)	IS 15790 (C; Cameroon)	0.626	IS 13335 (C; Ethiopia)	IS 2895 (B; Ethiopia)
All races	0.255	0.001	IS 15416 (D; Cameroon)	IS 15790 (C; Cameroon)	0.639	IS 13335 (C; Ethiopia)	IS 2895 (B; Ethiopia)
All intermediate races	0.288	0.002	98–873 (DC; Mauritania)	98–868 (CB; Mauritania)	0.545	IS 12263 (GC; Ethiopia)	IS 8592 (GC; Aden)
Wild	0.265	0.083	IS 2755 (Unknown; Uganda)	IS 11992 (s.d.3; Ethiopia)	0.429	IS 14130 (s.d.; Sudan)	IS 11329 (s.d.; Ethiopia)
B1	0.317	0.141	IS 13125 (Pakistan)	IS 12988 (Pakistan)	0.594	IS 12803 (Turkey)	IS 2895 (Ethiopia)
C	0.263	0.004	IS 15047 (Cameroon)	IS 6725 (Burkina Faso)	0.607	IS 2809 (Zimbabwe)	IS 13335 (Ethiopia)
D	0.239	0.003	98-892 (Mauritania)	98–974 (Mauritania)	0.485	IS 12243 (Ethiopia)	IS 13748 (Ethiopia)
G	0.224	0.005	IS 7832 (Nigeria)	IS 7974 (Nigeria)	0.491	IS 6756 (Burkina Faso)	IS 2768 (Uganda)
K	0.182	0.005	IS 13842 (S. Africa)	IS 13849 (S. Africa)	0.392	IS 13059 (S. Africa)	IS 13982 (S. Africa)
CB2	0.279	0.004	IS 1808 (USA)	IS 1803 (USA)	0.556	IS 14032 (Kenya)	IS 13362 (Ethiopia)
DB	0.299	0.012	IS 12146 (Ethiopia)	IS 12145 (Ethiopia)	0.539	IS 10855 (Chad)	IS 12147 (Ethiopia)
DC	0.283	0.005	IS 2962 (Ethiopia)	IS 2785 (Sudan)	0.577	IS 11648 (Ethiopia)	IS 389 (USA)
GB	0.289	0.106	IS 6837 (USA)	IS 6863 (USA)	0.513	IS 2702 (Uganda)	IS 6837 (USA)
GC	0.277	0.011	IS 2558 (USA)	IS 2533 (USA)	0.605	IS 13392 (S. Africa)	IS 2708 (Uganda)
KB	0.265	0.125	IS 13834 (S. Africa)	IS 13504 (Zimbabwe)	0.421	IS 13912 (S.Africa)	IS 13843 (S. Africa)

One accession each in intermediate races *guinea-durra* and *kafir-caudatum*. So diversity could not be calculated in these intermediate races.
1 = B-*Bicolor*; C-*Caudatum*; D-*Durra*; G-*Guinea*; K-*Kafir*; 2 = CB-*Caudatum-bicolor*; DB-*Durra-bicolor*; DC-*Durra-caudatum*; GB-*Guinea-bicolor*; GC-*Guinea-caudatum*; KB-*Kafir-bicolor*; 3 = s.d. = subspecies *drummondii*.

63.7, 61.6 and 84.1% with 5.1, 5.1, 4.9 and 6.7 latent roots in the entire set, all basic races, intermediate races and wild species, respectively. Two intermediate races, viz. *guinea-durra* and *kafir-caudatum* were not included in the analysis as they were represented by only one accession in each group. The PC1, which is the most important component accounted for 24.7% variation in the entire set (2.0 latent roots), 25.6% variation in the races as a group (2.0 latent roots), 26.2% variation in the intermediate races as a group (2.1 latent roots) and 35.6% variation in the wild species as a group (2.9 latent roots) (data not given). The PC1 separates accessions on two traits (plant height and ear head width) in the entire set as well as intermediate races as a group; on two traits (ear head length and width) in the races as a group; on three traits (ear head width, panicle exsertion and panicle weight) in the wild species as a group. Considering the analysis of entire set, basic races, intermediate races and wild species as four separate groups as well as individual races in each group, all the traits except basal tillers occurred at least 10 times in the first three PC, indicating their importance for characterisation of sorghum germplasm accessions. Scores of first two or three PC were used to construct scatter plots for 667 accessions in different combinations, wild and cultivated, basic and intermediate races, and individual basic and intermediate races. However, no discernible pattern was observed (data not given).

Clustering

The hierarchical cluster analysis was conducted using the method of Ward (1963) on the first three PC accounting for 63.1% of total variation. All five races, six intermediate races and two sorghum wild species were grouped into three clusters with the races *bicolor* and *guinea* and intermediate races *durra-bicolor* and *guinea-bicolor* (92 accessions) grouped together in Cluster I. Both the wild species (subspecies *drummondii* and *S. halepense*) comprising seven accessions grouped in a separate cluster (Cluster II). The remaining three basic races (*caudatum*, *durra*, *kafir*) and four intermediate races (*durra-caudatum*, *caudatum-bicolor*, *kafir-bicolor* and *guinea-caudatum*) comprising 565 accessions grouped together in the Cluster III (Fig. 1).

Identification of trait-specific accessions

Following the criteria for classifying the genotypes, all the 667 newly acquired germplasm accessions were found to be medium to tall in height (114–336 cm) with low to medium 100-seed weight (1.73–5.63 g) and low to medium panicle exsertion (0.37–38.47 cm). The check cultivar 'Parbhani Moti' was medium in height (240 cm) with medium number of days to flowering (73 days), low panicle exsertion (10 cm) and medium 100-seed weight (4.86 g). Of these, 104 cultivated accessions from four basic and five intermediate races (4 *bicolor*, 11 *caudatum*, 23 *durra*, 3 *guinea*, 26 *caudatum-bicolor*, 2 *durra-bicolor*, 6 *durra-caudatum*, 27 *guinea-caudatum*, 2 *kafir-bicolor*) and four accessions of *S. drummondii*, predominantly from Cameroon, Sudan, Ethiopia, and USA, were early flowering (47–60 days), thus capable to escape late season drought and other biotic stresses. All these accessions flowered significantly earlier than Parbhani Moti. Among the cultivated accessions, IS 11992, IS 12313, IS 12232, IS 6181 and IS 6931 took only 47–51 days to flower and would serve as sources for extra-early flowering in sorghum improvement programs. Dwarf sorghum is desirable for mechanical harvesting and in this set eight accessions (114.3–160.5 cm) were significantly shorter than Parbhani Moti (239.8 cm). Five most dwarf accessions were IS 10924, IS 12313, IS 13397, IS 12522 and IS 13362 (114.29–149.89 cm). Panicle exsertion is also an important

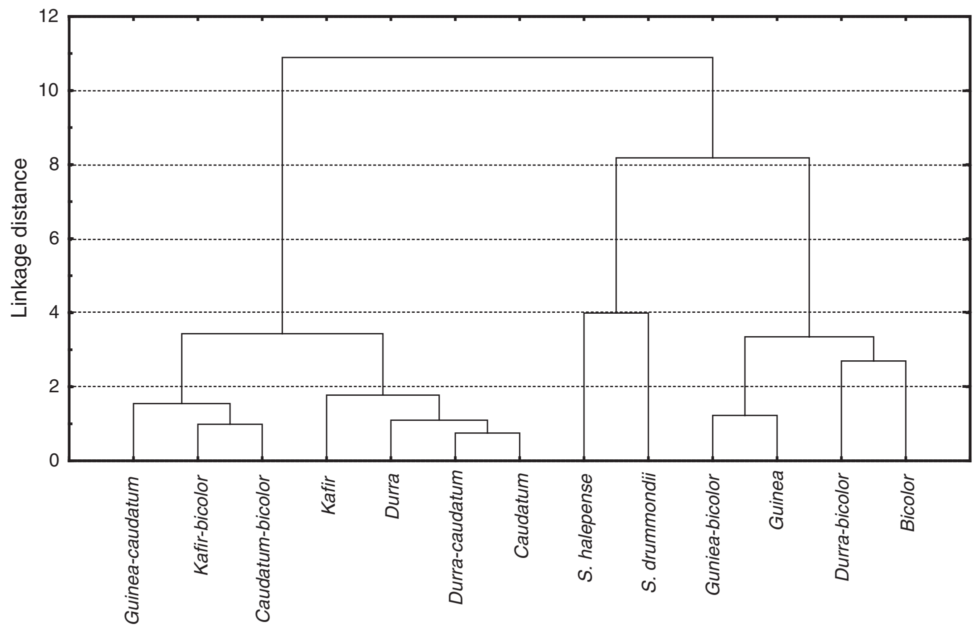

Fig. 1. Dendrogram constructed on the basis of first three principal component scores of five races, six intermediate races and two wild species of sorghum germplasm.

character. None of the accessions had higher panicle exsertion than Parbhani Moti, however, 34 accessions, mainly from Ethiopia, had medium (>30.0 cm) panicle exsertion, the most promising accessions were IS 2533, IS 13356, IS 15645, IS 11168 and IS 12956 (34.67–38.47 cm). All the accessions had low to medium 100-seed weight. Genotypes producing medium seeds are more preferred in the market due to their high nutritional quality, and 78 accessions (57 from basic races and 21 from intermediate races), predominantly from Ethiopia and Cameroon, had medium-sized seeds (≥4.0 g). The best five accessions were IS 13322, IS 14793, IS 14927, IS 14973, and IS 15582 (5.29–5.63 g).

The most diverse pairs of accessions have been identified among these trait-specific accessions for four important traits based upon the mean phenotypic diversity index (Table 6). For early flowering, IS 14201 of race *bicolor* from Congo in combination with five accessions, IS 10924 of *durra-caudatum* from USA, IS 12243 of *durra* from Ethiopia, IS

Table 6. Trait-specific diverse accessions with their racial classification and centre of origin among newly acquired sorghum germplasm accessions

Traits	Pair of accessions showing maximum diversity	
Early flowering	IS 14201 (*Bicolor*; Congo)	IS 10924 (*Durra-caudatum*; USA)
	IS 14201 (*Bicolor*; Congo)	IS 12243 (*Durra*; Ethiopia)
	IS 14201 (*Bicolor*; Congo)	IS 2963 (*Caudatum-bicolor*; Ethiopia)
	IS 14201 (*Bicolor*; Congo)	IS 6919 (*Guinea-caudatum*; Sudan)
	IS 14201 (*Bicolor*; Congo)	IS 2816 (*Guinea-caudatum*; Zimbabwe)
Short plant height	IS 10924 (*Durra-caudatum*; USA)	IS 12263 (*Guinea-caudatum*; Ethiopia)
	IS 13362 (*Caudatum-bicolor*; Ethiopia)	IS 12263 (*Guinea-caudatum*; Ethiopia)
	IS 13397 (*Caudatum-bicolor*; S. Africa)	IS 12263 (*Guinea-caudatum*; Ethiopia)
	IS 8233 (*Guinea-caudatum*; Uganda)	IS 12263 (*Guinea-caudatum*; Ethiopia)
	IS 13362 (*Caudatum-bicolor*; Ethiopia)	IS 12522 (*Caudatum-bicolor*; Ethiopia)
Medium panicle exsertion	IS 7977 (*Caudatum-bicolor*; Nigeria)	IS 13335 (*Caudatum*; Ethiopia)
	IS 6756 (*Guinea*; Burkina Faso)	IS 11168 (*Durra*; Ethiopia)
	IS 13335 (*Caudatum*; Ethiopia)	IS 12956 (*Bicolor*; India)
	IS 6756 (*Guinea*; Burkina Faso)	IS 11154 (*Durra*; Ethiopia)
	IS 13071 (*Caudatum-bicolor*; Australia)	IS 12956 (*Bicolor*; India)
Medium-sized seeds	IS 3057 (*Durra*; Ethiopia)	IS 13336 (*Caudatum*; Ethiopia)
	IS 14973 (*Caudatum*; Cameroon)	IS 13336 (*Caudatum*; Ethiopia)
	IS 3128 (*Durra*; USA)	IS 13336 (*Caudatum*; Ethiopia)
	IS 13030 (*Guinea*; Nigeria)	IS 3057 (*Durra*; Ethiopia)
	IS 7668 (*Guinea*; Nigeria)	IS 14973 (*Caudatum*; Cameroon)

2963 of *caudatum-bicolor* from Ethiopia, IS 6919 of *guinea-caudatum* from Sudan, and IS 2816 of *guinea-caudatum* from Zimbabwe showed high diversity. Similarly, diverse accessions have been identified for short plant height, medium panicle exsertion and medium-sized seeds (Table 6) for use in sorghum improvement programs to develop cultivars with a broad genetic base. Further, the clustering of these trait-specific accessions resulted into 12 groups for 108 early flowering accessions, 7 groups for 8 dwarf accessions, 11 groups for 34 accessions with medium panicle exsertion, and 12 groups for accessions with medium-sized seeds. The accessions grouped in the clusters did not show any racial or regional pattern for any of the four traits.

Discussion

The value of genetic resources in the progress of developing new cultivars has been well realised (Upadhyaya 2005). The sorghum germplasm collection at ICRISAT is one of the largest collections in the world holding 37 943 germplasm accessions from 92 countries. However, a few important countries have been represented poorly in this collection causing gaps in genetic diversity and geographical representation. These countries are considered as high priority areas and include Angola, Chad, China, Cote d'Ivoire, Eritrea, Mozambique, Thailand, Turkey and Zaire (Stenhouse *et al*. 1997). In addition, a very few accessions from other important countries such as Mauritania, Argentina, Australia and South Africa have been conserved in ICRISAT sorghum germplasm collection. To fill such gaps, new accessions are being assembled for conservation, as and when become available. Characterisation/evaluation of newly acquired germplasm for morpho-agronomic traits enhances their value in identifying trait-specific germplasm for crop improvement. The present study involving 667 newly acquired sorghum germplasm accessions has played a significant role in filling up the gaps as ~21% accessions are from the aforesaid high priority areas. Characterisation of these newly acquired accessions revealed large variation for all the qualitative and quantitative traits in the entire set as well as among the different races and intermediate races. The various qualitative traits can be used as morphological markers if found associated with the useful traits such as tan-coloured plants are most preferred in seed industry owing to their agronomic desirability, superior grain quality and tolerance to various fungal diseases and drought (Melake-Berhan *et al*. 1996). The tan-coloured accessions belonging to races *bicolor* and *guinea* and intermediate races *caudatum-bicolor, durra-caudatum* and *guinea-caudatum* in the present study thus have the potential for their utilisation in hybrid seed industries. These tan-coloured accessions are mainly from Uganda which shows that further exploration to this region would help in collecting new tan-coloured accessions available in that area to enrich ICRISAT genebank that contains <5% of such accessions. Dark glumes and closed glume type panicles have been found to contribute to grain-mould resistance (Audilakshmi *et al*. 1999; Murty 2000). The present study showed a large variability for glume colour and glume covering which may be utilised for screening grain mould resistance in sorghum. However, black-coloured glumes are present in the accessions belonging to races *bicolor*, *caudatum, durra*, *guinea* and intermediate races *durra-caudatum* and *guinea-caudatum* and subspecies *drummondii* and closed glume type panicles were present in all the wild accessions and most of the accessions belong to race *bicolor.*

The accessions of race *bicolor* were earliest in flowering with short height, whereas tall and late flowering accessions were from race *guinea*. The *durra* accessions had the highest 100-seed weight. Among intermediate races, accessions of *guinea-bicolor* had the highest number of basal tillers and highest 100-seed weight; accessions of subspecies *drummondii* were earliest to flower with long ear head; *S. halepense* accessions had maximum number of basal tillers and maximum ear head width.

The trait-specific germplasm accessions for four important traits have been identified, which would serve as new sources of variation in sorghum improvement programs. The most diverse pairs of accessions have been identified among these trait-specific accessions as well as among five races, eight intermediate races and wild types, individually, based upon the diversity index and mean phenotypic diversity. It would be interesting and fruitful to involve the most diverse lines in the hybridisation program to see the extent of segregation for different traits. Further, the trait-specific genotypes within and between the clusters hold potential for their effective utilisation in future hybridisation programs. The inclusion of these diverse germplasm lines from such collections in the hybridisation programs would increase the dominance effect and epistatic variations in the inheritance of quantitative traits (Halward and Wynne 1991) and would result in the useful recombinants/transgressive segregants in the subsequent generations. These lines could be utilised in future breeding programs for developing genetically diverse trait-specific improved sorghum cultivars with a broad genetic base. The inclusion of these 667 newly acquired sorghum lines have enriched the diversity already conserved at ICRISAT genebank and also played a vital role in filling up the gaps. Furthermore, evaluation of these new accessions for morpho-agronomic traits and the identification of diverse trait-specific germplasm accessions would provide a great opportunity to the breeders to select and use these new and diverse genotypes in their breeding program, which may revolutionise the sorghum improvement endeavours across the globe.

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