Physical and Chemical Kernel Properties Associated with Resistance to Grain Mold in Sorghum

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ABSTRACT

Identification of kernel properties associated with resistance to grain mold would be useful in screening germplasm in a breeding program. We screened and characterized a large and diverse collection of sorghum (*Sorghum bicolor* (L.) Moench) accessions for physical and chemical kernel properties, as well as for resistance to grain mold in the field. We identified sorghum accessions with a high level of grain mold resistance originating from diverse geographical areas and belonging to different botanical races. We found that resistance to grain mold in these sorghums was strongly associated with high concentration of phenolic compounds (apigeninidin, flavan-4-ols, and tannin), kernel hardness, and pericarp color. Each of these kernel properties contributed to grain mold resistance differently in white, red, and brown pericarp sorghum accessions. We developed a numerical index that integrated the more important kernel attributes, and this index effectively differentiated resistant and susceptible sorghum genotypes.

Grain mold caused by several fungi is a serious disease when the sorghum caryopsis develops and matures in high humidity and warm temperatures (Williams and Rao 1981, Forbes et al 1992). Mold damage reduces test weight, seed viability, and nutritional quality, as well as kernel appearance and market value (Castor and Fredriksen 1980). Use of resistant cultivars is the only feasible way to minimize damage from mold.

Identifying chemical and physical kernel properties associated with resistance of sorghum to grain mold would facilitate screening germplasm for resistance before subsequent inclusion in breeding programs. Phenolic compounds that inhibit fungal growth may confer resistance to grain mold damage before and after grain maturity (Waniska et al 1992). High levels of condensed tannins (Harris and Burns 1973), phenolic acids (Waniska et al 1992), and flavan-4-ols (Jambunathan et al 1986, Jambunathan and Kherdekar 1990, Jambunathan et al 1991, Mukuru 1992) in mature sorghum kernels were closely correlated with resistance to grain mold. Physical kernel properties, including a high proportion of corneous to floury endosperm, thick surface wax of the grain, and kernel density also have been associated with enhanced resistance to grain mold (Glueck and Rooney 1980, Ibrahim et al 1985, Jambunathan et al 1990, Waniska et al 1992). However, these findings were based on a limited number of genotypes. In a more diverse collection of sorghums, none of these variables solely explained much of the variation in grain mold resistance in sorghums. Use of a multiple-trait selection index, therefore, may enhance development of genotypes with a combination of desirable physical and chemical kernel attributes to minimize damage by mold.

The objectives of this study were to: 1) evaluate a large working collection of diverse tropical landraces of sorghum for grain mold resistance, 2) characterize a diverse sorghum germplasm collection for kernel traits associated with grain mold resistance, and 3) assess the cumulative contribution of physical and chemical kernel properties in sorghum on overall resistance to molding.

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MATERIALS AND METHODS

Genetic Material and Experimental Design

A diverse array of 231 photoperiod-insensitive sorghum accessions (referred to hereafter as the working collection) representing different cultivated races of sorghum from a large number of countries were evaluated for grain mold resistance in West Lafayette, IN. These accessions were planted in unreplicated plots at the Purdue Agronomy Research Center in 1984. Each accession was planted in three rows 6 m in length, spaced 75 cm wide. Resistant accessions (43) with grain mold scores of 1 and 2 and susceptible accessions (9) with grain mold scores of 4 and 5, based on the 1984 test, were selected as a subset of the working collection to confirm the reaction to infection by grain mold in 1985. The selected accessions were planted in a randomized complete block design with three replicates at the same location. Each accession was planted in a single row plot each 5 m in length and spaced 75 cm apart.

Sampling and Grain Mold Damage Assessment

Randomly selected plants (12) were tagged from each unreplicated plot in 1984 and from each replicated plot in 1985 at anthesis. Three tagged panicles were harvested at the end of November. The warm and humid weather at the Purdue Agronomy Research Center was conducive for the development of grain mold. Uniform and reliable levels of natural infection were readily obtained without artificial inoculation. We visually estimated grain mold severity in three harvested panicles using a rating system described by Williams and Rao (1981) and subsequently used by others (ICRISAT 1985, Bandyopadhyay et al 1988, Forbes et al 1992). Ratings were based on a 1–5 scale, where 1 = no visible mold, 2 = 1–10%, 3 = 11–25%, 4 = 26–50%, and 5 = more than 50% of the area of the kernels in each panicle molded. Grain mold scores of the three panicles in each replicate (plot) were averaged to obtain the scores of each accession.

Measuring Kernel and Panicle Traits

Panicle shape. A visual score of the compactness of a panicle was based on a 1–7 scale, where 1 = a very open panicle and 7 = the most compact panicle.

Endosperm texture. A sample of longitudinally sectioned kernels was rated on a scale of 1 (corneous) to 5 (floury).

Kernel weight. Measured as the weight in grams of 100 seeds.

Kernel color. Coded as 1 = white, 2 = straw, 3 = yellow, 4 = orange red, 5 =l light brown, 6 = brown, 7 = red brown, 8 = gray, and 9 = purple.

Days to flowering. Number of days from planting until 50% of the plants in a plot bloomed halfway down the panicle.

Determination of Phenolic Compounds

Kernels were cleaned manually and ground in a Cyclotec1093 sample mill for chemical analysis. Apigeninidin, luteolindin, flavan-4-ols, and tannins were determined using procedures described by Watterson and Butler (1993) with the following modifications. A 250-mg flour sample was extracted with 15 ml of 0.5% HCl in methanol for 20 min. After centrifugation for 5 min, the supernatant was carefully removed. A 0.5-ml sample was drawn from the supernatant and mixed with 7 ml of 30% HCl in 1-butanol for flavan-4-ol analysis. Blanks for flavan-4-ols and proanthocyanidins were prepared by mixing 0.5 ml of acidic methanol extract with 7 ml of methanol, 0.1*N* acetic acid, and butanol (15:15:70, v/v). The absorbance of the supernatant was measured at 550 nm for flavan-4-ols after correcting for blanks. The test tube was then placed in a boiling water bath for 2 hr, cooled for 5 min. Tannins (proanthocyanidins) were measured at 550 nm after correcting for blanks.

Analysis of 3-deoxyanthocyanidin pigments was made on a second 250-mg flour sample by extracting with 15 ml of 100% ethyl acetate for 30 min. The residue was extracted further with 15 ml of 0.05% HCl in methanol. Acid-treated poly(vinylpyrrolidone) (0.4 g) was added to 8 ml of the acidic methanol extract, mixed thoroughly by vortexing, incubated at room temperature for 10 min, and centrifuged. The absorbance of the supernatant was read at 475 nm for apigeninidin and at 495 nm for luteolinidin. Duplicate samples were assayed for all phenolic compounds.

Statistical Analysis

Before combining data from the two years for the 52 entries making up the subset, accession means were calculated from three replicates for 1985. An unweighted combined analysis of variance was then computed from the 1984 unreplicated data and the 1985 mean data as described by Cochran and Cox (1957). The least significant difference (LSD) was calculated by using accession × year interaction mean squares as an error. Means for each of the 52 selected accessions was calculated by averaging the unreplicated 1984 value and the mean of the replicated 1985 test. Means of all traits and the corresponding standard errors for the working collection and the subset were calculated by univariate procedure as outlined by SAS (1985). Pearson's simple correlation coefficients between grain mold damage scores, days to flowering, and panicle shape were computed from the 1984 unreplicated data for the working collection and the average of data from two years for the subset. Accessions with grain mold damage scores of 3 or less were grouped as resistant, and those with grain mold damage scores exceeding 3 were grouped as susceptible. The difference between resistant and susceptible accessions was tested based on paired *t*-test as outlined by SAS (1985). Principal component analysis was computed from the correlation matrix generated from all kernel traits (SAS 1985). The first principal component was used as an index to calculate a composite score for each accession: index = (eigenvector1 × trait1) + (eigenvector2 × trait2) + (eigenvector3 × trait3) + (eigenvector4 × trait4) + (eigenvector5 × trait5) + (eigencvector6 × trait6). Pearson's simple correlation coefficients between the composite scores and grain mold damage scores were also calculated.

TABLE I
Physical and Chemical Kernel Properties, Days to Flowering, and Panicle Shape for Sorghum Entries in the Working Collection

Trait	Minimum	Maximum	Mean	Standard Error
Days to flowering	62.00	101.00	83.11	0.45
Kernel color	1.00	9.00	3.41	0.17
Kernel weight (g)	1.40	4.73	2.73	0.05
Endosperm texture	1.00	5.00	2.85	0.07
Apigeninidin (A475/g)	0.05	3.36	0.68	0.03
Luteolinidin (A495/g)	0.05	3.10	0.67	0.03
Flaven-4-ols (A550/g)	0.00	1.83	0.25	0.02
Tannin (A550/g)	0.00	1.26	0.21	0.02
Panicle shape	3.00	8.00	5.79	0.07

RESULTS

Genotypes in both the large working collection (231 entries) and the subset of the working collection (52 entries) exhibited large differences in physical and chemical kernel attributes (Tables I and II). Marked differences among accessions also were observed for visible mold damage (Fig. 1). The frequency of accessions in the five mold score categories appeared to be normally distributed for the working collection but was skewed to the left for the subset of the working collection. Differences among accessions also were observed for days to flowering and panicle shape. Although the range for days to flowering was wide, its correlation with grain mold scores was low for both the large working collection ($r = -0.34$) and the small subset of the working collection ($r = -0.04$). The correlation between grain mold scores and panicle shape also were very low ($r < 0.20$) for both groups of accessions.

The contribution of physical and chemical kernel attributes to mold resistance in accessions with different kernel colors are shown in Table III. In general, white sorghum accessions without a pigmented testa were characterized by mostly corneous endosperm texture, relatively low (<0.6 A/g) levels of apigeninidin and luteolinidin, and negligible amounts of flavan-4-ols and tannin. On average, differences between resistant and susceptible white sorghum accessions were not significant for each trait, except for

TABLE II
Physical and Chemical Kernel Properties, Days to Flowering, and Panicle Shape for Sorghum Entries in Selected Accessions

Trait	Minimum	Maximum	Mean	Standard Error
Days to flowering	66.50	97.50	80.39	0.89
Kernel color	1.00	9.00	4.28	0.26
Kernel weight (g)	1.70	4.53	3.05	0.09
Endosperm texture	1.50	5.00	3.27	0.10
Apigeninidin (A475/g)	0.27	1.82	0.65	0.04
Luteolinidin (A495/g)	0.25	1.97	0.62	0.04
Flaven-4-ols (A550/g)	0.00	1.26	0.39	0.06
Tannin (A550/g)	0.00	1.34	0.36	0.05
Panicle shape	4.00	8.00	6.12	0.13

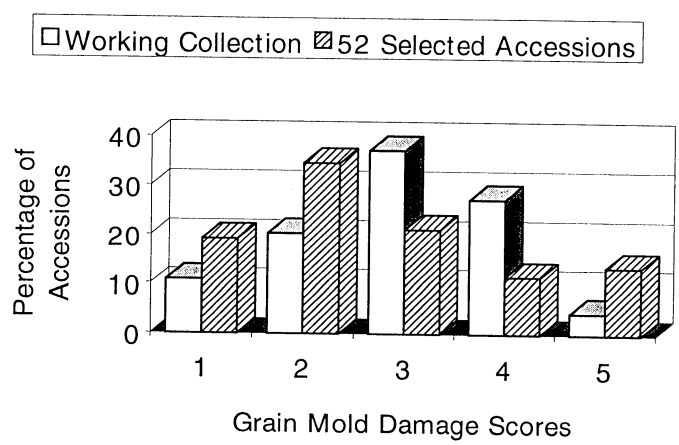

Fig. 1. Frequency distribution of visual grain mold damage scores for the working collection (white columns)of 231 accessions and the subset (striped columns) of 52 selected accessions.

days to flowering (Table III). However, late flowering was not always related to resistance to molding in white sorghum. For instance, P121186 and P954100 were more resistant to molding than IS0071 and IS9370, although the former flowered earlier than the latter (Table IV).

White sorghum accessions with testa contained tannin, moderate levels (6.0–8.5 A/g) of apigeninidin and luteolinidin, a very low amount of flavan-4-ols, and an intermediate endosperm texture (Table III). On average, resistant and susceptible accessions within this group did not differ from each other for each trait except for kernel weight (Table III). However, more corneous endosperm texture and higher levels of apigeninidin, luteolinidin, and tannin were associated with enhanced resistance to grain mold in some accessions (Table IV).

Sorghum accessions with red pericarp, but without pigmented testa, had mostly corneous endosperm texture, relatively high levels (>0.9 A/g) of apigeninidin, luteolinidin (>0.9 A/g), and flavan-4-ols (>0.45 A/g) and a negligible amount of tannin. Resistance in this group was strongly associated with high concentration of flavan-4-ols (Tables III and IV). However, we found an inverse relationship between concentration of flavan-4-ols and resistance to grain mold damage in some red sorghum accessions (data not shown). Resistant sorghum accessions with red pericarp, as a group, flowered later than susceptible accessions, although some resistant accessions (IS8612 and IS1301) flowered earlier than some susceptible ones (P954164) (Table IV).

Brown sorghum accessions contained high levels of flavan-4-ols and tannin and moderate levels (0.6–0.85 A/g) of apigeninidin and luteolinidin (Table III). In general, resistance in brown sorghum accessions was associated with increased levels of both flavan-4-ols and tannins. However, some resistant accessions did not have significantly higher levels of these compounds when compared to susceptible genotypes (Table IV). Days to flowering seemed to have little effect on resistance to molding in brown sorghum accessions (Tables III and IV).

Principal component analysis was computed to develop an index that would integrate the most important kernel attributes associated with resistance to molding. As the relationship between apigeninidin and luteolinidin was very strong ($r = 0.98$), we included only apigeninidin in this analysis. The first three principal components together accounted for >70% of the total variation of all traits in the two sets of accessions. The first principal component (PC1) alone explained 40 and 48% of the total variation of all traits in the working collection and the subset of the working collection, respectively (Table V). The second and third principal components each accounted for <20% of the total variation of all the traits (data not shown). Eigenvectors of the PC1 for each set of accession had large positive weights for kernel color, endosperm texture, apigeninidin, flavan-4-ols, and tannins. Smaller, but positive weight was given to kernel weight (Table V).

Considering PC1 as a selection index, we calculated a composite score for each accession as the sum of the products of an eigenvector and the corresponding value for each of the kernel traits. The correlation between PC1 composite scores and visual grain mold scores were significant ($P < 0.01$) and negative for both the large working collection ($r = -0.44$) and the small subset of the working collection ($r = -0.75$).

DISCUSSION

Differences in maturity can bias mold damage estimates in sorghum. However, results from this study and others (Ibrahim et al 1985, Mukuru 1992) did not find a strong association between days to 50% flowering and grain mold damage scores. Thus, late maturing genotypes do not necessarily sustain lower levels of damage by grain mold. Even though the accessions used in our study exhibited a broad range of panicle types, relative panicle compactness seemed to have little impact on expression of resistance or susceptibility to grain mold damage. This is consistent with previous reports (Williams and Rao 1981, Ibrahim et al 1985, Mukuru 1992).

Physical kernel attributes may become more important factors in resistance to grain mold after physiological maturity (Castor and Fredriksen 1980). Sorghum kernels with more corneous endosperm were more resistant to grain mold than those with floury endosperm (Ibrahim et al 1985, Jambunathan et al 1992, Mukuru 1992). These observations led Jambunathan et al (1992) and Mukuru (1992) to conclude that grain mold resistance in sorghum cultivars with white pericarp was mostly due to kernel hardness. In our study, however, resistance to grain mold was not always associated with the more corneous endosperm texture in white or red pericarp sorghums without pigmented testa. Studies at ICRISAT (1985) have identified hard-seeded white sorghum lines with decreased capacity to support fungal colonies. In our study, increased levels of resistance to grain mold in brown sorghums was not associated with endosperm texture (Tables III and IV). Several other studies have also reported that the presence of pigmented testa in brown sorghums confers a greater effect than endosperm texture on reducing grain mold damage (Glueck and Rooney 1980, Weitz et al 1983, Bandyopadhyay et al 1988).

In general, darker kernel color was associated with increased resistance to grain mold in our study. This could result from the presence of higher levels of free phenolic compounds that occurred in kernels with darker pericarp than in kernels with a white pericarp (Doherty et al 1987). Nevertheless, we identified mold resistant genotypes from all kernel color categories. Sorghum cultivars containing high tannin were more resistant to grain mold than low tannin sorghums (Harris and Burns 1973). This observation led some researchers (Harris and Burns 1973) to assume that resistance to grain mold in sorghum is conditioned by high molecular weight phenols (tannins). However, results from our study and others (Bandyopadhyay et al 1988, Jambunathan and Kherdekar 1990, Mukuru 1992) reveal that resistance to grain mold occurs in both high and low tannin sorghums. Even among brown sorghum

TABLE III
Kernel Physical and Chemical Properties of Mold Resistant and Susceptible White, Red, and Brown Sorghum Accessions from the Working Collection

	White Without Testa		White With Testa		Red		Brown	
Properties	**Resistant**	**Susceptible**	**Resistant**	**Susceptible**	**Resistant**	**Susceptible**	**Resistant**	**Susceptible**
Number of accessions	38	36	24	10	21	22	75	5
Days to flowering	83.79 a[a]	79.36 b	84.67 a	84.70 a	80.81 a	77.18 b	86.24 a	83.00 a
Panicle shape	5.40 a	5.14 a	6.58 a	7.00 a	5.52 a	5.50 a	5.99 a	6.60 a
Kernel weight (g)	2.75 a	2.63 a	2.87 a	2.55 b	2.55 a	2.63 a	2.87 a	2.26 b
Endosperm texture	2.17 a	2.39 a	3.00 a	3.20 a	2.57 a	2.86 a	3.36 a	3.20 a
Apigeninidin (A475/g)	0.50 a	0.57 a	0.67 a	0.75 a	0.90 a	0.80 a	0.72 a	0.81 a
Luteolinidin (A495/g)	0.49 a	0.58 a	0.68 a	0.77 a	0.93 a	0.83 a	0.67 a	0.82 a
Flavan-4-ols (A550/g)	0.01 a	0.01 a	0.06 a	0.05 a	0.72 a	0.48 b	0.40 a	0.07 b
Tannin (A550/g)	0.00 a	0.00 a	0.32 a	0.30 a	0.04 a	0.01 b	0.47 a	0.33 b

[a] Means within a row in each pair of columns followed by the same letter were not significantly different from each other at the $P = 0.05$ level based on a paired t-test.

accessions, higher levels of resistance to molding seemed to arise from the combined effect of tannin and flavan-4-ols. Since resistance to grain mold damage was not always related to a high concentration of tannin in brown sorghums (Table V), other phenolic compounds, such as free phenolic acids as well as physical kernel properties or some yet to be identified factors may be involved in resistance to grain mold damage in some brown sorghums (Waniska et al 1992).

Previous studies reported that kernels of mold resistant red sorghum cultivars lacking pigmented testa contained more flavan-4-ols than did susceptible cultivars (Jambunathan et al 1986, Jambunathan and Kherdekar 1990, Mukuru 1992). We confirmed this observation in a large number of sorghum accessions with diverse genetic background. While an inverse relationship was found between concentration of flavan-4-ols and fungal biomass (Jambunathan and Kherdekar 1990, Jambunathan et al 1991), flavan-4-ols did

TABLE IV
Country of Origin, Race, Mean Mold Rating, Days to Flowering (DTF), Physical and Chemical Kernel Properties of 52 Accessions

Accession	Origin	Race[a]	Color[b]	Rating	DTF	Weight[c]	Texture[d]	A475[e]	A495[f]	Flavan 4-ols[g]	Tannin[g]
IS-3722	Ethiopia	D	B(+)	1.0	84	2.16	2.75	0.60	0.51	0.68	1.34
IS-2821	Zimbabwe	C	B(+)	1.0	83	2.75	3.50	0.49	0.42	0.98	1.32
P-932062	Sudan	C	B(+)	1.0	80	3.71	4.00	0.90	0.79	1.17	0.73
IS-8545	Ethiopia	C	B(+)	1.0	83	2.34	4.00	0.94	0.84	0.75	0.68
IS-15070	Cameroon	C	B(+)	1.0	88	3.98	4.00	0.74	0.75	0.98	0.66
IS-9569	S. Africa	C	B(+)	1.0	80	3.16	4.00	1.35	1.19	1.26	0.82
IS-16046	Cameroon	C	B(+)	1.0	76	3.30	4.00	0.76	0.66	0.98	0.64
P-932027	USA	...	B(+)	1.0	82	2.99	4.00	0.77	0.70	1.10	0.55
P-932065	USA	...	B(+)	1.0	82	3.19	4.50	0.57	0.50	1.00	0.52
IS-6986	Sudan	DC	B(+)	1.0	78	3.32	4.25	1.09	1.13	1.06	0.69
IS-4225	India	D	B(+)	1.5	78	3.70	2.50	0.44	0.36	0.87	0.58
IS-9454	S. Africa	K	B(+)	1.5	76	4.39	4.00	0.75	0.63	0.74	0.61
IS-16100	Cameroon	GC	B(+)	1.5	78	2.79	5.00	0.79	0.65	0.11	0.69
IS-15676	Cameroon	C	B(+)	1.5	79	4.51	3.75	0.63	0.52	0.71	0.70
IS-15346	Cameroon	C	B(+)	1.5	89	3.57	3.75	0.40	0.34	0.82	0.40
P-956036	Zimbabwe	C	B(+)	1.5	76	2.73	2.75	0.56	0.57	0.03	0.08
IS-15991	Cameroon	C	B(+)	1.5	77	4.50	3.50	0.78	0.65	0.73	0.71
IS-16468	Cameroon	C	B(+)	1.5	96	2.98	3.75	0.99	0.84	0.19	1.11
IS-7822	Nigeria	G	B(+)	2.0	72	2.43	3.50	0.66	0.68	0.05	0.33
IS-2279	USA	KC	B(+)	2.0	89	2.57	3.75	1.82	1.97	0.10	0.33
IS-8070	Japan	C	B(+)	2.0	84	3.50	3.50	0.80	0.72	0.07	0.41
IS-0874	USA	K	B(+)	2.0	70	2.26	3.25	0.56	0.55	0.02	0.26
P-932127	USA	...	B(+)	2.0	72	2.73	3.50	0.52	0.53	0.05	0.33
IS-15106	Cameroon	CB	B(+)	2.0	84	3.22	3.50	0.57	0.46	0.10	0.42
IS-15067	Cameroon	C	B(+)	2.0	84	4.53	3.75	0.49	0.40	0.69	0.36
P-013931	USA	...	B(+)	2.0	72	2.48	3.25	0.42	0.42	0.04	0.29
IS-9746	Sudan	C	B(+)	2.5	86	2.91	3.00	0.67	0.71	0.05	0.21
IS-9323	S. Africa	K	B(+)	2.5	88	2.87	3.75	0.37	0.34	0.11	0.31
IS-12279	Zimbabwe	C	B(+)	2.5	70	3.02	3.50	0.27	0.25	0.04	0.24
IS-2317	Sudan	KC	B(+)	2.5	71	2.24	3.25	0.50	0.53	0.05	0.28
IS-7579	Nigeria	C	B(+)	3.5	84	2.88	3.75	0.48	0.44	0.08	0.37
P-955001	USA	...	B(+)	4.5	78	3.11	3.25	0.65	0.62	0.09	0.28
IS-8612	Uganda	C	R(–)	2.0	83	3.16	3.50	0.53	0.57	0.62	0.06
IS-1301	Australia	C	R(–)	2.5	83	2.82	2.25	0.73	0.77	1.14	0.07
IS-9334	S. Africa	K	R(–)	3.0	83	2.76	3.00	0.81	0.82	0.47	0.05
IS-2692	Uganda	C	R(–)	3.0	84	2.98	2.75	0.78	0.84	0.90	0.05
P-954164	Ethiopia	...	R(–)	3.5	88	3.20	2.50	0.31	0.28	0.33	0.02
P-932149	USA	...	R(–)	4.5	76	3.35	3.00	0.92	0.96	0.37	0.00
IS-0339	USA	DC	R(–)	4.5	76	3.49	3.00	1.17	1.24	0.41	0.00
IS-2740	Uganda	C	W(+)	2.5	84	2.47	2.50	0.37	0.39	0.06	0.30
IS-3441	Sudan	C	W(+)	2.5	83	2.93	2.75	0.61	0.64	0.09	0.36
IS-0919	Sudan	C	W(+)	3.0	80	2.86	3.50	0.69	0.61	0.08	0.28
IS-0862	USA	GK	W(+)	5.0	78	2.53	3.50	0.32	0.32	0.04	0.23
P-121186	USA	...	W(–)	2.0	66	3.32	2.00	0.35	0.37	0.01	0.01
P-954100	Ethiopia	GC	W(–)	3.0	78	3.91	2.25	0.43	0.38	0.01	0.00
IS-9370	S. Africa	K	W(–)	3.5	88	2.39	1.50	0.38	0.40	0.00	0.00
IS-10493	USA	K	W(–)	4.5	74	1.70	2.50	0.37	0.39	0.01	0.00
IS-0071	Mexico	DC	W(–)	5.0	84	3.52	3.00	0.27	0.26	0.00	0.00
IS-10524	USA	GK	W(–)	5.0	74	2.48	2.50	0.91	0.91	0.01	0.01
IS-7521	Nigeria	DC	W(–)	5.0	98	2.70	2.50	0.56	0.48	0.03	0.02
IS-10354	Israel	K	W(–)	5.0	73	2.63	2.25	0.52	0.55	0.00	0.02
P-954130	Ethiopia	...	Y(–)	3.5	80	2.44	2.75	0.51	0.51	0.00	0.00
LSD[h]				0.3	2	0.16	0.18	0.03	0.03	0.02	0.02

[a] C = caudatum, CB = caudatum-bicolor, D = durra, DC = durra-caudatum, G = guinea, GC = gunina-caudatum, GK = guinea-kafir, K = kafir, KC = kafir-caudatum.
[b] W = white, R =red, B = brown, Y = yellow kernel colors with (+) and without (–)testa.
[c] 100-seed weight (g).
[d] Endosperm texture.
[e] Apigeninidin/g.
[f] Lutheolinidin/g.
[g] Read at A550/g.
[h] Least significant difference (0.05).

TABLE V

Eigenvectors of the First Principal Component (PC1), Proportion of the Total Variance (PV) Explained by PC1, and the Correlation (*r*) Between PC1 Component Scores and Final Visual Grain Mold Damage Scores

Traits	Eigenvectors	
	Working Collection	Subset of Working Collection
Kernel color	0.46	0.44
Kernel weight	0.14	0.27
Endosperm texture	0.46	0.47
Apigeninidin	0.31	0.31
Flavan-4-ols	0.48	0.46
Tannin	0.48	0.46
PV	0.48	0.48
r	–0.44**	–0.75*

not directly inhibit the growth of fungal organisms in vitro (Schutt and Netzly 1991). Because apigeninidin inhibited the growth of fungal organisms in vitro, Schutt and Netzly (Schutt and Netzly 1991) suggested that flavan-4-ols accumulate in sorghum kernels as a biosynthetic precursor of apigeninidin. The concentration of apigeninidin and luteolinidin in sorghum seeds varied depending on kernel color. White sorghums devoid of testa had the lowest concentration of these compounds while red sorghums had the highest. Our principal component analysis showed that apigeninidin contributed to grain mold resistance although the concentration of both apigeninidin and luteolinidin among resistant and susceptible accessions did not follow a consistent trend.

In conclusion, we identified superior sources of resistance to grain mold in different races of sorghum and accessions from diverse geographical areas. We found that both physical and chemical kernel properties confer resistance to grain mold in different kernel color categories of sorghum. In red and brown pericarp kernels, phenolic compounds (tannins, flavan-4-ols) provide much of the defense against mold. The results from our study suggest that overall resistance to grain mold may not be explained by any one character, particularly in white sorghums without pigmented testa. A selection index developed to combine various kernel attributes was effective in distinguishing resistant and susceptible accessions. This method of screening germplasm may facilitate the development of highly resistant and agronomically acceptable parental lines and hybrids in an array of genetic background.

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