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Components of resistance to sorghum shoot fly, *Atherigona soccata*

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Abstract Sorghum shoot fly, *Atherigona soccata* is one of the major constraints in sorghum production, and host plant resistance is one of the components to control sorghum shoot fly. Thirty sorghum genotypes were evaluated for different mechanisms of resistance and morphological and agronomic traits during the rainy and postrainy seasons. The sorghum genotypes, Maulee, Phule Anuradha, M 35-1, CSV 18R, IS 2312, Giddi Maldandi, and RVRT 3 suffered lower shoot fly damage, and also exhibited high grain yield potential during the postrainy season. ICSB 433, ICSV 700, ICSV 25019, ICSV 25022, ICSV 25026, ICSV 25039, PS 35805, Akola Kranti, and IS 18551 exhibited antixenosis for oviposition and antibiosis against sorghum shoot fly, *A. soccata*. Leaf glossiness, plant vigor, leafsheath pigmentation and trichomes were associated with resistance/susceptibility to shoot fly. Path coefficient analysis indicated that direct effects and correlation coefficients of leaf glossiness, plant vigor, plant height, plant color and trichomes were in the same direction, suggesting that these traits can be used to select sorghum genotypes for resistance to shoot fly. Principal co-ordinate analysis based on shoot fly resistance traits and morphological traits placed the test genotypes into different groups. The genotypes placed in different groups can be used to increase the levels and broaden the genetic base of resistance to shoot fly. The environmental coefficient of variation and phenotypic coefficient of variation for shoot fly resistance and morphological traits were quite high, indicating season specific expression of resistance to sorghum shoot fly. High broadsense heritability, genetic advance and genotypic coefficient of variation suggested the predominance of additive nature of genes controlling shoot fly resistance, suggesting that pedigree breeding can be used to transfer shoot fly resistance into high yielding cultivars. This information will be useful for developing shoot fly-resistant high yielding cultivars for sustainable crop production.

Keywords Sorghum · Shoot fly · Antibiosis · Antixenosis · Heritability

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Introduction

Sorghum, *Sorghum bicolor* (L.) Moench, an annual diploid C_4 plant, is the fifth most important cereal crop of the world. The semi-arid regions produce more than half the worlds' sorghum, and is a dietary staple for over 500 million people living in the semi-arid tropics. Sorghum has also been used recently as a source of bio-fuel, but is mainly used as food, feed and fodder. In India, 6.18 million hectares of area is under sorghum cultivation, with a total production of 5.28 million tonnes, and an average productivity of 845.4 kg/ha (FAO 2014). The low productivity in sorghum is due to adoption of poor management practices and the biotic and abiotic constraints affecting the crop.

Sorghum is damaged by 150 insect pests from seedling to harvesting stage (Seshu Reddy and Davies 1978; Jotwani et al. 1980; Sharma 1985), of which sorghum shoot fly, *Atherigona soccata* (Diptera: Muscidae), is one of the major constraints during the seedling stage (Nwanze et al. 1990; Sherwill et al. 1999; Aruna and Padmaja 2009). Shoot fly infests the sorghum seedlings at 7 days after emergence (DAE), and the infestation continues till 30 DAE of the crop (Nwanze et al. 1990; Vadariya 2014). Sorghum shoot fly, *A. soccata* lays elongated cigar shaped eggs on third to sixth basal leaves parallel to the leaf midrib (Padmaja et al. 2010). The egg hatches into a maggot in 1–2 days, the maggot crawls along the leafsheath, and reaches the central whorl of the plant, where it makes an incision on the central leaf, which causes desiccation and death of whorl leaf, and forms a typical deadheart (Deeming 1972). The maggot feeds on the decaying tissue of the central whorl (Ponnaiya 1951). Sorghum shoot fly completes its life cycle in 17–21 days.

Postrainy sorghums are very crucial for food and fodder security in the drought prone areas of semi-arid regions, as there is no alternative crop which could be grown during this season (Gorad et al. 1995), when only meagre amount of the annual rainfall is received. Postrainy season sorghums are important because, the rainy season sorghum is mainly used for animal and poultry feed as the grain is not fit for human consumption, and dual purpose cultivars are preferred because of grain moulds during the rainy season (Reddy et al. 2012). Postrainy season sorghums are grown both for grain as food and the stalks as fodder for live stock under drought prone conditions in the semi-arid tropics.

Postrainy season sorghums grown under receding moisture conditions, are exposed to peak shoot fly populations between September and October. Shoot fly infestation decreases plant stand, and also causes severe losses in grain and fodder yield. Increase in shoot fly deadhearts by 1 % results in a loss of 143 kg grain yield/ha, and an overall loss of 90–100 % was reported under delayed sowings (Hiremath and Renukarya 1966; Chundurwar and Karanjkar 1979; Dhaliwal et al. 2004). The world wide yield loss due to shoot fly has been estimated to be over 274 million US$ (Sharma 2006). The pest is especially serious in the late-sown crops, but also infests early sowings when the preceding dry season is interrupted by frequent rain showers (Nimbalkar and Bapat 1987). Losses due to shoot fly damage can be reduced by using resistant varieties, timely planting, seed treatment with systemic insecticides, and need based application of foliar sprays during the seedling stage (Sharma 1985). However, planting times in the semi-arid tropics are dependent on the onset of rains, while the cost of insecticides restricts the poor farmers from applying them (Sharma 1993). Therefore, host plant resistance (HPR) can be exploited as one of the most effective means of keeping shoot fly populations below the economic threshold levels (Sharma 1985; Riyazaddin et al. 2015).

Developing high-yielding rainy or postrainy season-adapted varieties/hybrids is the major objective of sorghum improvement programs. Though considerable efforts have been made to develop hybrids with wider adaptability to different production environments, the results are not encouraging (Madhusudana et al. 2003). The grain yield in the rainy season sorghums has increased significantly, but the genetic gains in the postrainy season sorghums have been quite low because of the severity of shoot fly damage and drought stress (Kumar et al. 2011). The cultivars grown during the postrainy season must have moderate levels of resistance to shoot fly, but none of newly developed varieties or hybrids have been able to replace the landrace cultivars Maldandi (M 35-1) (Sharma 1993), which possesses acceptable grain and fodder quality (Sanjana Reddy et al. 2009; Reddy et al. 2012). Efforts have been made to transfer shoot fly resistance into cytoplasmic male-sterile and restorer lines to produce shoot fly resistant hybrids (Sharma et al. 2005), but the expression of resistance to shoot fly varies with insect density across the environments (Sharma and Nwanze 1997; Dhillon et al. 2005; Ashok Kumar et al. 2008), male-sterility system (Dhillon et al. 2005; Umakanth et al. 2012), and expression of different components of shoot fly resistance (Doggett et al. 1970; Raina et al. 1981; Sharma and Nwanze 1997; Kamatar et al. 2003; Dhillon et al. 2005, 2006a;

Sivakumar et al. 2008). As a result, expression of resistance to shoot fly varies between the rainy and the postrainy seasons (Aruna et al. 2011a; Reddy et al. 2012; Riyazaddin et al. 2015), suggesting the need for developing cultivars with adaptation to different seasons.

It is therefore important to identify sorghum lines with stable resistance, and different mechanisms of resistance with adaptation to postrainy season conditions. Hence, the present studies were undertaken to identify sorghum genotypes with diverse mechanisms of resistance to shoot fly and high grain yield to increase productivity of the postrainy season sorghums.

Materials and methods

Genetic materials

The experiments were carried out at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Telangana, India. The experimental material consisted of 30 sorghum genotypes, which were selected from a set of 90 lines, based on their resistant/susceptible reaction to shoot fly, *A. soccata* during the 2010 postrainy and 2011 rainy seasons. These 30 lines included the 28 test entries and the susceptible check, Swarna, and resistant check, IS 18551. The test material was sown in a randomized complete block design (RCBD) with three replications during the 2011 postrainy and 2012 rainy seasons, with one set of test material under protected conditions (by applying Carbofuran granules and spraying of Cypermethrin) to record the morphological and agronomic traits. A basal dose of fertilizer (Ammonium phosphate @100 kg/ha) was applied to the field. The experimental material was sown using a two cone planter. Each plot had two rows of 2.0 m length, with a plant to plant spacing of 10 cm and a row to row spacing of 75 cm. Twenty days prior to the sowing of the test material, four rows of interlards (infester rows of a susceptible cultivar, Swarna) were sown in the field, and moistened fish meal (250 g in a polythene bag) was placed within the infester rows to attract the natural population of the shoot flies to maximize shoot fly infestation in the test material (Soto 1974; Sharma et al. 1992). Thinning was carried out at 7 days after seedling emergence. Normal agronomic practices were followed for raising the crop. Earthing up and top dressing with urea (@100 kg/ha) was done at 30 DAE. Furrow irrigation was given to the experimental material during the 2011 postrainy season.

Shoot fly oviposition and damage parameters

Observations on shoot fly, *A. soccata* oviposition were recorded by counting the number of plants with shoot fly eggs, and the total number of eggs on all the plants in a test plot at 14 DAE, and expressed in percentages. Shoot fly damage was assessed by counting the number of deadhearts in a test plot at 21 DAE. Agronomic desirability and overall resistance to shoot fly was recorded at harvest.

Morphological, agronomic, and panicle traits

The data on the morphological, agronomic and panicle traits were recorded from seedling stage to the physiological maturity stages based on the sorghum descriptors (IBPGR and ICRISAT 1993) with slight modifications (Appendix 1).

Data were recorded on leaf glossiness, leafsheath pigmentation, and seedling vigor at 7–10 DAE, and trichome density on abaxial and adaxial leaf surfaces at 12 DAE. Data were also recorded on waxy bloom, plant color, inflorescence exsertion, panicle compactness, panicle shape, glume color, glume coverage, awns, grain color, grain lustre, grain subcoat, endosperm texture, and endosperm color. Leaf glossiness was evaluated visually on a 1–5 scale at 10–12 DAE (fifth leaf stage), when the expression of this trait is most apparent, in the morning hours, when there was maximum reflection of light from the leaf surface (Sharma and Nwanze 1997). The leafsheath pigmentation was visually scored on a 1–3 rating scale at 7 DAE (Dhillon et al. 2006b). Seedling vigor was recorded at 10 DAE on 1–3 scale (Sharma and Nwanze 1997). Days to 50 % flowering was recorded when half of the plants in the experimental plot attained 50 % anthesis stage, while plant height (of three plants selected at random within a plot) was recorded at maturity. Overall resistance score was recorded before harvesting on a 1–9 scale (1 = plants with uniform tillers and harvestable panicles, and 9 = plants with a few or no productive tillers). Agronomic desirability was recorded at crop maturity on a 1–5 scale (1 = good productive potential and ability to withstand insect damage, and 5 = poor productive potential and prone to insect damage). Data on 100 seed weight and grain yield/plot was recorded after harvesting and threshing the panicles, obtained from the plots protected from shoot fly, *A. soccata*.

Trichome density screening

Trichome density on both the leaf surfaces was recorded at 12 DAE by taking a 2.5 cm^2 middle portion of the fifth leaf (Maiti and Bidinger 1979). The leaf samples were taken at random from three plants in each test plot. The leaves were placed in stoppered vials of 5 ml capacity containing acetic acid and alcohol mixture (2: 1). After 24 h, acetic acid and alcohol mixture was decanted, and the leaf samples were preserved in 90 % lactic acid. The leaf samples were mounted on to a glass slide with a drop of the lactic acid, and then observed under 10× microscopic field, and expressed as number of trichomes/microscopic field (trichome density).

Statistical analysis

The data were subjected to analysis of variance (ANOVA) using GenStat, 14th edition (GenStat 2010). The significance of differences between the genotypes was tested by using the F-test, and the genotypic means were compared by least significance difference (LSD) at $p \leq 0.05$. The correlation, scatter plot and regression analyses were carried out by using excel 2007, principal co-ordinate analysis (PCoA) using GenStat, and path coefficient analysis using OPSTAT, to quantify the genotypic response across seasons, and identify the traits associated with resistance/susceptibility to shoot fly, *A. soccata*. The genetic parameters such as environmental coefficient of variation (ECV), genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), broadsense heritability (%H) as percentages and genetic advance percent of mean (GA %) were calculated by using the formulae based on mean sum of squares (Johnson et al. 1955).

Results

Expression of resistance to sorghum shoot fly, *A. soccata*

There were significant differences between the genotypes for deadheart formation and egg laying, with significant variance ratio at $p \leq 0.01$. Based on the shoot fly resistant traits, ICSB 433, ICSV 700, Phule Yashoda, Phule Chitra, ICSV 705, ICSV 25019, ICSV 25022, ICSV 25026, ICSV 25039, PS 35805, IS 2123, IS 2146, Akola Kranti, Phule Vasudha, ICSV 93046, IS 18551, and RVRT 2 exhibited resistance to shoot fly across seasons, with 10–30 % plants with eggs and 0.9–16 % of shoot fly deadhearts in the postrainy season and up to 90 % of plants with eggs and 50–75 % of deadhearts in the rainy season, when compared with the susceptible check Swarna (Table 1). These genotypes also exhibited tolerance to shoot fly by showing low to moderate levels of overall resistance score. Maulee, Phule Anuradha, M 35-1, CSV 18R, IS 2312, Giddi Maldandi, and RVRT 3 exhibited resistance to shoot fly only in the postrainy season, and ICSV 713 in the rainy season, which were better/onpar with the resistant check IS 18551.

Egg laying by the sorghum shoot fly, *A. soccata* was high ranging from 182.6 to 265.6 eggs per 100 plants, and 10.3–102.7 eggs per 100 plants in the postrainy season. The genotypes ICSB 433, ICSV 700, ICSV 25019, ICSV 25022, ICSV 25026, ICSV 25039, PS 35805, Akola Kranti, and IS 18551 showed antibiosis component resistance as these genotypes had lower percentage of plants with deadhearts (0.9–10.3 and 45.5–76.0 % respectively, in the postrainy and rainy seasons) than the plants with shoot fly eggs (11.0–24.0 and 93.8–99.2 % respectively, in the postrainy and rainy seasons). The genotypes Maulee, M 35-1, CSV 18R, Phule Vasudha, and RVRT 2 showed antibiosis mechanism of resistance only in the postrainy season, with lower shoot fly deadhearts (11.0–20.7 %) than the plants with shoot fly eggs (10.7–37.0 %), whereas Phule Chitra, ICSV 705, ICSV 713, IS 2123, and IS 2146 exhibited antibiosis mechanism of resistance with 60.5–80.8 % shoot fly deadhearts, lower to that of the plants with eggs (91.8–99.2 %) in the rainy season. These genotypes also had lower number of shoot fly eggs per 100 plants as compared to the susceptible check, Swarna, (215.5 eggs/100 plants).

Association of morphological and agronomic traits with expression of resistance to shoot fly, *A. soccata*

Leaf glossiness score and leafsheath pigmentation were significantly and positively correlated with shoot fly damage ($r = 0.83$** and $r = 0.42$*, respectively)

Table 1 Expression of resistance to sorghum shoot fly, *A. soccata* in sorghum (ICRISAT, Patancheru, 2011–2012)

Genotype	Number of shoot fly eggs/100 plants		Plants with shoot fly eggs (%)		Shoot fly deadhearts (%)		Overall resistance score	
	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS
ICSB 433	31.7	216.9	23.1	94.2	10.3	74.3	6.7	3.5
ICSV 700	22.3	206.9	21.4	99.2	12.9	74.6	5.0	3.0
Phule Yashoda	39.3	222.1	29.8	99.1	15.1	84.0	4.3	6.0
Maulee	27.0	242.7	24.3	99.2	14.4	86.7	4.7	6.0
Phule Chitra	18.4	224.2	16.2	97.7	11.8	78.3	4.3	6.0
Phule Anuradha	22.6	207.5	20.7	99.2	11.8	91.1	3.7	6.7
M 35-1	29.4	249.4	26.8	99.2	13.5	86.0	4.0	5.3
Parbhani Moti	40.6	228.4	36.3	100.0	28.5	86.6	4.0	7.3
CSV 18R	32.9	213.8	31.0	99.1	18.2	89.6	4.3	5.3
CSV 15	70.8	257.8	57.6	100.0	41.9	96.5	6.3	6.7
ICSV 705	12.4	204.1	10.7	92.6	6.3	60.5	6.0	5.5
ICSV 713	47.3	206.1	37.0	97.5	27.6	73.5	6.3	3.0
ICSV 25019	17.5	218.5	14.2	93.8	6.7	54.6	5.3	5.2
ICSV 25022	15.5	198.1	13.7	99.1	7.7	77.8	4.0	3.3
ICSV 25026	18.6	182.6	14.3	98.5	5.1	68.6	3.0	2.7
ICSV 25039	12.0	202.1	11.2	95.0	0.9	57.7	2.0	3.0
PS 35805	12.6	191.6	11.0	95.2	4.4	45.5	3.0	4.8
IS 2123	20.6	245.0	17.7	98.3	12.0	80.8	3.7	3.7
IS 2146	19.8	240.0	18.8	96.9	11.6	76.8	4.0	4.3
IS 2312	10.3	196.3	8.6	98.4	5.2	84.4	3.3	3.7
Akola Kranti	26.6	224.0	24.0	97.4	9.1	72.6	4.7	6.5
Phule Vasudha	33.4	208.3	29.8	91.8	11.0	81.2	4.3	7.0
ICSV 93046	18.6	236.4	17.6	99.3	14.1	83.6	3.3	4.3
IS 18551 (R)	20.1	265.6	17.4	97.5	7.1	76.0	3.3	4.2
Swarna (S)	102.7	215.5	55.8	100.0	58.3	98.3	8.0	9.0
RVRT 2	36.5	204.0	26.2	99.1	15.0	83.2	4.3	8.0
Giddi Maldandi	39.9	249.6	30.7	100.0	12.5	76.5	2.7	4.8
RVRT 3	38.8	198.4	32.8	98.4	20.7	79.9	4.0	6.7
Dagidi Solapur	44.0	199.7	35.8	100.0	25.7	95.5	4.0	7.7
296 B	92.3	208.6	77.4	100.0	68.6	94.3	7.0	7.7
Mean	32.5	218.81	26.40	97.86	16.92	78.96	4.46	5.36
SE ±	7.10	19.90	4.54	1.57	4.68	5.34	0.51	0.57
Vr (58,29)	9.62**	1.13	11.37**	2.17**	10.61**	5.41**	7.30**	9.16**
LSD ($p \leq 0.05$)	20.11	NS	12.86	4.44	13.25	15.11	1.43	1.62

** F test significant at p 0.01

R resistant check, *S* susceptible check, *RS* rainy season, *PRS* postrainy season, *NS* non-significant F value, *Overall resistance score* 1–9 ranking with 1 = plants with uniform tillers and harvestable panicles, 9 = plants with a few or no productive tillers

in the postrainy season, but negatively correlated with agronomic score across seasons (Table 2). Seedling vigor and plant color were negatively and significantly correlated ($r = -0.43$** and $r = -0.48$**, respectively) with shoot fly damage in the rainy season with non-significant contribution in the postrainy season. Trichome density in the abaxial and adaxial leaf surfaces was significantly and negatively correlated with shoot fly damage parameters across seasons. There was a significant and positive correlation between trichome density and agronomic score in the postrainy season. Endosperm texture was positively correlated with shoot fly damage parameters across seasons, with a few exceptions. Seed weight was positively correlated with shoot fly deadhearts ($r = 0.38$*) and the overall resistance score ($r = 0.69$**) in the rainy season.

Leaf glossiness score (slope = 8.76) and leafsheath pigmentation (slope = 8.56) were positively correlated with shoot fly damage, with a positive slope (Fig. 1a, b). Trichome density on the abaxial (slope = −0.29) and adaxial (slope = −0.22) leaf surfaces was negatively associated with shoot fly damage, with a negative slope (Fig. 1c, d).

Agronomic characteristics of the test sorghum genotypes

The agronomic characteristics were recorded from the test genotypes grown under protected conditions. The grain yield of Phule Yashoda, ICSV 25026, Akola Kranti and ICSV 93046 (3.4–5.3 and 2.5–3.2 t/ha in the postrainy and rainy seasons respectively) was high across seasons, and these lines also had good agronomic score (2.0–4.3) (Table 3). Maulee, Phule Chitra, Phule Anuradha, Parbhani Moti, CSV 18R, IS 2312, Phule Vasudha, RVRT 3, and Dagidi Solapur yielded quite high in the postrainy season with the highest grain yield of 5.3 t/ha in Phule Yashoda. The grain yield of ICSB 433, ICSV 700, M 35-1, CSV 15, ICSV 25022, and Swarna was high in the rainy season (2.3–4.8 t/ha).

The genotypes Maulee, Phule Anuradha, M 35-1, CSV 15, ICSV 705, ICSV 25019, IS 2123, IS 2146, IS 2312, RVRT 2 and Swarna were early flowering (58.0–66.0 days for 50 % flowering) and had a medium plant height ranging from 102.5 to 300 cm across seasons. The mean 100 seed weight was 2.8 g in the postrainy season and 2.6 g in the rainy season, with the highest 100 seed weight of 3.9 g in Parbhani Moti in the postrainy season, and 3.8 g in Swarna, in the rainy season.

Morphological characteristics of the sorghum genotypes

The genotypes Phule Yashoda, IS 2146, Akola Kranti, and Phule Vasudha exhibited leaf glossiness (1.3–2.5 and 1.8–2.3 score in the postrainy and rainy season respectively), leafsheath pigmentation (1.0–1.5 and 1.3–1.5 score in the postrainy and rainy season), high seedling vigor (1.5–1.8 and 1.0–2.3 score in the postrainy and rainy season respectively) and high trichome density on the abaxial (46.4–78.9 and 156.0–110.7 trichomes per microscopic area in the postrainy and rainy seasons, respectively) and adaxial (98.7–113.0 and 120.4–165.0 trichomes per

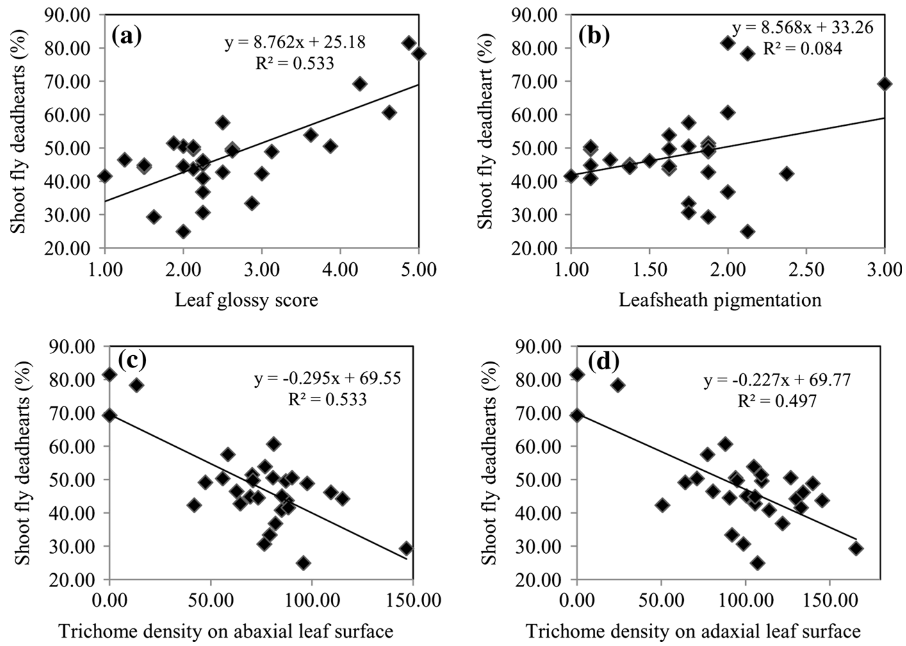
Table 2 Association of agronomic and morphological traits with expression of resistance to sorghum shoot fly, *A. soccata*

Traits	Number of shoot fly eggs/plant	Plants with shoot fly eggs (%)	Shoot fly deadhearts (%)	Overall resistance score	Agronomic score
Leaf glossy score	−0.22 (0.84**)	0.18 (0.83**)	0.34 (0.83**)	0.35 (0.68**)	−0.60** (−0.51**)
Leafsheath pigmentation	−0.1 (0.41*)	−0.09 (0.41*)	−0.05 (0.42*)	0.12 (−0.36)	−0.69** (−0.41*)
Seedling vigor score	−0.49** (−0.12)	−0.48** (−0.20)	−0.43** (−0.13)	−0.1 (−0.20)	−0.84** (−0.35)
Trichome density on abaxial leaf surface	−0.15 (−0.72**)	−0.45** (−0.70**)	−0.53** (−0.72**)	−0.45** (−0.76**)	0.29 (0.47**)
Trichome density on surface	−0.14 (−0.77**)	−0.36 (−0.75**)	−0.47** (−0.76**)	−0.53** (−0.73**)	0.28 (0.49**)
Plant color	−0.31 (−0.06)	−0.29 (−0.03)	−0.48** (−0.01)	−0.47** (−0.23)	−0.77** (−0.27)
Panicle shape	0.37* (−0.14)	−0.13 (−0.15)	0.01 (−0.16)	−0.27 (−0.37*)	0.42* (0.66**)
Awns	0.08 (−0.25)	0.40* (−0.13)	0.32 (−0.19)	−0.01 (−0.59**)	0.70** (0.45**)
Endosperm texture	0.34 (0.42*)	0.22 (0.55**)	0.36 (0.40*)	0.54** (−0.11)	0.41* (−0.14)
100 seed weight	0.02 (−0.25)	0.19 (−0.29)	0.38* (−0.22)	0.69** (−0.05)	0.1 (−0.10)

Values in the parentheses are the correlation coefficients for postrainy season whereas the values outside the parentheses are correlation coefficients for the rainy season

*, ** Correlation coefficients significant at the p 0.05 and 0.01, respectively

Fig. 1 Association of **a** leaf glossy score, **b** leafsheath pigmentation, **c** trichome density on abaxial leaf surface, **d** trichome density on surface with resistance to shoot fly, *A. soccata*



microscopic area in the postrainy and rainy seasons, respectively) leaf surfaces and were on par with the resistant check IS 18551 (Table 4). Maulee, Phule Chitra, Phule Anuradha, M 35-1, IS 2123, IS 2312, Giddi Maldandi and RVRT 3 possessed leaf glossiness, leafsheath pigmentation, and high seedling vigor with moderate trichome density.

Panicle and seed characteristics of the sorghum genotypes

The data on the panicle traits and seed characteristics is given in Appendix 2. These traits were useful in selecting sorghum genotypes with desirable panicle and seed characteristics for developing farmer preferred cultivars with shoot fly resistance, good agronomic and seed traits, and high grain yield.

Diversity of the sorghum genotypes for shoot fly, *A. soccata*

The principal co-ordinate analysis of the 30 sorghum genotypes based on shoot fly resistance traits placed the genotypes into three different groups (I, II, and III) (Fig. 2a) with susceptible genotypes (CSV 15, Swarna and 296 B) into group I and the genotypes showing resistance to shoot fly (ICSV 700, Phule Yashoda, Maulee, Phule Chitra, Phule Anuradha, M 35-1, Parbhani Moti, CSV 18R, ICSV 713, ICSV 25022, IS 2123, IS 2146, IS 2312, Akola Kranti, ICSV 93046, RVRT 2, Giddi Maldandi, RVRT 3, and Dagidi Solapur) that were on par with IS 18551, were grouped together in group II. The genotypes ICSB 433, ICSV 705, ICSV 25019, ICSV 25026, ICSV 25039, PS 35805, and Phule Vasudha showing moderate resistance to shoot fly, were placed in group III.

The diversity of the genotypes based on the morphological traits placed them into four groups (I, II, III, and IV) (Fig. 2b) suggesting morphologically diverse test genotypes used for shoot fly screening. Swarna, 296 B, and CSV 15 exhibiting the traits driving for shoot fly susceptibility were grouped together in group I, whereas Phule Yashoda, Maulee, Phule Chitra, Phule Anuradha, M 35-1, Parbhani Moti, CSV 18R, IS 2123, IS 2146, IS 2312, Akola Kranti, Phule Vasudha, RVRT 2, RVRT 3, and Dagidi Solapur with resistant morphological traits to shoot fly grouped together along with the resistant check IS 18551 in group IV. ICSB 433, ICSV 700, ICSV 705,

Table 3 Agronomic characteristics of sorghum genotypes evaluated for resistance to sorghum shoot fly, *A. soccata* (ICRISAT, Patancheru, 2011–2012)

Genotype	Days to 50 % flowering		Plant height (cm)		100 seed weight (g)		Grain yield (t/ha)		Agronomic score[a]	
	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS
ICSB 433	70.5	66.0	150.0	173.3	1.9	2.3	2.0	4.0	2.3	1.7
ICSV 700	69.8	75.0	237.5	333.3	2.6	2.7	2.8	2.3	3.3	4.0
Phule Yashoda	70.0	70.0	250.8	340.0	3.6	3.1	5.3	3.1	2.3	4.3
Maulee	61.0	60.0	223.3	286.7	3.4	3.0	3.7	1.8	2.7	5.0
Phule Chitra	69.8	65.0	251.7	326.7	3.2	2.8	3.6	0.5	2.7	4.3
Phule Anuradha	58.5	58.0	215.0	290.0	3.6	3.0	3.6	1.8	2.3	4.3
M 35-1	65.0	65.0	238.3	340.0	3.5	2.7	3.3	2.3	2.7	4.3
Parbhani Moti	69.8	68.0	242.5	330.0	3.9	3.1	3.8	1.1	3.0	4.0
CSV 18R	72.3	76.0	253.3	323.3	3.8	2.5	4.1	0.7	2.3	4.0
CSV 15	63.5	64.0	185.0	246.7	2.4	2.9	3.1	3.8	2.3	2.3
ICSV 705	63.5	65.0	102.5	120.0	1.8	2.4	1.7	1.5	2.3	2.0
ICSV 713	69.8	62.0	164.2	173.3	2.0	2.0	1.7	2.2	2.0	2.0
ICSV 25019	62.8	62.0	109.2	123.3	1.4	2.7	1.5	2.3	2.3	1.7
ICSV 25022	69.3	74.0	160.0	213.3	2.4	2.3	2.9	4.7	2.0	1.7
ICSV 25026	69.8	74.0	165.0	206.7	2.4	2.4	3.6	3.2	2.0	2.0
ICSV 25039	73.0	73.0	163.3	210.0	1.5	1.7	2.4	1.9	3.0	2.7
PS 35805	64.8	70.0	95.8	106.7	1.8	2.3	1.6	1.4	2.0	2.0
IS 2123	66.3	66.0	219.2	276.7	2.7	2.2	3.4	2.0	4.0	5.0
IS 2146	64.3	65.0	210.8	286.7	2.1	1.9	3.0	1.4	3.7	5.0
IS 2312	64.8	65.0	227.5	300.0	2.4	2.0	3.6	1.6	4.3	5.0
Akola Kranti	72.0	74.0	274.2	346.7	3.5	3.1	4.7	2.5	2.3	4.0
Phule Vasudha	71.3	65.0	260.0	356.7	3.5	3.1	4.3	2.0	2.3	4.3
ICSV 93046	70.0	74.0	238.3	293.3	2.7	2.7	3.4	2.8	3.0	4.0
IS 18551(R)	66.0	70.0	238.3	336.7	2.2	1.9	2.6	1.5	4.3	4.0
Swarna (S)	63.8	58.0	137.5	166.7	3.2	3.8	2.7	4.8	1.0	1.7
RVRT 2	66.0	60.0	224.2	280.0	3.8	3.0	3.5	1.9	2.3	4.3
Giddi Maldandi	76.5	82.0	164.2	226.7	2.7	2.2	3.3	2.1	2.3	4.3
RVRT 3	68.5	70.0	261.7	326.7	3.7	2.9	3.7	0.9	2.3	4.0
Dagidi Solapur	70.8	72.0	222.5	320.0	3.4	2.5	4.1	1.3	3.3	3.4
296 B	68.5	64.0	104.2	123.3	2.5	2.0	1.7	2.1	2.0	1.7
Mean (58, 29)	67.7	67.7	199.7	259.5	2.8	2.6	3.2	2.2	2.6	3.4
SE ±	0.7	1.1	7.3	14.4	0.1	0.1	0.4	0.2	0.4	0.3

R resistant check, *S* susceptible check, *RS* rainy season, *PRS* postrainy season

[a] *Agronomic score* 1–5 ranking with 1 good productive potential and ability to withstand insect damage, 5 poor productive potential and prone to insect damage

ICSV 713, ICSV 25019, ICSV 25022, ICSV 25026, ICSV 25039, PS 35805, ICSV 93046, and Giddi Maldandi possessing combination of the resistant and susceptible morphological traits exhibited moderate levels of shoot fly resistance and were grouped separately in group II and III.

Table 4 Morphological characteristics of sorghum genotypes evaluated for resistance to sorghum shoot fly, *A. soccata* (ICRISAT, Patancheru, 2011–2012)

Genotype	Leaf glossy score		Leafsheath pigmentation		Seedling vigor score		Trichome density on abaxial leaf surface	
	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS
ICSB 433	2.5	3.5	2.0	2.8	2.8	2.8	28.0	55.6
ICSV 700	2.0	2.3	1.8	1.5	2.3	1.3	58.8	116.4
Phule Yashoda	2.0	2.3	1.0	1.3	1.5	1.0	63.6	110.7
Maulee	2.0	2.0	1.8	1.8	1.8	1.3	51.9	109.4
Phule Chitra	2.0	2.5	1.5	1.3	1.3	1.3	46.1	124.2
Phule Anuradha	2.3	1.5	2.0	1.8	1.0	1.0	42.9	97.9
M 35-1	2.3	3.0	1.5	1.8	1.5	1.5	40.4	101.3
Parbhani Moti	2.8	2.3	1.8	1.8	1.0	1.3	48.7	68.1
CSV 18R	3.8	3.5	2.0	1.3	1.3	1.3	43.8	109.9
CSV 15	4.8	3.8	3.0	3.0	1.0	1.3	0.0	0.0
ICSV 705	2.0	3.8	1.8	1.8	2.8	2.8	53.1	105.2
ICSV 713	3.8	4.0	2.0	1.8	3.0	3.0	22.6	157.7
ICSV 25019	2.0	2.5	1.5	2.0	2.0	2.5	40.1	112.8
ICSV 25022	2.0	3.0	2.0	1.8	2.5	2.3	46.1	82.9
ICSV 25026	2.0	2.5	2.0	2.0	2.3	2.3	55.3	108.4
ICSV 25039	1.0	2.3	1.8	2.0	2.5	3.0	122.1	171.3
PS 35805	1.8	2.3	1.8	2.5	2.8	2.8	62.3	129.2
IS 2123	1.0	1.5	1.5	1.0	1.3	1.3	49.8	75.8
IS 2146	1.3	1.8	1.3	1.5	1.5	1.0	78.9	151.2
IS 2312	1.3	1.8	1.3	1.0	1.3	1.0	48.7	90.2
Akola Kranti	2.3	2.3	1.0	1.3	1.8	1.3	46.4	123.7
Phule Vasudha	2.5	2.0	1.5	1.5	1.0	2.3	62.1	156.7
ICSV 93046	2.3	4.0	1.8	2.0	2.3	1.5	59.7	135.7
IS 18551(R)	1.0	1.0	1.0	1.0	1.5	1.0	68.3	108.2
Swarna (S)	5.0	5.0	2.0	2.3	2.0	2.8	4.4	22.0
RVRT 2	2.3	3.0	2.0	1.8	1.8	1.5	28.2	66.3
Giddi Maldandi	2.0	2.0	1.8	1.5	1.8	1.5	55.4	91.2
RVRT 3	1.8	2.5	1.0	1.3	1.5	1.8	27.9	83.8
Dagidi Solapur	4.8	4.5	2.0	2.0	1.3	1.5	47.9	114.2
296 B	4.8	5.0	2.0	2.0	2.0	3.0	0.0	0.0
Mean	2.4	2.8	1.7	1.7	1.8	1.8	46.8	99.3
SE ±	0.2	0.4	0.2	0.2	0.2	0.2	6.2	15.3
Vr (58,29)	37.32**	7.91**	5.13**	5.34**	5.76**	8.56**	14.74**	7.42**
LSD ($p \leq 0.05$)	0.5	1.0	0.5	0.6	0.7	0.7	17.5	43.2

Genotype	Trichome density on adaxial leaf surface		Leaf midrib color		Waxy bloom		Plant color	
	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS
ICSB 433	50.7	50.8	2.0	2.0	3.0	3.0	2.0	2.0
ICSV 700	152.6	138.4	2.0	2.0	1.3	1.0	2.0	2.0
Phule Yashoda	98.7	120.4	1.0	1.0	1.3	1.0	1.0	1.0
Maulee	70.6	117.4	2.0	2.0	1.8	1.0	1.0	1.0

Table 4 continued

Genotype	Trichome density on adaxial leaf surface		Leaf midrib color		Waxy bloom		Plant color	
	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS
Phule Chitra	86.3	114.8	2.0	2.0	1.3	1.0	1.0	1.0
Phule Anuradha	100.3	118.2	1.0	1.0	1.8	1.0	1.0	1.0
M 35-1	79.2	110.9	2.0	2.0	2.0	1.0	1.0	1.0
Parbhani Moti	75.7	79.2	2.0	1.0	1.5	1.0	1.0	1.0
CSV 18R	96.1	113.8	1.8	2.0	1.3	1.0	1.0	1.0
CSV 15	0.0	0.0	2.0	1.0	3.0	1.0	2.0	2.0
ICSV 705	78.8	105.2	2.0	2.0	3.0	3.0	2.0	2.0
ICSV 713	53.3	200.1	2.0	2.0	3.0	3.0	2.0	2.0
ICSV 25019	76.2	121.2	2.0	2.0	3.0	2.0	2.0	2.0
ICSV 25022	103.6	107.6	2.0	2.0	3.0	2.0	2.0	2.0
ICSV 25026	116.8	127.2	2.0	2.0	3.0	2.0	2.0	2.0
ICSV 25039	171.6	159.4	2.0	2.0	3.0	2.0	2.0	2.0
PS 35805	94.0	120.3	2.0	2.0	3.0	2.0	2.0	2.0
IS 2123	74.2	87.1	1.0	1.0	1.5	1.0	1.0	1.0
IS 2146	113.0	146.9	1.0	1.0	1.8	1.0	1.0	1.0
IS 2312	100.7	110.7	1.0	1.0	1.0	1.0	1.0	1.0
Akola Kranti	99.0	128.9	1.0	1.0	1.5	1.0	1.0	1.0
Phule Vasudha	103.2	165.0	1.0	1.0	1.3	1.0	1.0	1.0
ICSV 93046	126.0	153.7	2.0	2.0	2.0	2.0	2.0	2.0
IS 18551(R)	139.9	125.9	1.0	1.0	1.0	1.0	1.0	1.0
Swarna (S)	16.4	32.1	2.0	2.0	3.0	3.0	1.0	1.0
RVRT 2	55.4	73.1	2.0	2.0	1.5	1.0	1.0	1.0
Giddi Maldandi	83.2	97.9	2.0	2.0	3.0	2.0	1.0	1.0
RVRT 3	57.0	85.3	1.0	1.0	1.0	1.0	1.0	1.0
Dagidi Solapur	80.2	95.9	2.0	2.0	2.0	1.0	1.0	1.0
296 B	0.4	0.0	1.0	1.0	3.0	3.0	2.0	2.0
Mean	85.1	106.9	1.7	1.6	2.1	1.6	1.4	1.4
SE ±	9.0	14.6	0.0	0.1	0.2	0.1	0.0	0.1
Vr (58,29)	18.87**	9.09**	108.59**	–	22.93**	–	0.0	–
LSD ($p \leq 0.05$)	25.3	41.4	0.1	–	0.5	–	0.0	–

R resistant check, *S* susceptible check, *RS* rainy season, *PRS* postrainy season, *Leafsheath pigmentation* 1–3 ranking with 1 highly pigmented, 3 non pigmented, *Seedling vigor score* 1–3 ranking with 1 highly vigorous, 3 poor plant vigor, Trichome density: number of trichomes/microscopic area, *Leaf glossy score* 1–5 ranking with 1 highly glossy, 5 non glossy, *Leaf midrib color* 1–4 ranking with 1 white leaf midrib, 4 brown leaf midrib, *Waxy bloom* 1–3 ranking with 1 slightly waxy, 3 completely waxy, *Plant color* 1–2 ranking with 1 pigmented-non tan, 2 non pigmented-tan

** F test significant at *p* 0.01

Path-coefficients of morphological and agronomic traits on expression of resistance to sorghum shoot fly, *A. soccata*

The direct effects and the correlation coefficients of leaf glossy score, plant vigor, trichome density on the abaxial leaf surface, plant height, and plant color were in the same direction (+ve or −ve), and hence these traits can be used as a criteria to select for resistance to shoot fly during rainy season (Table 5); whereas the direct effects and the correlation coefficients of trichome density on the adaxial leaf surface and 100 seed weight were in opposite direction, and hence these traits will not be useful for selecting the shoot fly

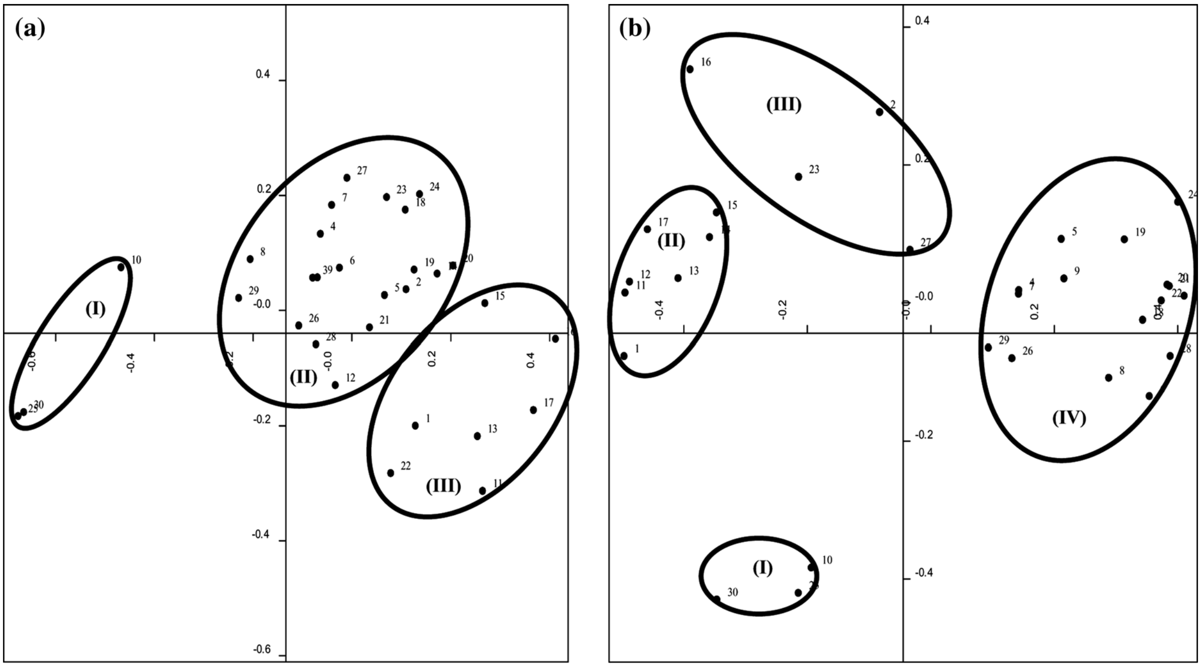


Fig. 2 Diversity (principal co-ordinates) among the sorghum genotypes based on **a** shoot fly resistance and **b** morphological traits across seasons. (*1* ICSB 433, *2* ICSV 700, *3* Phule Yashoda, *4* Maulee, *5* Phule Chitra, *6* Phule Anuradha, *7* M 35-1, *8* Parbhani Moti, *9* CSV 18R, *10* CSV 15, *11* ICSV 705, *12* ICSV 713, *13* ICSV 25019, *14* ICSV 25022, *15* ICSV 25026, *16* ICSV 25039, *17* PS 35805, *18* IS 2123, *19* IS 2146, *20* IS 2312, *21* Akola Kranti, *22* Phule Vasudha, *23* ICSV 93046, *24* IS 18551, *25* Swarna, *26* RVRT 2, *27* Giddi Maldandi, *28* RVRT 3, *29* Dagidi Solapur, *30* 296 B)

resistant sorghums. The residual effect (0.08) of path coefficient analysis in the rainy season was very low.

Path coefficient analysis with shoot fly deadhearts as a dependant factor indicated that the direct effects and the correlation coefficients of leaf glossiness, plant vigor, trichomes on abaxial leaf surface, plant height, and plant color were in the same direction (+ve or −ve), and hence, these traits can be used as a criteria to select for resistance to shoot fly during postrainy season. However, the direct effects and the correlation coefficients of leafsheath pigmentation, and trichomes on abaxial leaf surface were in opposite direction, and hence these traits will not be useful to select for resistance to shoot fly during the postrainy season. Lower residual effect of 0.03, was observed in the postrainy season.

Genetic parameters for shoot fly resistance and morphological traits

The genetic parameters for shoot fly resistance and morphological traits (Table 6) revealed that shoot fly oviposition differed across the seasons, with high levels of heritability (74.19 %) and genetic advance (113.94 %) in the rainy season; whereas, these estimates were low during the postrainy season. Shoot fly deadhearts, leaf glossiness, leafsheath pigmentation, plant vigor, and the trichome density on the abaxial and adaxial leaf surfaces exhibited high broadsense heritability and genetic advance indicating that these traits had high genetic heritability. The genetic parameters of shoot fly deadhearts varied across seasons with high heritability (76.22 %) and genetic advance (154.30 %) in the rainy season. The PCV percentage of leaf glossiness, leafsheath pigmentation, oviposition, and trichome density was high indicating the seasonal influence of these traits, with resistance to shoot fly. However, high GCV percentage, broad sense heritability and genetic advance suggested the predominance of additive nature of genes controlling shoot fly resistance, and there is a good possibility of breeding for shoot fly-resistant sorghums.

Discussion

The experiments were conducted both in the rainy and postrainy seasons to identify genotypes exhibiting

Table 5 Direct (diagonal) and indirect (off the diagonal) effects of agronomic and morphological traits on expression of resistance to shoot fly, *A. soccata* (plants with shoot fly deadhearts) in sorghum across seasons

Traits	Leaf glossy score	Leafsheath pigmentation	Plant vigor score	Trichome density on abaxial leaf surface	Trichome density on adaxial leaf surface	Plant height	Plant color	100 seed weight	Shoot fly deadhearts
Leaf glossy score	0.47 (0.16)	0.11 (−0.07)	−0.04 (0.00)	0.33 (−0.04)	−0.24 (0.03)	−0.24 (0.03)	−0.10 (0.03)	−0.04 (0.08)	0.34 (0.83**)
Leafsheath pigmentation	0.25 (0.10)	0.20 (−0.11)	−0.04 (−0.00)	0.28 (−0.02)	−0.23 (0.02)	−0.33 (0.06)	−0.16 (0.13)	−0.03 (−0.04)	−0.05 (0.42*)
Plant vigor score	0.24 (−0.01)	0.11 (−0.02)	−0.08 (−0.03)	0.02 (0.00)	−0.03 (−0.01)	−0.45 (0.09)	−0.17 (0.21)	0.05 (−0.22)	−0.43* (−0.13)
Trichome density on abaxial leaf surface	−0.20 (−0.112)	−0.07 (0.05)	0.00 (−0.00)	−0.78 (0.05)	0.53 (−0.05)	0.13 (−0.02)	0.01 (−0.01)	0.07 (−0.08)	−0.53** (−0.72**)
Trichome density on adaxial leaf surface	−0.20 (−0.11)	−0.09 (0.05)	0.00 (−0.00)	−0.75 (0.05)	0.56 (−0.05)	0.14 (−0.04)	−0.00 (0.00)	0.07 (−0.05)	−0.48** (−0.76**)
Plant height	−0.20 (−0.03)	−0.12 (0.05)	0.06 (0.02)	−0.19 (0.01)	0.14 (−0.02)	0.56 (−0.13)	0.18 (−0.19)	−0.08 (0.24)	0.45** (−0.21)
Plant color	0.17 (0.02)	0.13 (−0.05)	−0.05 (−0.02)	0.02 (−0.00)	0.00 (−0.00)	−0.39 (0.09)	−0.26 (0.28)	0.10 (−0.25)	−0.48** (0.02)
100 seed weight	0.07 (0.04)	0.02 (0.01)	0.02 (0.02)	0.20 (−0.01)	−0.13 (0.01)	0.16 (−0.10)	0.09 (−0.21)	−0.28 (0.34)	0.38** (0.22)

The values outside the parentheses are path coefficients for the rainy season and those inside the parentheses are path coefficients for the postrainy season

*, ** Correlation coefficients significant at p 0.05 and 0.01, respectively, residual effect = 0.08 (0.03)

Table 6 Genetic parameters of the shoot fly resistance and morphological traits in sorghum

Traits	Plants with shoot fly eggs (%)	Number of shoot fly eggs/plant	Shoot fly deadhearts (%)	Leaf glossy score	Leafsheath pigmentation	Plant vigor score	Trichome density on the abaxial leaf surface	Trichome density on the adaxial leaf surface
ECV (%)	29.81 (2.78)	37.87 (15.75)	47.93 (11.71)	15.49 (26.73)	21.94 (24.58)	27.86 (27.71)	22.91 (26.62)	18.21 (23.69)
GCV (%)	55.42 (1.74)	64.21 (3.23)	85.80 (14.20)	46.68 (35.15)	22.30 (25.60)	30.39 (38.09)	49.05 (38.95)	44.44 (38.91)
PCV (%)	62.93 (3.27)	74.55 (16.08)	98.28 (18.40)	49.18 (44.16)	31.29 (35.50)	41.23 (47.10)	54.13 (47.17)	48.02 (45.55)
%H	77.56 (28.11)	74.19 (4.04)	76.22 (59.51)	90.08 (63.36)	50.81 (52.02)	54.35 (65.39)	82.08 (68.16)	85.62 (72.95)
GA%	100.54 (1.90)	113.94 (1.34)	154.30 (22.57)	57.64 (57.64)	32.74 (38.04)	46.16 (63.44)	91.53 (66.23)	84.70 (68.46)

The values outside the parentheses are for the rainy season and those inside the parentheses are for the postrainy season

ECV (%) environmental coefficient of variation, *GCV (%)* genotypic coefficient of variation, *PCV (%)* phenotypic coefficient of variation, *%H* broad sense heritability, *GA%* genetic advance percent of mean shoot fly resistance across the seasons, so that suitable breeding strategies can be effectively applied in developing the shoot fly resistant hybrids. Seventeen genotypes exhibited resistance to shoot fly damage across seasons, of which ICSB 433, ICSV 700, ICSV 25019, ICSV 25022, ICSV 25026, ICSV 25039, PS 35805, Akola Kranti, and IS 18551 showed both antixenosis and antibiosis component resistance to this insect. Both chemical and morphological factors mediate antibiosis to sorghum shoot fly (Sharma and Nwanze 1997). The genotypes with different resistance mechanisms can be used for developing the shoot fly resistant sorghums.

The intensity of oviposition was high in the rainy season under moderate and high humidity (Appendix 3) than in the postrainy season, suggesting that environmental conditions during the rainy season are favourable for shoot fly survival.

Positive influence of leaf glossiness, leafsheath pigmentation, trichome density and endosperm texture on shoot fly resistance was observed, suggesting that these traits can be used as markers to select for shoot fly resistance in sorghum (Sharma and Nwanze 1997; Dhillon et al. 2006a; Riyazaddin et al. 2015). Path coefficients of leaf glossiness, plant vigor, plant height, plant color and trichome density exhibited direct effects and correlation in the same direction suggesting the importance of these traits in shoot fly resistance. Seedling vigor was negatively associated with shoot fly resistance as was reported by Dhillon et al. (2005) and Chamarthi et al. (2011), although it has been reported to be positively associated with resistance to shoot fly (Taneja and Leuschner 1985). Trichomes on either of the leaf surfaces contributed to the expression of resistance to shoot fly in sorghum, as trichomes probably hinder the movement of newly hatched larvae to the base of the whorl. Expression of resistance to shoot fly is high in genotypes possessing both the glossy and trichome traits together (Agrawal and House 1982; Dhillon et al. 2005). Nine genotypes exhibited leaf glossiness, leafsheath pigmentation, trichomes on abaxial and adaxial leaf surface and expressed resistance to shoot fly with lower oviposition and deadhearts across seasons, indicating the importance of these traits for shoot fly resistance and as well as the resistant nature of the genotypes. Identification of genomic regions/quantitative trait loci (QTL) governing shoot fly, *A. soccata* resistance can be used for rapid genetic manipulation through marker-assisted selection (MAS). Identification of QTLs controlling expression of resistance to shoot fly would improve our understanding of inheritance of these traits, enable us to analyze the association between these traits, clarify the relationships of QTLs to candidate genes, and finally provide the basis for MAS of these traits and can be effectively utilised in sorghum improvement (Aruna et al. 2011b; Nagaraja Reddy et al. 2013).

Some of the genotypes used in this study exhibited resistance to shoot fly either in the rainy or in the postrainy season, suggesting that environmental influence on expression of resistance to *A. soccata* (Riyazaddin et al. 2015). Seasonal variation in expression of resistance to insects is influenced by the effect of climatic factors on survival and development of insects, and the indirect effects through variation in plant growth and biochemical composition of the host plants (Sharma 2014). Trait heritabilities can be determined with greater accuracy if it is studied along with genetic advance, and genetic advance of percent mean (Johnson et al. 1955). The success of a variety crop improvement program depends largely on the genetic variability present in the population. Genetic coefficients of variation along with heritability estimates provide a better indication of the amount of genetic variation for a trait than the either parameter alone. In the present studies, the environmental factors influenced the expression resistance to sorghum shoot fly, but high heritability and genetic advance suggested the possibility of developing shoot fly-resistant sorghums. High heritability, GCV and genetic advance indicated predominance of additive gene effects in controlling the expression of shoot fly resistance. Trichome density and leaf glossiness have high heritability, and are highly correlated with expression of resistance to shoot fly (Maiti and Gibson 1983; Sharma and Nwanze 1997; Dhillon et al. 2005, 2006a; Aruna and Padmaja 2009). Season specific expression of shoot fly resistance indicated that there is a need to breed the sorghum genotypes specific for the rainy or postrainy seasons.

Principal co-ordinate analysis placed the test genotypes into different groups suggesting that there is considerable diversity among the genotypes tested. The shoot fly-resistant genotypes placed in different groups can be used to increase the level and broaden the genetic base of resistance to shoot fly. The shoot fly resistance and the morphological traits that exhibited direct effects and correlations in the same direction can be used to select shoot fly resistant sorghums.

Phule Yashoda, Maulee, Phule Anuradha, IS 2312, Phule Vasudha, and RVRT 2 suffered lower shoot fly damage, and had high grain yield during the postrainy season; while ICSB 433, ICSV 700, M 35-1, ICSV 25019 and ICSV 25022 showed high grain yield during the rainy season and also suffered low shoot fly damage. Hence, these genotypes can be exploited for developing high-yielding sorghums with resistance to shoot fly.

Conclusions

The genotypes exhibiting resistance to shoot fly, *A. soccata* across seasons can be effectively utilised in breeding the shoot fly-resistant sorghums. Leaf glossiness, leafsheath pigmentation, and trichome density can be used as the marker traits for selecting the shoot fly-resistant sorghums. Genotypes with diverse shoot fly resistance and morphological traits can be effectively utilised as parents in developing high yielding shoot fly-resistant sorghums. Shoot fly resistance, and morphological and agronomic traits exhibiting significant correlations, and direct/indirect effects (path coefficients) in the same direction (−ve or −ve) could be used as a selection criteria to develop shoot fly-resistant cultivars. High magnitude of broad-sense heritability along with higher genetic advance for shoot fly resistance and morphological traits suggested that these traits were under the control of additive genes, and can be used in selecting genotypes for use in sorghum improvement programs.

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Appendix 1

See Table 7.

Table 7 Sorghum descriptors (ICRISAT, Patancheru, 2011–2014)

S. no.	Plant trait	Description	Score
1.	Leaf glossy score	Highly glossy	1
		Glossy	2
		Moderately glossy	3
		Slightly glossy	4
		Non glossy	5
2.	Leafsheath pigmentation	Highly pigmented	1
		Medium	2
		Non pigmented	3
3.	Seedling vigor	High	1
		Intermediate	2
		Low	3
4.	Leaf midrib color	White	1
		Dull green	2
		Yellow	3
		Brown	4
5.	Waxy bloom	Slightly present	1
		Medium	2
		Completely present	3
6.	Plant color	Pigmented	1
		Non pigmented	2
7.	Plant height	Height of three randomly selected plants	Cms
8.	Awns	Absent	1

Table 7 continued

S. no.	Plant trait	Description	Score
		Present	2
9.	Inflorescence exsertion	Fully exserted	1
		Medium	2
		Poor exsertion	3
10.	Panicle compactness	Loose	1
		Semiloose	2
		Compact	3
11.	Panicle shape	Erect	1
		Drooping	2
		Oval	3
		Elliptic	4
12.	Glume color	White	1
		Mahogany	2
		Red	3
		Red black	4
		Black	5
		Purple	6
13.	Glume coverage	25 % grain covered	1
		50 % grain covered	3
		75 % grain covered	5
		Grain fully covered	7
		Glumes longer than Grain	9
14.	Grain color	White	1
		Yellow	2
		Red	3
		Brown	4
		Buff	5
15.	Grain lustre	Absent	1
		Present	2
16.	Grain subcoat	Absent	1
		Present	2
17.	Endosperm texture	Completely corneous	1
		Intermediate	3
		Completely starchy	5
18.	Endosperm color	White	1
		Yellow	2
		Red	3

Source IBPGR and ICRISAT 1993

Appendix 2

See Table 8.

Table 8 Panicle and grain characteristics of sorghum genotypes evaluated for resistance to sorghum shoot fly, *A. soccata* (ICRISAT, Patancheru, 2011–2012)

Genotype	Inflorescence exertion		Panicle compactness		Panicle shape		Glume color		Glume coverage		Awns	
	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS
ICSB 433	1.0	2.0	2.0	2.0	1.0	1.0	1.0	1.0	1.7	1.0	1.0	1.0
ICSV 700	2.0	3.0	2.0	2.0	1.0	1.0	2.0	2.0	3.7	3.0	2.0	2.0
Phule Yashoda	2.7	2.0	2.0	2.0	1.0	1.0	1.0	1.0	3.0	5.0	2.0	2.0
Maulee	3.0	2.0	2.0	2.0	1.0	1.0	1.3	1.0	1.7	3.0	2.0	2.0
Phule Chitra	2.7	3.0	2.0	2.0	1.0	1.0	1.0	3.0	1.7	5.0	2.0	2.0
Phule Anuradha	3.0	3.0	2.0	2.0	1.0	1.0	2.7	1.0	3.0	3.0	2.0	2.0
M 35-1	3.0	2.0	2.0	2.0	1.0	1.0	1.3	1.0	1.0	3.0	2.0	2.0
Parbhani Moti	3.0	1.0	2.0	2.0	1.0	1.0	1.0	1.0	1.7	1.0	2.0	2.0
CSV 18R	2.0	2.0	2.0	2.0	1.0	1.0	1.0	1.0	2.3	5.0	2.0	2.0
CSV 15	1.7	2.0	2.0	2.0	1.0	1.0	1.3	2.0	3.0	1.0	1.0	1.0
ICSV 705	2.3	3.0	2.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ICSV 713	1.0	2.0	2.0	2.0	1.0	1.0	1.3	1.0	2.3	1.0	1.3	1.0
ICSV 25019	2.0	3.0	2.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ICSV 25022	1.0	2.0	2.0	2.0	1.0	1.0	2.0	1.0	2.3	1.0	2.0	2.0
ICSV 25026	1.0	2.0	2.0	2.0	1.0	1.0	2.0	2.0	1.7	1.0	2.0	2.0
ICSV 25039	1.3	1.0	2.0	2.0	1.0	1.0	1.0	2.0	2.3	3.0	2.0	2.0
PS 35805	2.0	3.0	2.0	2.0	1.0	1.0	1.0	1.0	1.7	1.0	1.0	1.0
IS 2123	3.0	3.0	3.0	3.0	3.0	3.0	1.0	3.0	2.3	3.0	2.0	2.0
IS 2146	3.0	3.0	3.0	3.0	3.0	3.0	2.3	2.0	3.7	3.0	2.0	2.0
IS 2312	3.0	3.0	3.0	3.0	3.0	3.0	1.0	2.0	2.3	3.0	2.0	2.0
Akola Kranti	2.7	2.0	2.0	2.0	1.0	1.0	1.3	2.0	3.0	5.0	2.0	2.0
Phule Vasudha	2.7	2.0	2.0	1.0	1.0	2.0	1.3	3.0	2.3	3.0	2.0	2.0
ICSV 93046	2.0	3.0	2.0	2.0	1.0	1.0	1.0	1.0	3.7	3.0	2.0	2.0
IS 18551(R)	1.3	3.0	3.0	3.0	4.0	4.0	1.0	2.0	9.0	9.0	2.0	2.0
Swarna (S)	1.0	1.0	2.0	2.0	1.0	1.0	2.0	3.0	3.0	3.0	1.0	1.0
RVRT 2	3.0	2.0	2.0	1.0	1.0	1.0	2.3	3.0	1.0	3.0	2.0	2.0
Giddi Maldandi	3.0	3.0	3.0	2.0	4.0	1.0	3.0	3.0	2.3	5.0	2.0	2.0
RVRT 3	2.0	3.0	2.0	2.0	1.0	1.0	1.0	1.0	3.7	3.0	1.7	2.0
Dagidi Solapur	3.0	3.0	3.0	2.0	3.0	1.0	1.0	1.0	1.0	3.0	2.0	2.0
296 B	2.0	3.0	2.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	2.0
Mean (58, 29)	2.2	2.4	2.2	2.1	1.5	1.3	1.4	1.7	2.4	2.9	1.8	1.8
SE ±	0.2	0.1	0.0	0.1	0.0	0.2	0.2	0.2	0.5	0.3	0.1	0.1

Genotype	Grain color		Grain lustre		Grain subcoat		Endosperm texture		Endosperm color	
	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS
ICSB 433	1.0	1.0	2.0	2.0	2.0	2.0	3.0	3.0	1.0	1.0
ICSV 700	1.0	1.0	2.0	2.0	2.0	2.0	2.3	1.0	1.0	1.0

Table 8 continued

Genotype	Grain color		Grain lustre		Grain subcoat		Endosperm texture		Endosperm color	
	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS
Phule Yashoda	1.0	1.0	2.0	2.0	2.0	2.0	3.0	3.0	1.0	1.0
Maulee	1.0	1.0	2.0	2.0	2.0	2.0	3.0	5.0	1.0	1.0
Phule Chitra	1.0	1.0	2.0	2.0	2.0	2.0	1.7	3.0	1.0	1.0
Phule Anuradha	1.0	1.0	2.0	2.0	2.0	2.0	3.0	5.0	1.0	1.0
M 35-1	1.0	1.0	2.0	2.0	2.0	2.0	4.3	3.0	1.0	1.0
Parbhani Moti	1.0	1.0	2.0	2.0	2.0	2.0	3.0	3.0	1.0	1.0
CSV 18R	1.0	1.0	2.0	2.0	2.0	2.0	3.7	3.0	1.0	1.0
CSV 15	1.0	1.0	1.0	2.0	2.0	2.0	3.0	3.0	1.0	1.0
ICSV 705	1.0	1.0	2.0	2.0	2.0	2.0	1.0	1.0	1.0	1.0
ICSV 713	1.0	1.0	2.0	2.0	2.0	2.0	2.3	1.0	1.0	1.0
ICSV 25019	1.0	1.0	2.0	2.0	2.0	2.0	1.7	3.0	1.0	1.0
ICSV 25022	1.0	1.0	2.0	2.0	2.0	2.0	1.7	1.0	1.0	1.0
ICSV 25026	1.0	1.0	2.0	2.0	2.0	2.0	1.0	1.0	1.0	1.0
ICSV 25039	1.0	1.0	2.0	2.0	2.0	2.0	3.0	3.0	1.0	1.0
PS 35805	1.0	1.0	2.0	2.0	2.0	2.0	3.0	1.0	1.0	1.0
IS 2123	1.0	1.0	2.0	2.0	2.0	2.0	1.7	3.0	1.0	1.0
IS 2146	1.0	1.0	2.0	2.0	2.0	2.0	3.0	3.0	1.0	1.0
IS 2312	1.0	1.0	2.0	2.0	2.0	2.0	2.3	1.0	1.0	1.0
Akola Kranti	1.0	1.0	2.0	2.0	2.0	2.0	3.7	3.0	1.0	1.0
Phule Vasudha	1.0	1.0	2.0	2.0	2.0	2.0	3.0	3.0	1.0	1.0
ICSV 93046	1.0	1.0	2.0	1.0	2.0	2.0	1.7	1.0	1.0	1.0
IS 18551(R)	1.0	1.0	2.0	1.0	2.0	2.0	2.3	3.0	1.0	1.0
Swarna (S)	1.0	1.0	2.0	2.0	2.0	2.0	2.3	3.0	1.0	1.0
RVRT 2	1.0	1.0	2.0	2.0	2.0	2.0	3.0	5.0	1.0	1.0
Giddi Maldandi	1.0	1.0	2.0	2.0	2.0	2.0	3.0	5.0	1.0	1.0
RVRT 3	1.0	1.0	2.0	2.0	2.0	2.0	3.7	5.0	1.0	1.0
Dagidi Solapur	1.0	1.0	2.0	2.0	2.0	2.0	2.3	3.0	1.0	1.0
296 B	1.0	1.0	2.0	2.0	2.0	2.0	5.0	3.0	1.0	1.0
Mean (58, 29)	1.0	1.0	2.0	1.9	2.0	2.0	2.7	2.8	1.0	1.0
SE ±	0.0	0.0	0.0	0.1	0.0	0.0	0.5	0.2	0.0	0.0

R resistant check, *S* susceptible check, *RS* rainy season, *PRS* postrainy season, *Inflorescence exsertion* 1–3 ranking with 1 panicle fully exserted, 3 poor panicle exsertion, *Panicle compactness* 1–3 ranking with 1 loose inflorescence, 3 compact inflorescence, *Panicle shape* 1–4 ranking with 1 erect inflorescence, 4 elliptic inflorescence, *Glume color* 1–6 ranking with 1 white glume, 6 purple glume, *Glume coverage* 1–9 ranking with 1.25 % grain covered with glumes, 9 glumes longer than the grain, *Awns* 1–2 ranking with 1 awns absent, 2 presence of awns, *Grain color* 1–5 ranking with 1 white colored grain, 5 buff colored grain, *Grain lustre* 1–2 ranking with 1 non lustrous grain, 2 lustrous grain, *Grain subcoat* 1–2 ranking with 1 absence of grain subcoat, 2 presence of grain subcoat, *Endosperm texture* 1–5 ranking with 1 completely corneous endosperm, 5 completely starchy endosperm, *Endosperm color* 1–3 ranking with 1 white colored endosperm, 3 red colored endosperm

Appendix 3

See Table 9.

Table 9 The temperature and relative humidity (weather conditions) at ICRISAT, Patancheru, 2011–2012 postrainy and rainy seasons (1 month)

Standard week		Maximum temperature		Minimum temperature		Relative humidity1		Relative humidity2	
2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS	2011 PRS	2012 RS
40	26	31.6	32.5	20.4	22.6	86.0	87.0	44.0	51.0
40	27	31.8	29.8	20.3	22.6	90.0	87.0	46.0	69.0
40	27	32.2	29.5	20.5	22.2	93.0	83.0	46.0	64.0
40	27	31.8	30.2	21.0	22.3	98.0	81.0	52.0	64.0
40	27	26.6	31.8	21.0	23.6	98.0	77.0	85.0	53.0
40	27	30.5	32.7	19.0	23.8	96.0	76.0	52.0	53.0
40	27	30.9	30.4	20.0	20.8	93.0	90.0	50.0	59.0
41	27	31.4	30.7	20.2	22.7	95.0	84.0	56.0	66.0
41	28	31.4	32.6	20.0	22.0	96.0	92.0	56.0	55.0
41	28	31.8	31.2	20.8	21.7	96.0	93.0	49.0	55.0
41	28	31.6	33.2	21.8	22.8	97.0	85.0	59.0	50.0
41	28	30.8	33.7	22.4	22.5	91.0	84.0	64.0	50.0
41	28	29.3	33.6	21.2	23.8	98.0	83.0	81.0	51.0
41	28	31.3	32.7	21.0	21.0	97.0	98.0	58.0	63.0
42	28	32.8	29.0	21.8	21.5	95.0	98.0	48.0	71.0
42	29	32.2	28.4	24.4	21.6	98.0	97.0	55.0	74.0
42	29	33.2	27.5	18.8	22.0	95.0	92.0	57.0	81.0
42	29	33.2	31.3	18.0	21.9	94.0	93.0	36.0	67.0
42	29	32.8	29.2	19.0	20.8	89.0	91.0	35.0	71.0
42	29	32.0	27.4	19.0	22.0	72.0	91.0	39.0	77.0
42	29	31.8	28.0	20.0	20.8	93.0	98.0	37.0	78.0
43	29	32.6	26.0	17.0	21.6	92.0	92.0	32.0	90.0
43	30	32.5	27.8	16.7	21.8	83.0	85.0	30.0	78.0
43	30	32.0	31.3	17.4	22.0	85.0	91.0	39.0	61.0
43	30	32.0	30.4	18.4	22.4	84.0	87.0	37.0	67.0
43	30	32.0	28.8	21.5	21.0	91.0	91.0	41.0	77.0
43	30	29.0	27.6	21.7	22.4	91.0	87.0	56.0	73.0
43	30	30.7	27.7	21.7	22.0	91.0	90.0	54.0	73.0
44	30	30.6	30.8	19.0	21.5	95.0	88.0	52.0	61.0
44	31	30.5	29.8	18.8	21.8	84.0	90.0	48.0	64.0
44	31	30.6	29.2	17.2	22.0	92.0	85.0	48.0	66.0
44	31	30.8	28.2	19.8	20.9	96.0	91.0	47.0	68.0
44	31	30.6	29.9	21.7	21.0	97.0	91.0	52.0	62.0
44	31	28.2	29.2	21.0	20.8	88.0	91.0	62.0	69.0
44	31	25.0	27.5	18.6	21.8	93.0	91.0	79.0	92.0

RS rainy season, *PRS* postrainy season, *Relative humidity1* recorded early in the morning, *Relative humidity2* recorded at 1400 h

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