Resistance to Grain Mold and Downy Mildew in a Mini-Core Collection of Sorghum Germplasm

Rajan Sharma, V. P. Rao, H. D. Upadhyaya, V. Gopal Reddy and **R. P. Thakur,** International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502324, Andhra Pradesh, India

ABSTRACT

Sharma, R., Rao, V. P., Upadhyaya, H. D., Reddy, V. G., and Thakur, R. P. 2010. Resistance to grain mold and downy mildew in a mini-core collection of sorghum germplasm. Plant Dis. 94:439-444.

Grain mold and downy mildew are important biotic constraints to grain sorghum (*Sorghum bicolor*) production worldwide and are best managed through host plant resistance. A sorghum mini-core collection composed of 242 germplasm accessions developed from a core collection of 2,246 landrace accessions from 58 countries was evaluated to identify sources of grain mold and downy mildew resistance. Of the 242 accessions, 140 that flowered during the rainy season (the other 102 accessions were photoperiod sensitive) were screened for grain mold resistance in a grain mold nursery under field epiphytotic conditions during 2007 and 2008. All 242 accessions were screened for downy mildew in the greenhouse using a sandwich inoculation technique. Fifty accessions were resistant to grain mold (≤10% mean severity). These resistant accessions represented four basic and six intermediate races of sorghum that originated from 21 countries and exhibited considerable diversity for agronomic and morphological traits. Downy mildew resistance (mean incidence ≤10%) was observed only in six (IS 28747, IS 31714, IS 23992, IS 27697, IS 28449, and IS 30400) of the 242 accessions. One accession, IS 23992, exhibited resistance to both the diseases. The morphologically and agronomically diverse accessions that are resistant to grain mold or downy mildew should be useful to sorghum disease resistance breeding programs.

Sorghum (*Sorghum bicolor* (L.) Moench) is the world's fourth most important cereal crop after wheat, rice and maize (21). It is a major source of food, feed, fiber, and fuel across a range of environments and production systems. Most *Sorghum* spp. are tolerant to heat and drought and are especially important in arid regions. Thus, sorghum is the key for the sustenance of human and livestock populations in hot and dry areas of the world. However, diseases and insects, in addition to abiotic stresses, are major impediments toward realizing the high yield potential of sorghum cultivars. Developing cultivars resistant to these stresses is the key to improving sorghum productivity in farmers' fields.

Among the diseases, grain mold is one of the most important biotic constraints to production of grain sorghum worldwide (23,32). A complex of pathogenic and saprophytic fungi causes grain mold, and the major fungi associated with early infection events are *Fusarium* spp., *Curvularia lunata, Alternaria alternata*, and *Phoma sorghina* (22,23). Damage resulting from early infection includes reduced kernel development; discoloration of grains; colonization and degradation of endosperm; and decreased grain density, germination, and seedling vigor (23). Several species of *Fusarium* associated with grain mold complex have been shown to produce mycotoxins, such as fumonisins and trichothecenes, that are harmful to human and animal health (23).

Downy mildew, caused by *Peronosclerospora sorghi*, is another important disease of sorghum that can cause severe epidemics, resulting in considerable yield losses. Sorghum downy mildew is economically important and widespread in many tropical and subtropical regions of the world where sorghum and maize are grown (10,31). The disease is highly destructive due to its systemic nature of infection, resulting in the death of plants or lack of panicle initiation.

Availability of adequate genetic variation is a prerequisite for genetic improvement of any crop species. Germplasm accessions collected and maintained in gene banks represent vast genetic variation that can be utilized in crop improvement. However, large-scale evaluation of germplasm collections against various biotic or abiotic stresses is resource and time consuming. To overcome the need for a large-scale evaluation of the entire germplasm collection of a species, Frankel and Brown (5) proposed the concept of a core collection (10% of the entire collection) representing over 70% of the genetic variation available in the entire collection, and Brown (4) suggested this as a gateway to capture and utilize genetic diversity of a crop species in crop breeding programs. Core collections based on phenotypic data have been reported in several crops (3,26,28,30,33). Rao and Rao (16) were the first to develop a core collection of sorghum at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). Grenier et al. (7) also developed a core collection of 2,247 sorghum landrace accessions from 58 countries. However, a core collection consisting of 10% of the total accessions could still be too large in crops like sorghum for a systematic evaluation of traits of economic importance, such as disease resistance. Consequently, Upadhyaya and Ortiz (27) suggested a concept of a mini-core collection (10% of the core and 1% of entire collection) that can represent most of the useful variation in a crop species. Thus, a sorghum mini-core consisting of 242 accessions from the core collection of 2,246 landrace accessions was developed at ICRISAT in 2005 (29). The objective of this study was to evaluate this mini-core of sorghum accessions in order to identify accessions having resistance to grain mold or downy mildew that could be utilized in disease resistance breeding programs.

MATERIALS AND METHODS

Seed source. Seed of the 242 germplasm accessions of the sorghum mini-core comprising all the 5 basic races—*bicolor* (20), *caudatum* (39), *durra* (30), *guinea* (29), and *kafir* (21)—and 10 intermediate races—*caudatum-bicolor* (30), *durra-bicolor* (7), *durra-caudatum* (19), *guinea-bicolor* (2), *guinea-caudatum* (27), *guinea-durra* (2), *guinea-kafir* (3), *kafir-bicolor* (2), *kafir-caudatum* (7), and *kafir-durra* (4)—was obtained from the Genetic Resources Division, ICRISAT, Patancheru, India. The sorghum mini-core was developed from a core collection of 2,246 accessions. The core collection was evaluated for 11 qualitative and 10 quantitative traits. The hierarchical cluster analysis of data using phenotypic distances resulted in 21 clusters. From each cluster, about 10% or a minimum of one accession was selected to form a mini-core that comprised 242 accessions (29).

Corresponding author: R. P. Thakur
E-mail: r.thakur@cgiar.org

Accepted for publication 14 December 2009.

doi:10.1094/PDIS-94-4-0439

Screening for grain mold resistance. The 242 sorghum mini-core accessions along with susceptible checks (SPV 104 and Bulk Y) and a resistant check (IS 8545) were evaluated in the sorghum grain mold nursery during the 2007 and 2008 rainy seasons (June to September) at ICRISAT, Patancheru, India. Each accession was grown in one row of 2 m in length with two replications in a complete randomized block design.

Screening was done without artificial inoculation because sufficient natural inocula of mold fungi are present during the rainy season over sorghum fields at ICRISAT, India for natural field epiphytotic conditions (2,24). The accessions were sown in the first half of June so that grain maturing stages coincided with periods of frequent rainfall in August and September. To enhance mold development, high humidity (>90% relative humidity) was provided through sprinkler irrigation of test plots twice a day for 30 min each between 10:00 a.m. and 12:00 noon and between 4:00 and 6:00 p.m. on rain-free days from flowering to physiological maturity (when most grains in the middle of the panicle develop a black layer at the hilum). Ten uniformly flowering plants were tagged in each row. The visual panicle grain mold rating (PGMR) was taken on each of the tagged plants at the prescribed physiological maturity (23) using a progressive 1-to-9 scale, where 1= no mold infection, 2 = 1 to 5, 3 = 6 to 10, 4 = 11 to 20, 5 = 21 to 30, 6 = 31 to 40, 7 = 41 to 50, 8 = 51 to 75, and 9 = 76 to 100% molded grains on a panicle. Data were also recorded for agronomic traits, such as days to flowering (time of full panicle emergence in 50% of the plants in a row) and plant height (measured from the base of the plant to the tip of the panicle at maturity on 5 of the 10 tagged plants in a row), and morphological traits, such as panicle compactness (compactness of panicle at maturity), glume coverage (proportion of the grains covered with glumes at maturity), glume color, and grain color at maturity during 2008 (19). Most of the morphological traits appeared genetically fixed and were expressed uniformly in all plants of an accession; therefore, the data were recorded as an overall expression of the trait for each accession. The qualitative morphological traits, such as panicle compactness, glume color, and grain color were assigned numerical ratings following the distinctiveness, uniformity, and stability (DUS) ratings developed by the National Research Centre for Sorghum (19) to facilitate statistical analysis. The PGMR data were converted to percentages using the midpoint value (1 = 0, 2 = 3, 3 = 8, 4 = 15.5, 5 = 25.5, 6 = 35.5, 7 = 45.5, 8 = 63, and 9 = 88%) for statistical analysis (12).

Screening for downy mildew resistance. The 242 mini-core accessions were evaluated in a greenhouse along with a susceptible check (296 B) and a resistant check (QL 3) using a sandwich inoculation technique (24). The experiment was conducted in a completely randomized design with two replications and 45 to 50 seedlings per replication. Seed of the test accessions were incubated in moist petri dish chambers (petri dish lined with wet blotting paper) for 24 h at 35°C. Sprouted seed (with 0.5- to 1.0-mm-long plumules and radicles) were placed on the adaxial surface of a piece of systemically infected sorghum leaf and covered with another piece of infected leaf (adaxial surface touching the seed), thus "sandwiching" the sprouted seed in moist petri dishes. The petri dishes were incubated in darkness at 20°C for 24 h for infection of the seedlings. The seedlings were transplanted in 15-cm-diameter pots (45 to 50 seedlings/pot) filled with sterilized soil-sand-farmyard manure mix (2:1:1 by volume) and placed in a greenhouse maintained at 25 ± 1°C. Downy mildew incidence was recorded 14 days after transplanting as the percentage of plants with downy mildew symptoms. The selected resistant accessions (mean incidence ≤10%) were re-evaluated to confirm their resistance.

Statistical analysis. Analyses of variance (ANOVAs) for data on grain mold severity, downy mildew incidence, and agronomic traits, such as days to flowering and plant height, were done using the GENSTAT statistical package (version 10.1; Rothamsted Experiment Station, Herpenden, Herts AL52JQ, UK). The ANOVAs were obtained in terms of block effects and the accession effects, considering replications as random and accessions as fixed. For each field experiment conducted during 2007 and 2008, data on grain mold severity were analyzed separately using ANOVA. The Bartlett's test of homogeneity was conducted, which indicated that the error variances were homogeneous. The data of both the years were pooled and ANOVA performed using a mixed model (considering years and replications as random and accessions as fixed). The significance of main effects, year, and accession and their interactions were tested against residual mean squares.

The associations between pairs of variables—grain mold severity, plant height, days to flowering, panicle compactness, glume coverage, glume color, and grain color—were evaluated in terms of the Pearson's correlation coefficients using the correlations procedure of GENSTAT (version 10.1).

RESULTS

Grain mold resistance. Of the 242 sorghum mini-core accessions grown for grain mold evaluation during the rainy season in 2007, grain mold was scored only on 140 accessions; the other 102 accessions flowered very late and, thus, could not be evaluated. These 140 accessions were again evaluated during the 2008 rainy season. The ANOVA exhibited significant ($P < 0.001$) variation among the 140 mini-core accessions for grain mold resistance in both experiments (2007 and 2008, *data not given*) as well as in the pooled data (Table 1). Although there was significant interaction between accession and years, the MS variance for accessions was very high, indicating that differences in the mold severity were mainly contributed by accessions. Based on mean grain mold severity for the two experiments, 53 accessions were found to be resistant (grain mold severity ≤10%), 32 moderately resistant (mold severity 11 to 30%), 25 susceptible (mold severity 31 to 50%), and 30 highly susceptible (mold severity >50%) compared with 83 and 88% severity in susceptible checks SPV 104 and Bulk Y, respectively, and 2% severity in resistant check IS 8545. Fifty accessions were found to be resistant in both the experiments, indicating stable resistance in these accessions for grain mold. These accessions represented four basic—*bicolor* (14), *caudatum* (9), *guinea* (2), and *kafir* (2)—and six intermediate—*caudatum-bicolor* (10), *durra-caudatum* (3) *guinea-caudatum* (4), *guinea kafir* (2), *kafir-bicolor* (1), and *kafir-caudatum* (3)—races of sorghum (Table 2).

The 50 grain-mold-resistant accessions exhibited wide diversity for agromorphological traits such as days to flowering, plant height, panicle compactness, glume coverage, and grain and glume color (Table 2). Significant variations were recorded for days to flowering and plant height. The days to flowering in these accessions ranged between 49 and 76 and the plant height between 188 and 430 cm. The

Table 1. Analysis of variance for grain mold severity and downy mildew incidence in the mini-core accessions of sorghum[a]

	Grain mold severity		Downy mildew incidence	
Source of variation	**df**	**MS**	**df**	**MS**
Year (Y)	1	7.71	…	…
Replication (Year)	2	2.94	…	…
Replication	…	…	1	9.82
Accession (A)	142	3,009.73***	243	1,427.67***
Y × A	142	53.78***	…	…
Residual	284	14.03	243	25.73

[a] Asterisks (***) indicate significant at $P < 0.001$.

grain-mold-resistant accessions had representation of both white-grain and dark-grain (red or brown) lines with straw- to black-colored glumes and 25 to 100% glume coverage. Diversity for panicle compactness such as compact, semi-compact, loose, and very loose was also observed in these accessions. Grain mold severity was negatively correlated with grain color (r = –0.45), glume coverage (r = –0.32), and glume color (r = –0.22) whereas it was positively correlated with panicle compactness (r = 0.47). However, correlations of grain mold severity with plant height and days to flowering were nonsignificant.

Grain-mold-resistant accessions in the mini-core originated from 21 countries, indicating wide geographical diversity of resistant lines (Table 3). Of the 50 resistant accessions, 12 originated from the United States, 7 each from South Africa and Swaziland, 3 each from China and Republic of Korea, 2 each from Malawi and Zimbabwe, and 1 each from the remaining 14 countries.

Downy mildew resistance. The ANOVA exhibited significant ($P < 0.001$) variation among the 242 mini-core accessions for downy mildew resistance (Table 1). Most of the accessions (91%) showed high susceptibility to downy mildew. Six accessions showed resistance (≤10% inci-

Table 2. Grain mold severity, race type and variable agro-morphological traits of grain mold resistant sorghum accessions selected from mini-core collection

		Grain mold severity (%)[a]			Agronomic traits[b]			Morphological traits[c]		
IS no.	Race	2007	2008	Pooled	Days	Height (cm)	Panicle	GC	Glume color	Grain color
602	*bicolor*	0	0	0	50	213	L	100	P	LB
603	*bicolor*	0	3	2	53	250	L	75	P	LB
608	*bicolor*	0	0	0	50	213	L	100	BL	LB
1233	*bicolor*	0	2	1	49	210	L	100	BL	LB
2413	*bicolor*	0	1	1	65	363	L	50	R	B
3121	*bicolor*	0	0	0	76	345	L	75	BL	B
12697	*bicolor*	0	7	4	63	340	SL	100	BL	B
12804	*bicolor*	0	1	0	51	318	VL	100	R	B
20727	*bicolor*	3	0	2	52	238	SL	100	BL	B
20740	*bicolor*	3	0	2	71	350	L	100	BL	B
20743	*bicolor*	3	0	2	63	333	L	100	B	RB
20816	*bicolor*	3	1	2	61	253	SL	100	S	B
30562	*bicolor*	3	7	5	55	260	VL	100	S	B
31681	*bicolor*	3	2	2	52	295	SL	100	BL	B
2379	*caudatum*	3	4	3	66	348	SC	50	LR	CW
2864	*caudatum*	4	7	6	62	223	L	25	BL	LB
12302	*caudatum*	6	4	5	64	318	SC	25	R	LR
13971	*caudatum*	3	3	3	62	303	SL	50	BL	RB
17941	*caudatum*	3	7	5	61	188	SC	50	BL	CW
19389	*caudatum*	3	10	6	62	270	L	25	BL	B
23992	*caudatum*	3	1	2	63	383	SL	50	BL	RB
26694	*caudatum*	3	4	4	61	278	SL	50	S	B
29335	*caudatum*	3	2	2	53	220	SL	50	RB	RB
21512	*guinea*	3	4	3	67	343	SL	25	LB	W
21645	*guinea*	3	5	4	64	340	SL	75	RB	W
12945	*kafir*	8	9	9	64	308	SL	50	BL	S
22294	*kafir*	3	6	4	63	350	SC	50	S	LR
995	*caudatum-bicolor*	3	9	6	60	260	SC	75	P	B
2426	*caudatum-bicolor*	3	2	2	54	278	L	100	BL	B
12706	*caudatum-bicolor*	3	1	2	52	218	SL	50	BL	B
16151	*caudatum-bicolor*	3	3	3	49	208	SL	75	P	B
24453	*caudatum-bicolor*	3	2	2	63	288	SL	75	BL	LB
26701	*caudatum-bicolor*	3	4	4	52	215	SL	50	BL	B
29326	*caudatum-bicolor*	4	2	3	50	200	L	50	BL	B
30383	*caudatum-bicolor*	3	1	2	49	233	SL	50	S	RB
30533	*caudatum-bicolor*	3	7	5	62	340	L	50	RB	RB
30536	*caudatum-bicolor*	3	1	2	51	273	L	75	S	RB
20956	*durra-caudatum*	3	5	4	72	348	SL	50	S	W
29314	*durra-caudatum*	3	3	3	50	218	SL	50	RB	LR
30092	*durra-caudatum*	5	2	4	65	345	SL	50	BL	S
10969	*guinea-caudatum*	8	3	6	74	430	SL	25	LB	Y
23590	*guinea-caudatum*	5	8	7	75	348	SL	50	R	S
29187	*guinea-caudatum*	3	3	3	53	265	SL	50	RB	RB
29269	*guinea-caudatum*	3	4	3	50	210	SL	50	RB	RB
473	*guinea-kafir*	8	5	7	55	300	SL	25	S	S
29304	*guinea-kafir*	3	7	5	54	290	SL	50	S	S
1212	*kafir-bicolor*	0	0	0	49	258	L	50	B	RB
13893	*kafir-caudatum*	3	3	3	66	328	SL	50	S	RB
29241	*kafir-caudatum*	3	2	3	51	223	SL	50	RB	RB
29568	*kafir-caudatum*	4	7	5	62	288	SL	50	BL	LR
8545-check	*caudatum*	3	2	2	51	170	SC	50	B	B
SPV 104-check	…	88	78	83	65	213	C	50	W	W
Bulk Y-check	…	88	88	88	57	149	L	25	B	W
LSD ($P < 0.05$)[d]	…	6	8	5	2	20	…	…	…	…

[a] Mean of two replications, 10 plants/replication at physiological maturity.
[b] Days = days to flowering and Height = plant height; panicle compactness: C = compact, SC = semicompact, SL = semiloose, L = loose, VL = very loose.
[c] GC = glume coverage (%); W = white, CW = chalky white, S = straw, Y = yellow, LR = light red, R = red, RB = reddish brown, LB = light brown, B = brown, P = purple, BL = black.
[d] Trial least significant difference.

dence) and two exhibited moderate resistance (11 to 20% incidence) compared with 100% incidence in the susceptible check (H 112) and 23% in the resistant check (QL 3). Among the resistant accessions, IS 28747 from Yemen was free from downy mildew, two accessions (IS 31714 and IS 23992) recorded ≤5% downy mildew incidence, while three (IS 27697, IS 28449, and IS 30400) had 6 to 10% incidence. Four of the six downy-mildew-resistant accessions originated from the Republic of Yemen and one each from China and Sierra Leone (Table 3). Resistance in these six accessions was confirmed by reevaluating them under greenhouse conditions.

Table 3. Origin of sorghum mini-core germplasm accessions and their reaction to downy mildew and grain mold

	Downy mildew incidence (%)[a]			Grain mold severity (%)[b]	
Country of origin	**No.**	**Range**	**Resistant**	**No.**	**Range**
Afghanistan	1	100	…	1	2 (1)
Algeria	1	99	…	1	2 (1)
Argentina	1	100	…	1	31
Australia	1	100	…	1	4 (1)
Bangladesh	1	83	…	1	6 (1)
Benin	1	44	…	…	…
Botswana	5	24–100	…	5	4–33 (1)
Burkina Faso	1	95	…	…	…
Burundi	1	94	…	…	…
Cameroon	13	72–100	…	2	3–23 (1)
Chad	2	100–100	…	…	…
China	12	10–100	IS 30400	12	0–4 (3)
Cuba	1	48	…	1	30
Egypt	1	100	…	1	88
Ethiopia	12	21–100	…	6	7–29 (1)
Gambia	1	54	…	…	…
Ghana	1	62	…	…	…
Honduras	1	100	…	…	…
India	30	22–100	…	17	5–88 (1)
Indonesia	1	89	…	1	4 (1)
Iran	1	100	…	1	1 (1)
Japan	1	62	…	…	…
Kenya	5	52–96	…	1	47
Republic of Korea	5	77–100	…	5	2–43 (3)
Lesotho	8	22–100	…	8	5–59 (1)
Madagascar	1	56	…	…	…
Malawi	2	42–59	…	2	3–4 (2)
Mali	6	19–100	…	…	…
Mexico	1	75	…	…	…
Morocco	1	26	…	1	88
Mozambique	1	100	…	…	…
Myanmar	1	100	…	…	…
Nicaragua	1	96	…	1	9 (1)
Niger	2	70–100	…	…	…
Nigeria	7	38–100	…	…	…
Pakistan	1	59	…	1	50
Rwanda	1	96	…	…	…
Saudi Arabia	1	100	…	1	15
Senegal	1	86	…	…	…
Sierra Leone	1	6	IS 27697	…	…
Somalia	3	27–99	…	1	78
South Africa	25	23–100	…	23	2–59 (7)
Sri Lanka	1	38	…	…	…
Sudan	6	24–100	…	3	14–51
Swaziland	9	41–100	…	9	2–26 (7)
Syrian Arab Republic	1	93	…	1	68
Tanzania	4	86–100	…	…	…
Thailand	1	100	…	1	22
Togo	1	98	…	…	…
Turkey	1	100	…	1	0 (1)
United States	17	47–100	…	14	0–60 (12)
Uganda	6	67–100	…	…	…
Venezuela	1	100	…	…	…
Republic of Yemen	15	0–100	IS 23992, -28449, -28747, -31714	7	2–59 (1)
Zaire	1	98	…	…	…
Zambia	3	78–100	…	…	…
Zimbabwe	11	30–100	…	9	4–57 (2)
SE (m) ±	…	3.6	…	…	2.0[c]

[a] Based on the mean of two replications in greenhouse evaluation using "sandwich method." No. = number of accessions and Resistant = resistant accessions.

[b] Based on the mean of 2 years of screening in field conditions. No. = number of accessions. Range: number of resistant accessions across 2 years in parentheses.

[c] Standard error (SE) of individual accession mean over seasons and replications.

DISCUSSION

Resistance to grain mold is a complex trait and several morphological traits have been shown to be associated with resistance (1). We observed significant negative correlations of grain mold severity with grain color, glume coverage, and glume color. Negative correlations of grain mold severity with grain or glume color and glume coverage indicate that accessions with dark grain color (red or brown) and large and dark-colored (purple or black) glumes are most likely to be resistant to grain mold. Positive correlation between panicle compactness and grain mold severity indicates that accessions with a loose panicle are more likely to be resistant to grain mold because the compact heads hold more moisture that favors mold development. The roles of flowering time, panicle compactness, glume coverage, and grain color (due to pericarp and testa pigmentation) in sorghum grain mold resistance are well documented (1,6,23). Grain mold resistance is reported to be correlated not only with open panicles and long glumes (6) but also with greater glume coverage, length, and area (13). Thus, there is a need to identify morphologically diverse sources of genetic resistance with desirable agronomic traits for utilization in resistance breeding to develop hybrids and cultivars for diverse use as food, feed, and other industrial products. Diversity for agronomic traits, such as days to flowering and plant height, and morphological characters such as grain or glume color, glume coverage, and panicle compactness provides opportunity of breeding lines with a different adaptation.

In this study, we identified 50 grain-mold-resistant sorghum accessions from the mini-core, which represent a wide diversity of race types, morphological traits, agronomic desirability, and geographical distribution. Among resistant accessions, six dark-grain (IS 12706, -26701, -29241, -29269, -29314, and -29335) and one chalky white-grain (IS 17941) accessions had desirable agromorphological traits, such as early flowering (<65 days to flowering), medium plant height (151 to 225 cm), semicompact to semiloose panicles, and 50% glume coverage. These would be desirable sources of resistance for a sorghum breeding program. Among different races constituting the sorghum mini-core, maximum mold-resistant accessions were of *bicolor* type (14 of the 15 screened). The resistance in the *bicolor* accessions might be due to loose panicles and dark grain color. None of the 14 *durra*-type accessions (compact panicle) screened had resistance to grain

mold. The resistant accessions were found from 17 of the 21 clusters of the core collection that were used to develop the mini-core (29). The number of resistant accessions ranged from one each from cluster 8 (having 110 accessions in core collection) and cluster 20 (29 accessions) to six from cluster 9 (185 accessions). The representation of grain-mold-resistant accessions in 17 clusters of the core collection reveals a high level of genetic diversity in these accessions. This diversity could be indicative of genetic diversity in resistance as well.

Grain mold severity has generally been higher on white-grain, short-duration cultivars and hybrids than on colored-grain, long-duration ones (23). Some advances have been made to develop white-grain, high-yielding experimental hybrids with tolerance to grain mold (17); however, the levels of resistance have not been adequate. Thus, there has been a need to identify genetic resistance in white-grain accessions with desirable agronomic traits for utilization in breeding program. In this study, grain mold resistance was identified in three white-grain (IS 20956, -21512, and -21645) and two chalky white-grain (IS 2379 and -17941) accessions from the sorghum mini-core collection. These would be desirable sources of resistance for a breeding program aiming to develop white-grain hybrids for human consumption, particularly in Asia. Among the 140 accessions, IS 21512 and -21645 were the only *guinea*-type sorghum included in the experiment and were resistant to grain mold. Therefore, it would be desirable to screen more white-grain *guinea*-type accessions from the core collection to identify mold resistance in white-grain sorghum.

Attempts were made to identify resistance in the sorghum mini-core collection for downy mildew as well. Sorghum line QL 3 has been reported to be resistant to downy mildew (18) and was included as a resistant check in the present study. QL 3 recorded 23% downy mildew incidence. This indicates a likely virulence change in the pathogen population and calls for identification of new sources of downy mildew resistance in sorghum. A sudden reemergence and disease outbreak of sorghum downy mildew resulting in significant yield loss has been recorded in Texas during the spring of 2001 and again in 2002 (9). *P. sorghi* isolates from the epidemic area were found to be insensitive to metalaxyl fungicide, which had been used as an effective seed treatment for many years. Characterization of isolates collected from previously resistant hosts revealed the evolution of a new pathogenic race of *P. sorghi.* In the present study, we identified six accessions from the sorghum mini-core collection having resistance to the Patancheru isolate of *P. sorghi* (pathogenic variation in *P. sorghi* from India has not been reported yet). One accession (IS 23992) exhibited resistance to both grain mold and downy mildew. This accession was selected from cluster 16 of the core collection, which consists of 94 accessions (29). It would be useful to evaluate the remaining accessions from cluster 16 that were not included in the mini-core collection to identify additional sources with resistance to both the diseases. Holbrook and Anderson (8) compared peanut germplasm and a core collection for late leaf spot resistance and observed that the success rate to identify resistant lines was greater ($P < 0.01$) while screening the lines within clusters than the success rate for the lines not in those clusters. Similarly, a subsample of the core collection of common bean was useful for identifying white-mold-resistant accessions within the active *Phaseolus* spp. collection (14). The six downy-mildew-resistant accessions were selected from five clusters; two from cluster 1 (279 accessions) and one each from clusters 4 (166 accessions), 13 (92 accessions), 16 (94 accessions), and 8 (110 accessions). Therefore, it would be desirable to evaluate accessions from these clusters to identify additional sources of downy mildew resistance.

It is evident from this study that resistance to stresses such as diseases can be effectively identified from a mini-core comprising only 1% of the total germplasm of a crop species. We could identify 50 grain-mold-resistant accessions, 6 downy-mildew-resistant accessions, and 1 accession with resistance to both the diseases from the sorghum mini-core collection. There are several reports where mini-cores have successfully been used to identify resistance sources for diseases (15), salinity (20), and drought (11,25). Thus, the mini-core collections can be used as a starting point to screen for desirable traits in a crop species. The information regarding the clusters to which a particular accession with traits of interest belongs will help in extensive evaluation of accessions with similar traits in the larger subsets in the core collection and, eventually, the entire germplasm. Identification of grain-mold- and downy-mildew-resistant accessions from the sorghum mini-core would permit use of diverse resistance sources for future breeding efforts and to ensure a better chance of success in sorghum improvement.

LITERATURE CITED

1. Audilakshmi, S., Stenhouse, J. W., Reddy, T. P., and Parasad, M. V. R. 1999. Grain mold resistance and associated characters of sorghum genotypes. Euphytica 107:91-103.
2. Bandyopadhyay, R., Mughogho, L. K., and Rao, K. E. P. 1988. Sources of resistance to sorghum grain molds. Plant Dis. 72:504-508.
3. Bhattacharjee, R., Khairwal, I. S., Bramel, P. J., and Reddy, K. N. 2007. Establishment of a pearl millet (*Pennisetum glaucum* (L.) R. Br.) core collection based on geographical distribution and quantitative traits. Euphytica 155:35-45.
4. Brown, A. H. D. 1989. Core collection: a practical approach to genetic resources management. Genome 31:818-824.
5. Frankel, O. H., and Brown, A. H. D. 1984. Plant genetic resources today: a critical appraisal. Pages 249-268 in: Crop Genetic Resources: Conservation and Evaluation. J. H. W. Holden and J. T. Williams, eds. Allen and Unwin, Winchester, MA.
6. Glueck, J. A., Rooney, L. W., Rosenow, D. T., and Miller, F. R. 1977. Physical and structural properties of field deteriorated (weathered) sorghum grain. Pages 101-112 in: Third Annu. Progr. Rep., TAES-US/AID Contract ta-c-1902. Texas Agricultural Experiment Station, College Station.
7. Grenier, C., Hamon, P., and Bramel-Cox, P. J. 2001. Core collection of sorghum: II. Comparison of three random sampling strategies. Crop Sci. 41:241-246.
8. Holbrook, C. C., and Anderson, W. F. 1995. Evaluation of a core collection to identify resistance to late leaf spot in peanut. Crop Sci. 35:1700-1702.
9. Isakeit, T., Odvody, G., Jahn, R., and Deconini, L. 2003. *Peronosclerospora sorghi* resistant to metalaxyl treatment of sorghum seed in Texas. (Abstr.) Phytopathology 93:S39.
10. Jegera, M. J., Gilijamsea, E., Bockb, C. H., and Frinkinga, H. D. 1998. The epidemiology, variability and control of the downy mildews of pearl millet and sorghum, with particular reference to Africa. Plant Pathol. 47:544-569.
11. Kashiwagi, J., Krishnamurthy, L., Upadhyaya, H. D., Krishna, H., Chandra, S., Vadez, V., and Serraj, R. 2005. Genetic variability of drought-avoidance root traits in the mini-core germplasm collection of chickpea (*Cicer arietinum* L.). Euphytica 146:213-222.
12. Li, S., Hartman, G. L., and Chen Y. 2009. Evaluation of aggressiveness of *Fusarium virguliforme* isolates that cause soybean sudden death syndrome. J Plant Pathol. 91:77-86.
13. Mansuetus, S. B. A., Frederiksen, R. A., Waniska, R. D., Odvody, G. N., and Craig, J. 1990. The role of glumes of sorghum in resistance to grain mold. (Abstr.) Phytopathology 80:1069.
14. Miklas, P. N., Delorme, R., Hannan, R., and Dickson, M. H. 1999. Using a sub-sample of the core collection to identify new sources of resistance to white mold in common bean. Crop Sci. 39:569-573.
15. Pande, S., Kishore, G. K., Upadhyaya, H. D., and Rao, J. N. 2006. Identification of sources of multiple disease resistance in mini-core collection of chickpea. Plant Dis. 90:1214-1218.
16. Rao, P. K. E., and Rao, R. V. 1995. The use of characterization data in developing a core collection of sorghum. Pages 109-116 in: Core Collection of Plant Genetic Resources. T. Hodgkin, ed. A Willey-Sayee Publication, Chichester, UK.
17. Reddy, B. V. S., Bandyopadhyay, R., Ramaiah, B., and Ortiz, R. 2000. Breeding grain mold resistant sorghum cultivars. Pages.195-224 in: Technical and Institutional Options for Sorghum Grain Mold Management. R. Chandrashekar, R. Bandyopadhyay, and A. J. Hall, eds. Proc. Int. Consultation, ICRISAT, Patancheru, India.
18. Reddy, B. V. S., Mughogho, L. K., Narayana, Y. D., Nicodemus, K. D., and Stenhouse, J. W. 1992. Inheritance pattern of downy mildew resistance in advanced generations of sorghum. Ann. Appl. Biol. 121:249-255.
19. Reddy, B. V. S., Sharma, H. C., Thakur, R. P., and Ramesh, S. 2006. Characterization of ICRISAT-bred sorghum hybrid parents (set I). Int. Sorghum Millets Newsl. (Special Issue) 47:1-21.
20. Serraj, R., Krishnamurthy, L., and Upadhyaya, H. D. 2004. Screening chickpea mini-core germplasm for tolerance to salinity. Int.

Chickpea Pigeonpea Newsl. 11:29-32.
21. Smith, C. W., and Frederiksen, R. A. 2000. Sorghum: Origin, History, Technology and Production. John Wiley & Sons, New York.
22. Thakur, R. P., Rao, V. P., Navi, S. S., Garud, T. B., Agarkar, G. D., and Bhat, B. 2003. Sorghum grain mold: variability in fungal complex. Int. Sorghum Millets Newsl. 44:104-108.
23. Thakur, R. P., Reddy, B. V. S., Indira, S., Rao, V. P., Navi, S.S., Yang, X. B., and Ramesh, S. 2006. Sorghum grain mold. In: Inf. Bull. No. 72. International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502324, Andhra Pradesh, India.
24. Thakur, R. P., Reddy, B. V. S., and Mathur, K. 2007. Screening techniques for sorghum diseases. In: Inf. Bull. No. 76. International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502324, Andhra Pradesh, India.
25. Upadhyaya, H. D. 2005. Variability for drought resistance related traits in the mini-core collection of peanut. Crop Sci. 45:1432-1440.
26. Upadhyaya, H. D., Gowda, C. L. L., Reddy, K. N., and Singh, S. 2009. Augmenting the pearl millet core collection for enhancing germplasm utilization in crop improvement. Crop Sci. 49:573-580.
27. Upadhyaya, H. D., and Ortiz, R. 2001. A mini-core collection for capturing diversity and promoting utilization of chickpea genetic resources in crop improvement. Theor. Appl. Genet. 102:1292-1298.
28. Upadhyaya, H. D., Ortiz, R., Bramel, P. J., and Singh, S. 2003. Development of a groundnut core collection using taxonomical, geographical and morphological descriptors. Genet. Resour. Crop Evol. 50:139-148.
29. Upadhyaya, H. D., Pundir, R. P. S., Dwivedi, S. L., Gowda, C. L. L., Reddy, V. G., and Singh, S. 2009. Developing a mini-core collection of sorghum (*Sorghum bicolor* (L.) Moench) for diversified utilization of germplasm. Crop Sci. 49:1769-1780.
30. Upadhyaya, H. D., Pundir, R. P. S., Gowda, C. L. L., Reddy, V. G., and Singh, S. 2008. Establishing a core collection of foxtail millet to enhance utilization of germplasm of an underutilized crop. Plant Genet. Resor. doi:10.1017/S1479262108178042.
31. Williams, R. 1984. Downy mildew of tropical cereals. Adv. Plant Pathol. 3:1-103.
32. Williams, R. J., and Rao, K. N. 1981. A review of sorghum grain moulds. Trop. Pest Manage. 27:200-211.
33. Yan, W. G., Rutger, J. N., Bryant, R. J., Bockelman, H. E., Fjellstrom, R. G., Chen, M. H., Tai, T. H., and McClung, A. M. 2007. Development and evaluation of a core collection of the USDA rice germplasm collection. Crop Sci. 47:869-876.