Several trait-based hybrid parents bred at ICRISAT had grain Fe (> 30 ppm) and Zn contents (> 22 ppm), fairly higher than the trial average levels (Fe=28 ppm; Zn=19 ppm). Substantial genetic variability coupled with high heritability and weak association of Fe and Zn contents with β-carotene and phytate contents suggest that it is possible to breed Fe and Zn and β-carotene-dense cultivars with low phytate contents. Further, significant and fairly higher positive correlation between grain Fe and Zn contents and their poor correlation with agronomic traits such as days to 50% flowering and plant height and with farmer-preferred grain traits such as grain size and grain hardness indicated the possibility of delivering high Fe and Zn contents in cultivars with farmer's preferred traits such as early maturity, high yield potential, bold grain and lustrous grains.

Considering that the grain sorghum is grown in different soil types with varying levels of native soil fertility with/without farmer's managed fertility in India, it is necessary to examine the stability of micronutrient-dense cultivars across different soil types and soil fertility levels typical to the areas for which these cultivars are targeted.

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Response of Selected Sorghum Lines to Soil Salinity-Stress under Field Conditions

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Introduction

The demand for sorghum to meet the food and non-food requirement of an ever-growing population necessitates sorghum production in marginal and problematic soils such as acidic and saline soils. Soil acidity, and its associated Al^{3+} toxicity and salinity are probably the most important constraints to sorghum productivity in tropical environments. Saline and sodic soils cause mineral stresses on approximately 0.9 billion ha of land in the world (Gourley et al. 1997). There are vast areas in India, Yemen, Saudi Arabia, and Iran with salinity-affected soils. Extension of the cultivation of sorghum to these salinity-affected soils would not only help meet increased demand, but also ensure sustainable and eco-friendly management of such problematic soils. Soil salinity reduces germination and seedling emergence, retards leaf area expansion and ultimately affects partitioning of photosynthates to harvestable economic parts, thus reducing both grain and fodder yield potentials. Salinity tolerance could be empirically defined as the ratio of economic yield (grain/fodder) at a given salinity stress to that under salinity-free conditions. The extent of yield reduction may change with the degree of the salinity-stress. Although sorghum possesses higher salinity-stress tolerance (Igartua et al. 1994) compared to maize, the development of high-yielding salinity-tolerant sorghums is the best option to increase the productivity in such soils. In this paper, we report and discuss the responses of sorghum cultivars (previously selected for tolerance to induced salinity-stress in pot-culture experiments) to salinity-stress under field condition.

Materials and Methods

Forty-two entries were selected based on the biomass production of a diverse set of 100 breeding lines at 39 days after sowing under induced salinity-stress (ECe 23.4 dS m^{-1}) relative to biomass production of the plants in the salinity-free soils in pot-culture experiments at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India. These entries included 24 hybrid parents [15 maintainer (B-) lines, nine restorer (R-) lines], 16 varieties, one hybrid, and one salinity-stress sensitive check. These 42 entries were evaluated for yield potential using a randomized complete block design with three replications in saline-affected soils (ECe 8.0 dS m^{-1}) at the Agricultural Research Station (ARS), Gangavathi, Karnataka, and in normal (salinity-free) soils at ICRISAT, Patancheru, during the 2004 rainy season as a part of the International Center for Biosaline Agriculture (ICBA), Dubai, and ICRISAT collaborative research project. Each entry was planted in two rows of 2 m length at both the locations. The spacing between rows was 75 cm at ICRISAT-Patancheru, while it was 45 cm at ARS, Gangavathi. The data on days to 50% flowering, plant height, plant agronomic and stay green scores at maturity and grain yield were recorded on five randomly selected plants in each entry at both the locations. Apart from these traits, stover yield was also recorded at ARS, Gangavathi.

Statistical analysis: The computed mean values of the data recorded from sample plants on all the traits were used for statistical analysis. Analyses of variance were carried out to assess the genetic variability as per Steel and Torrie (1980). The phenotypic and genotypic variances were estimated and were standardized as phenotypic coefficient of variability (PCV) and genotypic coefficient of variability (GCV), respectively, to compare the extent of variability for different traits under soil salinity-stress and salinity-free conditions. The broad-sense heritability was estimated as the ratio of genotypic variance to phenotypic variance.

Results and discussion

The results indicated significant genetic variability for days to 50% flowering, plant height and grain yield in salinity-affected (ECe 8 dS m^{-1}) soils at ARS, Gangavathi. The grain yield of the entries ranged from 0.5 t ha^{-1} to 3.9 t ha^{-1} with an average of 2 t ha^{-1}; days to 50% flowering ranged from 70 to 92 with an average of 75 days; plant height ranged from 1.0 to 2.7 m with an average of 1.7 m; plant agronomic score ranged from 2.3 to 4.7 (on a 1–5 scale, where, 1=very good and 5=poor) with an average of 3.4; stay-green score ranged from 2.0 to 4.7 with an average of 3.6 (on a 1–5 scale, where, 1= most green and 5=least green) (Table 1). In general, delayed flowering, reduced plant height, poor plant agronomic and stay-green scores and reduced grain yield (by nearly 40%) were some of the responses of the cultivars to soil salinity-stress compared to those in salinity-free conditions at ICRISAT, Patancheru, although the responses varied with the cultivar. For example, while 50% flowering was delayed by 11 days in PSH 1, it was delayed by only one day in S 35 under salinity-stress; similarly, while grain yield of ICSV 112 was reduced by 48%, the reduction was 38% in SPV 1022 under salinity-stress (Table 1). However, these responses cannot be attributed solely because of salinity-stress as other environmental factors inherent in different locations could be confounded with the differences in salinity-stress levels. The evaluation of diverse cultivars in different salinity-stress levels and salinity-free soils in similar environments is necessary to confirm and understand these cultivar-dependent responses to salinity-stress.

Components of variability: The large differences between the estimates of PCV and GCV indicated significant influence of environment on grain yield and other traits under salinity-stress conditions at ARS, Gangavathi, which are amply reflected in lower magnitude of heritability estimates (Table 1). It appears therefore, that progress of genetic enhancement of sorghum for grain yield and other traits under salinity-stress might slow down. The results from the evaluation of diverse set of lines in multi-environments under a broad range of salinity-stress levels would provide reliable and dependable estimates on the extent of variability, heritability and genotype × salinity stress level interaction. These, along with nature of gene action, would be helpful in designing a most effective breeding program for genetic enhancement of sorghum under salinity-stress.

Cultivar performance and selection environment strategy: Some of the high-yielding popular varieties such as ICSV 112 (3.4 t ha^{-1}), S 35 (3.1 t ha^{-1}) and JJ 1041 (2.9 t ha^{-1}) and a hybrid PSH 1 (3.4 t ha^{-1}) (Table 1) bred and released earlier for salinity stress-free conditions performed better for grain yield under salinity-stress conditions at ARS, Gangavathi. These varieties, JJ 1041 (6.9 t ha^{-1}), ICSV 112 (6.5 t ha^{-1}), S 35 (5.6 t ha^{-1}) and a hybrid PSH 1 (5.9 tha^{-1}) (Table 2) were among the top yielders under salinity-free conditions at ICRISAT, Patancheru, proving again their superior genetic potential. It is interesting to note that two of these varieties, ICSV 112 and S 35, were among the best performers for fodder yield under salinity-stress soils (ECe 10 dS m^{-1}) in farmers' fields at Oman (Personal communication from Dr John Stenhouse, Plant Genetic Resources Specialist, ICBA, Dubai). Further, the line ICSB 406 (0.9 t ha^{-1}) identified earlier as sensitive to salinity-stress based on pre-anthesis biomass production in pot culture experiments conducted at ICRISAT, Patancheru, (Krishnamurthy et al. 2003) produced significantly lower grain yield. These results indicated that there is a certain degree of corroboration between performance of the entries evaluated under salinity-free and salinity-stress conditions, which is also adequately supported by fairly high correlation coefficient (0.53). However, the correlation is only indicative, as it is based on the results from two locations

Table 1. The mean performance of best sorghum lines and estimates of genetic parameters under salinity-stress (at ARS, Gangavathi, India) and salinity-free soils (at ICRISAT-Patancheru, India), 2004 rainy season.

		Days to 50% flowering		Plant height (m)		Plant agronomic score[1]		Stay green score[2]		Grain yield (t ha^{-1})	
Sl No.	Genotype	S	SF	S	SF	S	SF	S	SF	S	SF
1	GD 65008 Brown	79	71	2.7	3.0	2.7	1.0	3.0	3.0	3.9	6.0
2	PSH 1	78	67	2.0	2.5	3.0	1.3	3.7	3.0	3.4	5.9
3	ICSV 112	78	70	1.5	2.1	2.3	1.0	3.7	2.7	3.4	6.5
4	S 35	71	70	2.0	2.5	3.3	2.0	3.7	3.3	3.1	5.6
5	JJ 1041	76	69	2.1	2.7	2.7	1.3	4.0	3.0	2.9	6.9
6	SPV 1022	78	66	2.1	2.5	3.0	2.7	3.3	3.0	2.9	4.7
8	ICSB 406 (Sensitive check)	75	63	2.0	1.0	3.7	2.0	3.7	2.0	0.9	2.9
	F-test	**	**	**	**	**	**	**	**	**	**
	Mean	77	70	1.7	2.1	3.4	1.9	3.6	2.7	2.0	4.1
	Range	70-92	57-83	1.0-2.7	1.0-3.4	2.3-4.7	1.0-3.3	2.0-4.7	1.7-4.3	0.5-3.9	0.6-6.9
	LSD (5%)	4.0	2.4	0.4	0.3	1.4	0.8	1.3	0.8	1.4	1.3
	PCV	4.7	7.3	28.7	27.0	28.6	45.9	25.9	24.8	55.7	42.7
	GCV	3.5	7.1	23.9	25.8	11.5	37.2	14.3	15.3	34.0	38.0
	Heritability (%)	0.55	0.92	0.70	0.91	0.16	0.66	0.31	0.38	0.37	0.79

SF: Salinity-free soils at ICRISAT-Patancheru; S: Salinity-stress soils (ECe 8 dS m^{-1}) at ARS, Gangavathi

1. Agronomic score taken on a 1 to 5 scale where 1=very good and 5=poor
2. Stay green score taken on a 1 to 5 scale where 1=most green and 5=least green

** Significant at P=0.01

Table 2. Category-wise performance of the sorghum lines for grain yield and agronomic traits, under salinity-stress (ECe 8 dS m^{-1}) soils at ARS, Gangavathi, India, 2004 rainy season.

Category of lines	No. of lines in the category	Days to 50% flowering	Plant height (m)	Agronomic score at maturity[1]	Stay green score at maturity[2]	Grain yield (t ha^{-1})	Stover yield (t ha^{-1})
B-lines	15	76	1.4	3.5	3.7	1.88	5.39
R-lines	9	80	1.8	3.3	3.6	1.48	6.94
Varieties	16	78	1.9	3.2	3.5	2.26	8.39
Hybrid[3]	1	78	2.0	3.0	3.7	3.4	10.80
ICSB-406 (Check)	1	75	2.0	3.7	3.7	0.9	2.8
Mean	-	77	1.7	3.4	3.6	2.00	6.90
F-test	-	**	**	NS	NS	**	**
LSD (5%)	-	1.13	0.13	0.41	0.38	0.41	0.93

**Significant at P=0.01; NS: Non-significant;

1. Agronomic score taken on a 1 to 5 scale where 1=best and 5=poor;
2. Stay green score taken on a 1 to 5 scale where 1= most green and 5= least green;
3. Hybrid data was not included for analysis of variance, as there was only one hybrid.

differing in several environmental factors (other than salinity levels) and that the differential cultivar response could be due to the factors other than soil salinity levels. Further, the magnitude and direction of correlation might change with changes in salinity-stress levels. Therefore, it is imperative to evaluate the lines at the same location under salinity-stress and salinity-free conditions to preclude the influence of other edaphic and environmental factors (such as photoperiod, temperature and rainfall distributions) for meaningful comparison of the relative performance of lines under salinity-stress and normal conditions. From plant breeding and agronomic points of view, cultivars performing better under both stress and non-stress conditions are desirable (Reddy 1986; Calhoun et al. 1994). Theoretical investigations (Rosielle and Hamblin 1981) indicating general increase in mean yield in both stress and stress-free environment if selection is practised for mean productivity (average yield in stress and stress-free environments) would lend adequate support to these practical considerations.

Cultivar options: Comparison of the performance of different categories of lines revealed interesting results. While B-lines and R-lines were comparable for grain yield, varieties were significantly superior to hybrid parents (Table 2). The only hybrid with higher grain yield among the entries was the best. Comparative evaluation of large number of hybrids vs. varieties would validate the present results. The superiority of hybrids over varieties under soil salinity-stress environment has been demonstrated previously by Peng et al. (1994), therefore, hybrids should be target cultivars to enhance productivity in saline-affected soils.

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Modeling Male Fertility in Sorghum

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Introduction

Environmental variation can affect pollen viability in sorghum. Temperatures below 13°C during sensitive stages can induce male-sterility (Downes and Marshall 1971; Brooking 1976) and high temperatures appear to have a similar effect (Dhopte 1984). Significant relationships between reduced pollen viability and reduced seed set and increased ergot severity in sorghum have been documented (Ogunlela and Eastin 1984; McLaren 1997). Therefore, it is desirable to develop lines with improved male fertility characteristics to avoid seed losses and ergot epidemics in hybrid seed production fields. The objective of this study was to determine relationships between pollen production, time to shed, and pollen viability in sorghum and various weather variables.

Materials and Methods

Blocks of eight sorghum hybrids including 'Wheatland x TX 2737', 'Wheatland x TX 430', 'SA3042 x TX 2737', 'TX 2752 x TX 430', 'OK 11 x TX 2737', 'OK 11 x TX 2741', 'Wheatland x TX 2783' and 'Wheatland x TX 2862', were planted every two weeks for five planting dates beginning 8 May 2000 in Manhattan, KS, so that pollen could be collected across a wide range of environmental conditions. At mid-bloom, peduncles were struck and rated for pollen production on a scale of 1 (sparse pollen cloud) to 5 (a dense pollen cloud). Time to pollen shed was recorded in hours after sunrise. Differences in pollen viability were quantified by pollen germination. Pollen grains were germinated on culture medium containing 1% agar, 0.9 M sucrose, 2.43 mM boric acid, and 2.12 mM calcium nitrate for 4 h as described by Tuinstra and Wedel (2000). Pollen germination was evaluated by observation of 200 random pollen grains for each hybrid and was quantified as the percentage of germinated pollen grains. Weather parameters were collected in the plot each day. Triad values (mean of 3 consecutive days) of maximum temperature, minimum temperature, maximum relative humidity, minimum relative humidity, total solar radiation, and precipitation were used in correlation analyses to evaluate the relationship between each male fertility characteristic and weather variables. Multiple regression analyses were conducted to model the relationship between each male fertility characteristic and correlated weather variables.

Results

The male fertility characteristics of sorghum were evaluated on 31 different days during the summer and fall of 2000. Several different weather variables were found to be useful for predicting specific components of male fertility (Table 1). Multiple regression analysis yielded the model $Y = -37.86 + -0.792\ X_1 + 0.865\ X_2 + 0.163\ X_3 + -0.286\ X_4 + 0.371\ X_5$ for pollen viability, where Y = expected pollen viability in a genetically diverse set of sorghum hybrids, X_1 = mean maximum temperature 18–20 days before anthesis, X_2 = mean maximum relative humidity 12–14 days before anthesis, X_3 = mean minimum relative humidity 1–3 days before anthesis, X_4 = mean minimum relative humidity 12–14 days before anthesis, and X_5 = mean total precipitation 15–16 days before anthesis. This model accounted for 65% of the variation in pollen viability ($R^2 = 0.655$). The analysis for time to shed yielded the model $Y = 13.87 + -0.115\ X_1 + -0.0864\ X_2$, where Y = expected time to shed in a genetically diverse set of sorghum hybrids, X_1 = mean maximum temperature 0–2 days before anthesis and X_2 = mean maximum relative humidity 9–11 days before anthesis. This model accounted for 58% of the variation in time to shed ($R^2 = 0.582$). The analysis for pollen production yielded the model $Y = -5.93 + 0.0964\ X_1 + -0.0465\ X_2 + -0.158\ X_3 + 0.164\ X_4 + 0.0200\ X_5 + 0.066\ X_6 + 0.023\ X_7$, where Y = expected pollen production rating in a genetically diverse set of sorghum hybrids, X_1 = mean maximum temperature 0–2 days before anthesis, X_2 = mean minimum temperature 0–2 days before anthesis, X_3 = mean minimum temperature 5–7 days before anthesis, X_4 = mean minimum temperature 6–8 days before anthesis, X_5 = mean minimum temperature 7–9 days before anthesis, X_6 = mean maximum relative humidity 10–12 days before anthesis and X_7 = mean total precipitation 13–15 days before anthesis. This model accounted for 86% of the variation in pollen production rating scores ($R^2 = 0.863$).

Discussion

Mean maximum temperature, maximum and minimum relative humidity, and precipitation before anthesis were all highly correlated with pollen viability at flowering. Negative correlations between mean maximum temperatures and pollen viability suggest a critical stage for heat stress. High temperatures just before and during microsporogenesis seem to significantly decrease pollen viability. Although precipitation has not been correlated with pollen viability in previous studies, positive correlations between pollen viability and maximum and minimum relative humidity