Breeding Grain Mold Resistant Sorghum Cultivars

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Sorghum (*Sorghum bicolor* (L.) Moench) is the fifth important cereal crop after wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), rice (*Oryza sativa* L.), and barley (*Hordeum vulgare* L.) in the world. It is cultivated in about 46 million ha with a total production of 62 million t (FAO 1998). Asia and Africa account 86% of the total area under sorghum, but their contribution towards total production is only 58% (FAO 1998). Nearly 90% of sorghum is grown in rainy season while postrainy season sorghum in India accounts for the remaining area. Sorghum grain yield potential is high. However, there is a gap of about 3 t ha^{-1} in yield between research station yield trials and farmers' fields in India (AICSIP 1994). This reduction in the realized grain yield at farm level is due to several abiotic and biotic constraints.

Grain mold is an important biotic constraint of sorghum and seriously compromises the grain yield and quality grains obtainable from improved cultivars. Grain mold occurs throughout the humid tropical and subtropical climates particularly when improved, short- and medium-duration cultivars that mature before the end of the rains are grown (Bandyopadhyay et al. 1988). It is caused by several non-specialized fungi. These include: *Fusarium monliforme* Sheld., *Fusarium pallidoroseum* (Cooke) Sacc., *Curvularia lunata* (Wakker) Boedijn and *Phoma sorghina* (Sacc.) Boerema, Dorenbosch, & van Kesteren (Bandyopadhyay et al. 1988, 1998).

Major efforts in breeding for grain mold resistance at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), and other places in India as well as USA have met with partial success in breeding together high resistance levels of grain mold and grain yield. Annual global losses due to grain molds have been estimated at US$ 130 million (ICRISAT 1992).

We have summarized in this paper the current efforts in breeding for resistance to grain mold with emphasis on ICRISAT work and outlined the future prospects.

Screening Techniques and Sources of Resistance

Following stringent techniques using sprinkler irrigation to maintain high humidity during the grain-filling period, with and without inoculation with conidial-mycelial suspension at Texas A&M University (USA) (Castor 1977) and at ICRISAT (Bandyopadhyay and Mughogho 1988), several sources resistant to grain mold were identified. These include both colored and white grain types. This method involved evaluating the materials grown under sprinklers, 14 days after physiological maturity after stratifying materials according to maturity groups—early, medium, and late (Stenhouse et al. 1998). A laboratory-based screening method has been developed recently and used to screen white-grained photoperiod sensitive materials, which could not be reliably screened using field-screening method. The photoperiod sensitive guinea lines identified by this method are IS 7326, IS 4963, IS 5726, IS 4011, IS 5292, and IS 27761 (Singh and Prasada Rao 1993). Other details of screening techniques have been provided by Bandyopadhyay et al. (1998).

Resistance Mechanisms

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Understanding the mechanisms or characters associated with resistance and their interactions is useful in breeding for improved resistant cultivars. Several grain, panicle, and glume characters contribute to resistance in varying levels. Grain characters include hardness, structure of endosperm, pericarp thickness and color, presence of testa, and wax layer. Hardness of the grain is a significant mechanism of mold resistance (Jambunathan et al. 1992; Kumari and Chandrashekar 1992; Audilakshmi et al. 1999). Kernel hardness and pericarp color differentially contribute to grain mold resistance in white, red, and brown pericarp sorghum accessions (Menkir et al. 1996).

At ICRISAT, the F_4 and F_6 progenies evaluated under sprinkler irrigation were selected for threshed grain mold rating (TGMR) below 3 on a 1–5 scale, where 1 indicates no mold and 5 represents >50% of threshed grain surface molded. The resulting 166 white-grained, 105 red-grained, and 194 brown-grained selections were evaluated for grain hardness and grain mass. The characteristic features of white-, red-, and brown-grained groups of selections are given in Table 1, and the correlations among these traits are given in Table 2. The results showed that:

- White- and red-grained mold resistant selections (lacking testa) were harder than brown-grained selections.
- Red- and brown-grained selections had higher levels of grain mold resistance and greater 100-grain mass.
- Ratio of hardness to grain mass in white-, red-, and brown-grained selections suggested that resistance in white and red grains might be partially due to hardness (Table 1).

Correlations between hardness, grain mass, and TGMR (Table 2) generally supported the above conclusions (Reddy et al. 1992).

Table 1. Characteristics of grain mold resistant selections of sorghum at ICRISAT, Patancheru, India, rainy season 1991.

Grain color	TGMR[1]	Hardness[2] (kg)	100-grain mass (g)
White	2.96±0.03	5.0±0.10	2.2±0.32
Red	2.40±0.03	5.2±0.09	2.4±0.05
Brown	2.60±0.02	4.6±0.08	2.5±0.04

1. TGMR=Threshed grain mold rating on 1-5 scale, where 1=no mold and 5=>50% of the threshed grain surface molded,
2. Pressure (kg) required for breaking the grain

Table 2. Correlation coefficients among grain hardness, grain mass, grain mold resistance in sorghum progenies of various grain colors at ICRISAT, Patancheru, India, rainy season 1991.

Grain color	Hardness vs Grain mass	Grain mass vs TGMR1	Grain mass vs TGMR[1]
White	0.53**2	-0.03	-0.20*2
Red	0.54**	0.15	-0.01
White	0.25**	0.01	0.05

1. TGMR=Threshed grain mold rating on 1-5 scale, where 1=no mold and 5=>50% of the threshed grain surface molded,

2. * Correlation significant at P=0.05. ** Correlation significant at P=0.01.

Thin pericarp, thick and contiguous surface wax layer, and grain integrity were also linked to resistance to grain mold (Glueck and Rooney 1980). Corneous endosperm types were more resistant than floury endosperm types (Glueck et al. 1977).

Presence of testa has been shown to be the single most important trait conferring grain mold resistance, and red pigmentation of pericarp to a lesser extent (Esele et al. 1993; Menkir et al. 1996). Both mechanisms of resistance are found only in pigmented sorghums, and therefore are unsuitable for breeding for food quality sorghum for grain mold resistance (Stenhouse et al. 1998). Rapid grain filling also seems to result in resistance to grain mold (Singh et al. 1995).

Panicle and glume traits have been shown to be associated with grain molds. Open panicles (as in the guinea sorghums) and long glumes were reported to reduce grain mold incidence (Glueck et al. 1977). Four guinea sorghum lines with loose panicles and hard white grains were found resistant to molds (Rao et al. 1995). Glume cover, length, and area is related to mold resistance (Mansuetus et al. 1990).

Pigmented glumes (phenolic compounds) offer some protection from molds (Mansuetus et al. 1988; Audilakshmi et al. 1999). Several phenolic compounds (apigeninidin, flavan-4-ols, and tannin) in mature grains reduce grain molds (Harris and Burns 1973; Jambunathan et al. 1986; Menkir et al. 1996; Audilakshmi et al. 1999). However, a search for phenols in grains of white-grained cultivars with major differences in resistance and susceptibility has failed to identify any phenolics that could form the basis for selection for resistance (Stenhouse et al. 1998).

Recently, antifungal proteins have been identified in sorghum grains and appear to play a role in protecting the grains from fungal attack (Singh et al. 1995; Audilakshmi et al. 1999). Endosperm of hard grains (resistant lines) contained more protein and prolamine than that of soft grains (susceptible lines). The role of proteins in the resistance to fungal infection in low-tannin lines has been documented (Kumari and Chandrasekhar 1992).

Thus, the mechanisms important in breeding white, grain mold resistant sorghums are: hard corneous endosperm, thin pericarp, thick wax layer on pericarp, fast grain filling rate, large glume coverage, pigmented glumes, and open panicles. Antifungal proteins may also play an important role.

Genetics of Resistance

General combining ability effects seemed to be important for grain mold resistance (Rana et al. 1978; Dabholkar and Baghel 1983). Through P_1, P_2, F_1, and F_2 generation mean analysis it was shown that inheritance of resistance to grain mold was governed by additive or partial dominance type of gene action (Murty et al. 1980). Other investigations with F_1, F_2, and BC_1 populations showed that inheritance of resistance to grain mold was governed by four independently segregating genes—two with complementary (dominant) interaction and the other two with additive interaction (Shivanna et al. 1994).

A recent study suggested that there are five quantitative trait loci (QTLs) for grain hardness, four for flouriness, two for mold after harvest, and three for mold during germination (Rami et al. 1998). No QTLs for 100-grain mass could be detected.

By using four parental lines with distinct caryopsis characters in F_1, F_2, and BC_1 populations, it was demonstrated that presence of pigmented testa ($B_{1\_}$ $B_{2\_}$), a red pericarp (R_Y_), a thin mesocarp (Z_), and an intensifier gene (I_) were all dominantly inherited. A pigmented testa was the single most important trait conferring mold resistance. The effect of red pericarp was enhanced by the presence of an intensifier gene. The effects of both pigmented testa and red pericarp were additive (Esele et al. 1993). The inheritance of grain hardness, grain density, germination percentage, decreased water absorption rate and fungal load were studied in a 11×11 half diallel, and found that additive gene action and additive $\times$ additive epistasis were important. The parents CMRP 4, B 75219, B 50501, and

SPV 775 were good parents for the above traits (Ghorade and Shekar 1996). In another study, grain density inheritance was reported to be non-additive (Rao et al. 1982).

Red grain color was dominant in F_1 hybrids of red-grained females and white-grained males (Reddy et al. 1992). It was found to be controlled by 2 to 3 interacting genes influenced by the type of cytoplasm (Khusnetdinova and El'konin 1987).

In another study, hardness was inherited dominantly in F_1 hybrids of soft red-grained females and hard white-grained males (Reddy et al. 1992). It was also demonstrated that both hardness in male parents and red color in the females inherited dominantly into F_1 hybrids, which were resistant to grain molds while the parents themselves were susceptible (Table 3). In another investigation, additive × additive epistasis was important for hardness (Ghorade and Shekar 1996). Flouriness (the converse of corneous endosperm that is hard) had recessive inheritance (Hou et al. 1997). The inheritance of grain weight, a trait negatively correlated with hardness, was additive (Rao et al. 1982; Nguyen et al. 1998) or partially recessive (Biradar et al. 1996). Predominance of additive gene action for large grain was also reported (Borikar and Bhale 1982). However, other investigations suggest predominance of dominance or partial dominance for larger grain size (Chandak and Nandanwankar 1983).

Inheritance of high tannin content in grain is predominantly additive, but not dominant in sorghum grain (Dabholkar and Baghel 1982; Chang et al. 1987; Rodrigues et al. 1998). Generation mean analysis including parents, F_1, F_2, BC_1, and BC_2 of three crosses showed that additive effects with significant epistasis controlled tannin production in the grain (Kataria et al. 1989; Rodrigues et al. 1998).

Effect of B_1 Gene

A large proportion of tannins in the grain is found in the testa layer and its presence is due to the complementary genes B_1 and B_2 (the genotype $B_{1\_}$ $B_{2\_}$ with brown testa, and the genotypes b_1b_1 b_2b_2, $B_{1\_}b_2b_2$, and $b_1b_1B_{2\_}$ without brown testa). As a result, the grains are brown in the former group of genotypes and white in the latter group (Rooney et al. 1980). The white-grained male-sterile lines and restorer lines usually carry the B_2 gene; hence their hybrids are usually white-grained. Segregation of the B_1 and B_2 genes in the white-grained R-lines (ICSR numbers 35, 72, 160, 165, 172, 89058, 93032, and 93033) and in the A-line, ICSA 88020, enabled us to develop hybrids segregating for white and brown grain. Eight hybrids were screened in a randomized complete block design under sprinklers and the white- and brown-grained heads were scored separately for panicle grain mold rating (PGMR) on 1–9 scale, where 1 indicates free from molds and 9 represents >50% mold. Furthermore, white- and red-grained panicles were threshed separately, and scored for TGMR. The threshed grain from the hybrids multiplied in the previous postrainy season was sprayed with inoculum of *Fusarium* and *Curvularia* species during germination in petri dishes in the laboratory, and scored for germinating grain mold rating (GGMR).

The brown-colored hybrids were highly resistant compared to white-grained hybrids for PGMR and TGMR, indicating the role of a single dominant gene (B_1) in the resistance under field conditions (Table 4). But the difference in GGMR in the laboratory between the white-grained and the red-grained hybrids was absent. The score for PGMR of the nine parents ranged from 5.3 to 7.7, whereas it ranged from 6 to 9 for TGMR, and from 4.5 to 9.0 for GGMR.

Table 3. Performance of the selected red-grained sorghum hybrids and their parents at ICRISAT (Patancheru) and Bhavanisagar, India, rainy season.

Pedigree	Grain yield ($t\ ha^{-1}$) IC[1]	Grain yield ($t\ ha^{-1}$) BS[1]	Days to 50% flowering	Plant height (m)	Agronomic score[3]	Grain mold rating[4]	Grain hardness[5] (kg)	Flavan-4-ols ($A_{550}g^{-1}$dry mass, H^+/Me extract)

Hybrids								
ATx2755 xICSR41	3.5	5.0	67	1.8	1.6	2	5.2	4.7
ATx2754 xICSR3	3.7	5.6	67	1.7	1.7	2	5.2	3.3
ATx2755 xICSR111	3.5	4.8	65	1.8	1.8	2	4.6	7.5
Parents								
BTx2754	2.2	3.2	69	0.9	3.4	3	2.8	6.2
BTx2755	2.2	3.0	68	1.0	3.3	4	2.7	5.2
ICSR 3	2.4	3.3	70	1.5	2.9	4	6.2	0.1
ICSR 41	2.6	3.2	72	1.6	2.3	3	4.8	0.2
ICSR 111	3.0	5.0	70	1.5	2.1	4	5.1	0.1
Control								
ICSH (153)								
CSH (11)	4.0	5.3	66	1.9	1.3	4	3.4	0.2
SE ±	0.4	0.5	0.6	0.03	0.002	0.002	0.28	0.46
Mean	2.9	3.6	67	1.6	2.7	3.3	4.1	3.5
CV (%)	20	23	3	6	21	12	12	13

1 IC=ICRISAT mean of several trails in high and low fertility fields , with and without sprinkler irrigation.

2 BS=Bhavanisagar high fertility without irrigation.

3 Scored on a 1 to 5 scale, where 1= most desirable and 5=least desirable.

4 Based on threshed grain mold rating (TGMR) on a 1 to 5 scale, where 1= no molds and 5=> 50% of threshed grain surface molded

5. Pressure (kg) required to break the grain.

Partially dominant or dominant genes in F_1 hybrids of cytoplasmic male-sterile lines controlled flavan-4-ols (Reddy et al. 1992). Two genes with greater dominance effects and duplicate type of epistasis determined tannin content in the leaves (Chariya Srichantub 1988; Kumar and Singh 1998).

A single dominant gene controls reddish purple glumes (Mani 1986). Other studies showed a single dominant gene or two genes with inhibiting interaction for red glume over straw (Swarnalata et al. 1987), or one gene with partial dominance (Deshmukh et al. 1980). Two to three interacting genes influenced by cytoplasm control glume length and coverage (Khusnetdinova and El'konin 1987). Information on genetics of grain filling rate is scanty, although significant variation for grain filling rate was observed among sorghum genotypes (Toure et al. 1992).

Information on the genetics of resistance mechanisms is inadequate. The genetics depends on the type of materials used, mechanisms studied, the measurements taken, the level of humidity experienced, and the interference from head bug (*Calocoris angustatus* Lethiery) damage in the measurement of grain mold infection.

Breeding for Grain Mold Resistance

Varieties or restorer lines

The breeding efforts at ICRISAT and other breeding programs until 1990 aimed at the genetic improvement for mold resistance of varieties and restorer lines. The breeding program at ICRISAT can be divided into five phases:

1.White-grained lines from natural screening of white-grained introductions and populations.

2..White-grained lines from segregating white-grained populations screened under artificial conditions.

Table 4. Grain mold severity rating of the sorghum hybrids carrying white and red grain color genes evaluated at ICRISAT, Patancheru, India, rainy season 1992[1].

	Panicle grain mold rating (PGMR in Field[2])			Threshed grain mold rating (TGMR) in field[3]			Germinating grain mold rating in laboratory[4]		
Hybrid	White	Brown	Average	White	Brown	Average	White	Brown	Average
ICSH 93141	5.7	3.0	4.3	7.0	3.0	5.0	8.5	9.0	8.8
ICSH 93142	5.0	3.0	4.0	6.3	5.0	5.7	6.0	8.0	7.0
ICSH 93143	5.7	3.0	4.3	6.7	3.0	4.8	4.5	5.0	4.8
ICSH 93144	6.0	2.0	4.0	6.0	2.0	4.0	6.5	4.0	5.3
ICSH 93145	6.0	4.7	5.3	6.7	6.0	6.3	7.5	8.0	8.0
ICSH 93146	5.3	2.7	4.0	5.7	3.0	4.3	5.0	6.5	5.8
ICSH 93147	5.7	3.0	4.3	7.0	3.0	5.0	9.0	6.5	7.8
ICSH 93148	5.7	4.0	4.8	6.7	3.0	4.8	8.0	8.5	8.3
Mean	5.6	3.2	4.4	6.5	3.5	5.0	6.9	7.0	6.9
SE ±									
Hybrids			0.05			0.07			0.05
Grain color			0.03			0.04			0.02
Hybrids x Grain color			0.08			0.10			0.06
CV (%)			14			19			6

1. Split-plot design, under sprinklers in the field.
2. Panicles evaluated on a 1 to 9 scale, where 1=<5% grain with mold, 9= 80% grains with mold.
3. Threshed grain evaluated on a 1 to 9 scale, where 1=no mold, 9=50% grain surface area molded.
4. Split=plot design with two replications, germinated seeds inoculated with mixed spore suspension *of Fusarium moniliforme*, *F. pallidoroseum*, and *Curvularia lunata*.

3.White-grained lines from segregating populations of white-grained high-yielding lines × red-grained mold resistance sources crosses.

4.Red-grained lines from segregating populations of white grained lines × red-grained sources crosses.

5.White-grained guinea lines improvement.

White-grained materials under natural screening. The earliest released early-maturing hybrid CSH 1, which was popular in the 1960s and 1970s in India, is highly susceptible to grain mold as it matures early in peak rainy season. This shortcoming led to the search for lines tolerant to grain molds. Several derivatives of zera zera germplasm from Sudan and Ethiopia were less susceptible to molds when screened under natural conditions. The approach was to select materials under multilocation testing for good food quality types with less grain deterioration in rainy season. As a result hybrids such as CSH 5 and CSH 6 and varieties such as CSV 4 that deteriorated less under rain were developed in India. The fact that derivatives of zera zera material were superior in resisting grain deterioration compared to earlier cultivars (CSH 1) confirmed their inherent tolerance. This program continued up to mid-1970s.

White-grained materials under artificial screening. A screening technique for mold resistance under sprinklers with artificial inoculation by grain mold fungi was developed by the mid-1970s. Several zera zera germplasm accessions and their derivatives, and high-yielding and adapted lines from various breeding programs were used extensively in crosses from mid-1970s onwards. In particular E 35-1, CS 3541, SC 108-3, SC 108-4-8, and SC 120 were used by ICRISAT breeders. The crosses were advanced to F_2 in which selection for height, days to flower, and agronomic desirability were practiced. The progenies from F_3/F_4 onwards were evaluated under artificial screening and the high-yielding lines with mold resistance were selected (Murty et al. 1980). This program continued up to late 1970s.

White-grained materials from colored-grain sources. The zera zera based program has been highly successful and widely followed at ICRISAT and other locations in India and in USA. Zera zera material dominates the elite improved germplasm. Serious concerns have been expressed about the narrowing of the genetic base. Therefore, concerted efforts were made to broaden the base of the parents used in developing high-yielding, white-grained mold-resistant varieties. Grain mold resistant lines (mostly colored, with or without testa) (Table 5) were used in crosses with white-grained, high-yielding (zera zera) lines. For the first time, several F_1, F_2, and F_3 progenies derived from crosses between mold-resistant, colored-grain sorghum and susceptible white-grained sorghum were screened under an artificial environment to determine if white-grained segregates with high mold resistance could be identified (ICRISAT 1984). The F_1s from crosses between a mold susceptible colored line (Q 953) and mold susceptible white-grained lines (SPV 104 and SPV 351) had colored grain but were susceptible to mold. Identification of white-grained, mold resistant segregates in 1983 confirmed that grain mold resistance was not always associated with colored grain (ICRISAT 1984) and it could be transferred to white-grained lines. In the following rainy season, 597 mold resistant lines were selected based on TGMR, of which 2 had score 1, 134 had score 2, and 461 had score 3 (ICRISAT 1985). These were further selected for agronomic desirability. Thus, 36 white-grained mold resistant lines derived from parents were selected for further testing. The performance of some of the selected lines is given in Table 6. This program of breeding white-grained mold resistant lines was continued through the mid-1980s.

Red-grained lines. The white-grained selections showed only moderate levels of resistance, and their plant type was not appropriate. The white-grained mold resistance breeding program had limited success. Agronomic desirability, plant type, and resistance levels in the lines with red pericarp without testa (with flavan-4-ols) showed considerable advantage compared to white-grained selections (Table 7). However, red-colored grains are not acceptable for food preparation in some areas. Therefore, breeding for red-grained mold resistant lines, which was continued until the late 1980s, received reduced emphasis after the 1980s.

White-grained guinea lines. From early 1990s, the emphasis was given to exploit white-grained guinea sorghums, which were identified after laboratory screening as resistant to grain mold. Both pedigree and population breeding approaches have been used to develop derivatives that combine white grain color with plant type and yield levels of improved sorghum, yet retaining the guinea grain and glume characters (Stenhouse et al. 1998). Some success has been achieved and a number of dwarf early lines with semi-compact heads and guinea grain and glumes have been produced through pedigree breeding. Similar breeding efforts to produce improved guinea sorghums are underway in several programs in West Africa (Stenhouse et al. 1998). However, neither red-grained nor white-grained guinea products have been screened or selected for mold resistance under artificial screening. The data on grain yield, mold score, and agronomic traits for improved guinea lines are given in Table 8.

Table 5. Grain mold resistant sources of sorghum used as parents in breeding grain mold resistant varieties/restorers.

Souce	Origin	Race	Grain color	Days to 50% flowering	Plant height (m)	Panicle grain mold score[1]	Threshed grain mold score[2]	Grain size (mm)	Grain mass (g kg^{-1})	Grain hardness
Parents contributed to white-grained varieties										
IS2333	Sudan	Caudatum	Reddish brown	81	4.1	2.4	2.0	3.5	3.20	Partly hard
IS18165	Lebanon	Caudatum	Light red	66	2.7	2.5	2.0	2.5	1.97	Partly hard
IS20844	China	Caudatum	Reddish brown	54	1.4	2.0	1.8	2.8	2.53	Mostly hard
IS25017	Sudan	Caudatum	Straw	73	3.7	2.3	2.7	2.8	2.39	Partly hard
Parents contributed to color-grained varieties										
IS7972	Nigeria	Guinea	Light red	127	3.7	-	-	4.0	5.64	Partly hard
IS18165	Lebanon	Caudatum	Light red	66	2.7	2.5	2.0	2.5	1.97	Partly hard
IS20708	USA	Bicolor	Light red	61	2.5	3.0	-	2.5	2.96	Partly hard
IS20844	China	Caudatum	Reddish brown	54	1.4	2.0	1.8	2.8	2.53	Mostly hard
IS21509	Malawi	Guinea Caudatum	Light red	63	2.8	2.0	2.0	2.5	1.90	Partly hard
IS24996	Sudan	Guinea Caudatum	Reddish brown	78	4.1	1.8	2.0	4.0	4.12	Mostly hard
IS25017	Sudan	Caudatum	Straw	73	3.7	2.3	2.7	2.8	2.39	Partly hard
IS25032	Sudan	Guinea Caudatum	Brown	78	3.5	2.3	2.1	3.5	3.57	Mostly hard
Parents contributed to guinea-varieties										
IS2825	Zimbawe	Caudatum	Reddish brown	53	1.7	2.0	1.8	4.0	3.27	Soft
IS7072	Sudan	Caudatum bicolor	Light brown	69	2.5	1.8	1.8	3.0	3.06	Partly hard
IS14384	Zimbawe	Guinea	Light red	57	3.4	2.2	2.1	1.8	2.46	Partly hard
IS21059	Kenya	Caudatum	Light brown	120	3.7	-	-	3.0	2.46	Mostly soft

IS25025	Sudan Durra Caudatum	Reddish brown	73	3.1	2.0		2.0	3.5	3.00	Mostly soft
IS25032	Zimbawe Guinea Caudatum	Brown	78	3.5	2.3		2.1	3.5	3.57	Mostly soft

1. Panicles evaluated on a 1to 9 scale, where 1= <5% grains with mold, 9=80% grains with mold.
2. Threshed grains evaluated on a 1to 9 scale, where 1=no mold, 9=50% grain surface area molded.

Table 6. Selected entries from a yield trail of 36 white grained mold resistant sorghum breeding lines at ICRISAT, Patancheru, India, rainy season 1996.

Entry	Pedigree	Days to 50% flowering	Plant height (cm)	Grain yield ($t\ ha^{-1}$)	Moldscore[1]
ICSV 96105	(IS 25015 x ICSV 233) -16-2-2-2-3-1	71	2.5	3.23	3.9
ICSV 96087	(IS 2333 x ICSV 88032) -3-1-1-2-1-1	69	1.7	3.21	4.9
ICSV 96102	(IS 25017 x ICSV 233) -6-4-2-1-1-2	72	2.4	3.06	4.8
ICSV 95010	(IS 25017 x ICSV 233) -16-2-2-2-2-1	73	2.8	3.04	4.3
ICSV 96089	[(IS18165xICSR33)xIS18165)] -2-1-1-1-1-1	70	1.7	2.77	4.3
ICSV 96094	(IS 20844 x ICSV 88022) -4-2-1-2-1-1	63	1.7	2.41	3.5
ICSV 112	Control	75	1.9	2.65	5.5
ICSV 14	Control	73	2.5	3.42	6.1.
ICSV 13	Control	72	0.9	3.01	7.5
Total mean		70	2.0	2.8	5.4
SE±		1.0	0.04	0.3	0.5
CV (%)		1.9	2.6	12.4	14.8

1. Grain mold evaluated on a 1 to 9 scale , where 1= free from mold and 9= >50% of the grains with mold.

Source: ICRISAT (1997).

Table 7. Selected entries from a yield trail of 39 colored-grain sorghum lines at ICRISAT, Patancheru, India, rainy season 1996.

Entry	Pedigree	Days to 50% flowering	Plant height (cm)	Grain yield ($t\ ha^{-1}$)	Mold score[1]

ICSV 95023	(IS 25032 x ICSV 710) -11-1-2-1-1	72	2.1	3.24	3.3
ICSV 96127	(IS 20708 x ICSV 88041) -1-1-1-1	63	1.5	3.01	3.8
ICSV 95039	(IS 18165 x ICSV 88936) -1-1-1-1-1	63	1.5	2.74	2.4
ICSV 96141	(IS 24996 x ICSV 88035) -3-1-1-1-1-1	66	1.4	2.74	3.8
ICSV 96136	(IS 21509 x ICSV 430) -10-2-1-1-2	67	1.7	2.71	3.4
ICSV 112	Control	77	1.8	2.70	6.2
Trail mean		68	1.7	2.44	3.8
SE±		1.9	0.06	0.5	
CV (%)		4.0	5.1	12.5	21.9

1. Grain mold evaluated on a 1 to 9 scale , where 1= free from mold and 9= >50% of the grains with mold.

Source: ICRISAT (1997).

Population improvement

Development of random mating population was initiated in 1984 by incorporating white-grained, mold resistant breeding lines; colored-grain, mold resistant lines; and high-yielding improved lines into ms_3 US/R and US/B bulks. By the end of 1988, four random matings had been carried out (Stenhouse et al. 1991). Half-sib family selection was carried out for two cycles and then random mated. Several guinea lines were incorporated twice thereafter into this population, which underwent four random matings before selection. However, the population improvement program, though initiated in 1984, has not been fully exploited at ICRISAT.

Seed parents

Male-sterile lines available at ICRISAT before 1989 were not developed with any emphasis on resistance for pests or diseases. During ICRISAT's fifth phase of research from 1990 to 1997, efforts were made to develop male-sterile lines specifically resistant to different yield limiting factors. Several germplasm lines with putative resistance to grain mold were identified during 1980 to 1990. The grain color in all lines is brown (B), red (R), or light red (LR). The most promising lines are IS 2501 (B), IS 2815 (LB), IS 3436 (LR), IS 10288B (LR), IS 10475B (LR), IS 10646 (B), IS 21599 (LR), and IS 23585 (RB) (Table 9). These were tall and mostly photoperiod sensitive and were not suitable as male-sterile lines, because they are poor yielders in the rainy season. Hence, these resistant lines were crossed with high-yielding maintainer lines (A_1 cytoplasm) such as ICSB 11, ICSB 17, ICSB 37, ICSB 42, ICSB 51, and ICSB 70, which are susceptible to grain mold. Selection for highly heritable traits such as days to flower, plant height, and grain color was practiced in F_2 generation and the resulting F_3s were screened following the modified screening technique as outlined by Bandyopadhyay et al (1998). Grain mold resistance score (GMRS) on panicle and on threshed grain on 1 to 9 scale were taken.

Table 8. Selected entries from a yield trail of 11 derivatives of guinea x caudatum sorghum crosses at ICRISAT, Patancheru, India, rainy season 1996.

Entry	Pedigree	Days to Flowering	Plant Height (cm)	Grain Yield (t ha^{-1})	Mold Score[1]
ICSV 95023	(IS 25032 x ICSV 710)-11-1-2-1-1	72	2.1	3.24	3.3
ICSV 96127	(IS 20708 x ICSV 88041)-1-1-1-1	63	1.5	3.01	3.8
ICSV 95039	(IS 18165 x ICSV 88936)-1-1-1-1-1	63	1.5	2.74	2.4
ICSV 96141	(IS 24996 x ICSV 88035)-3-1-1-1-1-1	66	1.4	2.74	3.8
ICSV 96136	(IS 21509 x ICSV 430)-10-2-1-1-2	67	1.7	2.71	3.4
ICSV 112	Control	77	1.8	2.70 `	6.2
Total mean		68	1.7	2.44	3.8
SE ±		1.9	0.06	0.5	
CV (%)		6.0	5.1	12.5	21.9

1. Grain mold evaluated on a 1 to 9 scale, where 1=free from mold and 9 =>50% of the grains with mold.

Source: ICRISAT (1997).

Table 9. Grain mold resistant sources used as parents in breeding seed parents at ICRISAT, Patncheru, India.

Source	Origin	Race	Grain color	Days to 50% flowering	Plant height (m)	Panicle grain mold score1	Threshed grain mold score2	Grain size (mm)	Grain mass (g 100-1)	Grain hardness
Phase 1										
IS 2501	Sudan	Caudatum	Brown	83	2.0	-	-	4.5	1.65	Soft
IS 2815	Zimbabwe	Caudatum	Light Brown	78	2.0	-	-	4.0	3.57	Mostly soft
IS 3436	South-Africa	Kafir bicolor	Light Red	57	1.6	-	-	4.0	3.45	Partly hard
IS 10288B	USA	Caudatum bicolor	Light Red	52	1.3	5.0	-	2.8	2.80	Partly hard
IS 10475B	USA	Kafir bicolor	Light Red	56	1.1	5.0	-	3.0	3.56	Partly hard
IS 10646	USA	Caudatum bicolor	Brown	67	1.3	5.0	-	2.5	2.00	Partly hard
IS 21599	Malawi	Guinea	Light Red	74	3.7	2.4	1.8	2.8	2.02	Mostly hard
IS 23585	Ethiopia	Guinea Caudatum	Brown	75	3.1	2.0	2.0	3.0	3.11	Mostly soft

Phase 11										
ICSB 362	Bred line	-	White	64	1.8	5.7	5.1	-	3.30	Hard
ICSB 364	Bred line	-	White	64	1.7	6.6	5.3	-	3.10	Soft
ICSB 383	Bred line	-	Brown	67	2.0	5.4	3.8	-	3.10	Soft
ICSB 391	Bred line	-	Red	64	2.0	6.7	5.6	-	3.40	Hard
ICSB 392	Bred line	-	Red	68	1.6	6.5	5.3	-	3.80	Partly hard
ICSB 393	Bred line	-	Red	67	1.9	6.4	5.2	-	3.40	Hard
ICSB 403	Bred line	-	Brown	68	1.9	5.3	3.1	-	2.80	Hard
ICSB 405	Bred line	-	Red	64	1.6	6.5	5.8	-	3.60	Hard
IS 14375	Zimbabwe	Guinea	Red	69	3.0	2.2	2.1	1.8	2.10	Partly hard
IS 14380	Zimbabwe	Guinea	Light red	68	3.2	2.0	2.4	1.8	2.26	Mostly hard
IS 14384	Zimbabwe	Guinea	Light red	69	3.3	2.2	2.1	1.8	2.46	Partly hard
IS 14385	Zimbabwe	Guinea	Light brown	70	3.4	2.0	2.3	1.8	1.71	Mostly hard
IS 14390	Swaziland	Guinea	Light red	69	3.1	2.4	2.4	1.8	1.71	Partly hard
IS 25015	Sudan	Guinea caudatum	Gray	83	3.7	2.4	2.4	3.5	3.30	Partly hard
IS 25060	Ghana	Guinea caudatum	Reddish brown	79	4.2	2.0	2.0	3.0	3.00	Soft
IS 8614	Uganda	Caudatum	Reddish brown	56	1.1	1.6	1.8	3.0	3.58	Soft
IS 9308	South Africa	Caudatum	Reddish brown	56	2.3	2.2	1.7	3.0	2.87	Soft
IS 13817	South Africa	Caudatum	Reddish brown	56	2.2	1.6	1.8	3.0	2.85	Mostly soft
IS 13885	South Africa	Guinea	Light red	72	3.2	2.2	1.6	2.8	1.80	Partly hard
IS 14332	South Africa	Guinea	White	68	3.1	2.9	3.2	1.8	1.99	Mostly hard
IS 14388	Swaziland	Durra Caudatum	Reddish brown	55	1.7	1.2	1.8	2.0	1.96	Soft

1. Panicles evaluated at 1 to 9 scale, where 1= <5% grains with mold , 9= >80% grains with mold.
2. Threshed grains evaluated on a 1 to 9 scale, where 1= no mold, 0= >50% grain surface area molded.

The panicle GMRS is based on the scale where 1 means below 5% mold infected grain, and 9 indicates >80% mold infected grain. The threshed grain GMRS is based on the scale where 1 represents no mold on the surface of grain and 9 indicates >50% surface of the grain molded. Selection among families was based on panicle and threshed

GMRS and selection for high-yielding and agronomically desirable plants was practiced within the selected resistant families (Fig. 1). This procedure was continued from F_3 to F_7. Test-crossing with A_1 cytoplasm was followed simultaneously from F_4 onwards and the selected resistant progenies with male-sterility maintainers were converted into male-steriles through backcrossing. The A/B-lines obtained were evaluated for other characters.

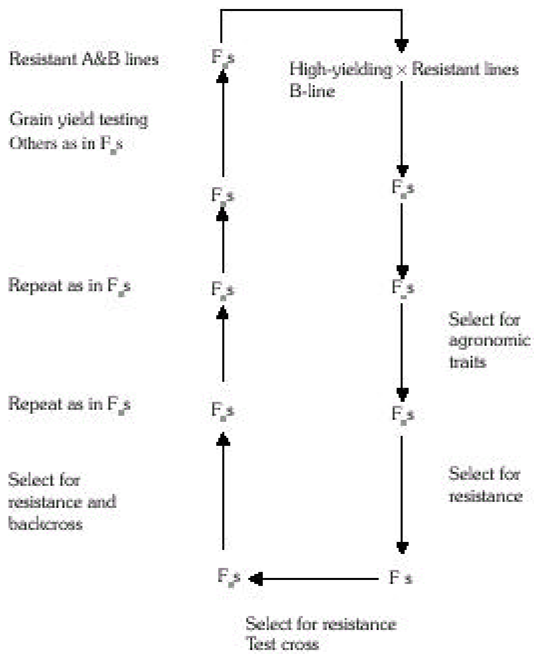

Figure 1. Method of breeding for grain mold resistant male-sterile lines in sorghum.

Fifty-eight seed parents with A_1 cytoplasm were thus produced at ICRISAT. Of these, 35 were white-grained, 20 red-grained, and three were brown-grained. The data on various agronomic characters, grain yield, and grain mold resistant sources were put in a web page (http://grep.icrisat. cgiar.org/). Performance of some selected A/B-lines is given in Table 10. Several resistant sources (IS 2815, IS 21599, IS 10288, IS 3436, IS 10646, IS 10475, and IS 23585) contributed to these 58 male-sterile lines. Of these, IS 2815 contributed to nearly more than 50% of the derivatives.

Various crossing systems were analyzed for their efficiency in producing desirable resistant lines in various grain colors. Biparental crossing system was superior to the backcross or three-way cross system both in terms of grain mold levels and number of desirable selections (Table 11). Also, the grain mold resistant sources, IS 9470 with A1 (milo), A2, A3, and A4 (Maldandi), and IS 15119 with A3 and A4 (Maldandi) cytoplasms were converted into male-sterile lines.

The above program was based on colored-grain resistant sources. Diversification of grain mold resistant male-sterile lines with guinea lines (Table 9) is being targeted in the second cycle of seed parents improvement, which began in 1999.

Hybrids

The selected grain mold resistant hybrids, ICSH 91200 (ATx2755 × ICSR 41), ICSH 91201 (ATx2754 × ICSR 3), and ICSH 91202 (ATx2755 × ICSR 111) (Table 3), obtained by crossing mold susceptible, red-grained female lines and white-grained susceptible male lines continued to maintain grain mold resistance in the third consecutive screening (Reddy and Singh 1993). They produced 5.0 to 5.6 t ha^{-1} grain yield while the mold susceptible control hybrid ICSH 153 yielded 6.4 t ha^{-1} (SE ±0.17).

Some more hybrids were derived by crosses between white-, red-, and brown-grained pollinators (bred by ICRISAT), and the red-grained but mold susceptible female lines developed at Texas, USA. Comparison of females, restorers, and their fertile hybrids for grain mold resistance is given in Table 12.

Table 10. Performance of some selected grain mold resistant sorghum and parents.

B-line	Pedigree	Threshed grain mold score[1]	Days to 50% flowering	Plant height (m)	Agronomic score	Grain yield (t ha^{-1})	Grain size (g 100^{-1})	Grain color
ICSB 353	(ICSB 11 x IS 2815) -2-1-2-1-2	5.1	70	1.7	2.3	3.8	3.1	White
ICSB 355	(ICSB 11 x IS 2815) -12-1-1	3.6	68	1.5	3.0	3.4	3.3	White
ICSB 376	(ICSB 11 x IS 2815) -43-1-2-1	5.1	75	1.7	2.0	4.2	3.5	White
ICSB 377	(ICSB 11 x IS 2815) -48-1-1	3.6	68	1.6	2.3	4.6	3.2	White
ICSB 395	(ICSB 37 x IS 10475B) -11-1--1-2	4.8	70	1.4	2.7	3.5	2.9	White
ICSB 402	(ICSB 42 x IS 23585) -1-7-1-1-1	3.3	69	1.5	2.0	4.0	3.6	White
ICSB 369	(ICSB 11 x IS 2815) -30-1-3-1-1	4.3	69	1.7	2.3	3.6	3.1	Red
ICSB 371	(ICSB 11 x IS 2815) -32-1-1-3-2-2	4.6	69	1.7	2.3	4.5	3.1	Red
ICSB 388	(ICSB 37 x IS 21599) -4-1-3-2-1-2	5.1	68	1.9	2.7	3.8	3.1	Red
ICSB 383	(ICSB 17 x IS 10646) -5-1-2	3.8	69	1.8	1.7	4.7	3.1	Brown
Control 296B		8.4	83	1.1	3.0	4.0	3.3	White

1. Threshed grains evaluated on a 1 to 9 scale, where 1=no mold on the surface of the grain and 9= >50% surface of grain with mold.

Grain mold resistance was dominant in brown-grained hybrids of brown-grained males × red-grained females and in red-grained hybrids of red-grained males × red-grained females; and over dominant in red-grained hybrids of white-grained males × red-grained females. Red-grained but grain mold susceptible females and red- and brown-grained but resistant males, which were known to contain flavan-4-ols in quantities sufficient to maintain resistance, were the parents. The flavan-4-ols might have been inherited as a dominant trait resulting in resistant hybrids. Hardness in white-grained males could have contributed to the enhanced resistance expressed by white-grained hybrids.

Table 11. Panicle grain mold resistance scores in the progenies derived from different crossing systems, ICRISAT, Patancheru, India 1992 rainy season.

Cross	Score[1] Mean (±)	Minimum	Maximum	No.of progenies
White grain				
Biparental cross	2.8 (0.00)	1.7	3.0	259
Backcross[2]	2.9 (0.02)	2.6	3.0	15
Three-way cross[3]	2.8 (0.02)	2.4	3.0	24
Red grain				
Biparental cross	2.5 (0.02)	1.7	3.0	210
Backcross	2.6 (0.06)	1.7	2.8	13
Three-way cross	2.6 (0.05)	2.2	2.8	11
Brown grain				
Biparental cross	1.8 (0.03)	1.7	2.4	30
Backcross	1.9 (0.04)	1.7	2.0	2
Three-way cross	2.5 (0.04)	2.2	2.8	6

1. Grain mold evaluated on a 1 to 9 scale, where 1=no mold, 9= >50% surface of grain with mold.
2. Backcross to resistant parent.
3. Two susceptible parents and one resistant parent.

Table 12. Greain mold scores on panicles in hybrids and their parents at ICRISAT, Patancheru, India, 1992 rainy season

Males		Score of	Hybrids	
Grain color	Score[1]	red-grained females	Grain color	Score
White	7.3 (4)[2]	7.0 (4)	Red	6.0 (4)
Red	5.1 (48)	6.9 (13)	Red	4.8 (48)
Brown	3.5 (5)	7.2 (5)	Brown	4.2 (5)

1. Score on 1 to 9 scale, where 1=free from molds, 9= >50% grain surface area molded.
2. Numbers in parentheses indicate the number of lines/hybrids on which the means are based.

Source: ICRISAT (1993).

The investigations at ICRISAT clearly demonstrated that it was possible to produce grain mold resistant hybrids from the existing materials if appropriate parents are crossed. However, grain mold resistance was low in white-grained hybrids compared to other grain color types.

Limitations

Several mechanisms are known to contribute to resistance. Breeding for white-grained mold resistant lines has exploited only hardness in the grain without affecting grain food quality. For example, hard grains are not suitable to make some foods such as *roti* (India), *injera* (Ethiopia), and *kisra* (Sudan). Further hardness limits the grain size, while the farmer looks for bold attractive grains. Glume pigmentation and glume cover can be used only to the extent that they do not lead to grain discoloration or threshing problems. Open panicle character of guinea are yet to be fully exploited in breeding white- grained mold resistant sorghum. Openness in panicles beyond a limit leads to poor productivity. Fast grain filling helps in increasing resistance levels, but measurement of this trait is difficult and limits the scope to evaluate large populations as required in breeding. Therefore, in areas where improved white-grained sorghums are important, such as in India, the options are numerous; but their effects on increase in grain mold resistance are meager especially in bold grains. In other parts of Africa, where hard white grain is preferred in food preparation (*tô*) the characters associated with guinea sorghums (hard corneous endosperm, open panicles, and extensive glume coverage) can be exploited.

Identification of markers for antifungal proteins is also expected to be useful. However, as antifungal proteins co-evolved with fungal pathogens in a particular plant species, it is doubtful if such proteins give complete protection from mold. The true potential of antifungal proteins is likely to be achieved only when they are deployed against fungal pathogens with which they have not co-evolved. Hence, transformation should be used for transfer of antifungal proteins between species, which is a difficult process.

Flavan-4-ols in red grain (without testa), and tannins and flavan-4-ols in grains (with testa) are strong and stable mechanisms, which may be combined with increased grain test weight. However, the areas where sorghum with a pigmented pericarp or testa are used are very limited in Africa.

Outlook

Conventional breeding exploited grain hardness in improving mold resistance in white-grained sorghum. Programs in India and ICRISAT developed several high-yielding hard-grain restorer lines and male-sterile lines. Recently US programs also started breeding hard white-grained male and female parents aiming to export markets in Africa and India, where white-grained sorghum is a staple food. In all these programs, zera zera sorghums have been used extensively. Limited efforts were directed in breeding red-grained mold resistant lines at ICRISAT. It is important that the genetic changes brought about by breeding for grain mold resistance in advanced lines over the years should be assessed. ICRISAT is planning such an experiment.

Further improvements in combining grain yield and mold resistance is possible through conventional breeding, which should include expanded systematic screening and selection in segregating progenies of specifically planned crosses. Such programs should involve guinea resistant sorghums in the crosses and exploit open panicles, large glume coverage in addition to grain hardness. However, the progress from such programs is expected to be slow because grain mold resistance expresses late in the life cycle of the crop, is difficult to measure, has complex inheritance, and is significantly influenced by the environment. Therefore, this program should be complemented with marker technology by identifying markers for genes contributing to resistance.

The proposed conventional breeding although helps to diversify grain sorghum for mold resistance and grain yield, it is unlikely that it would help in breeding high-yielding, bold, white-grained sorghum with complete protection against grain mold. Biotechnological approaches hold promise, but are resource intensive and may not provide new cultivars in the short term. The grain mold problem in sorghum may be assuaged but will not be solved in the foreseeable future by resistance breeding alone. Therefore, complementary methods at field and pre-consumption grain processing levels together with genetic enhancement are needed for a holistic mold management.

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