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Research article

Evaluation of sorghum genotypes and influence of weather variables on anthracnose (*Colletotrichum sublineolum*) disease development under field conditions at Jimma, southwestern Ethiopia

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ABSTRACT

The severity and temporal dynamics of sorghum anthracnose on six and nine sorghum genotypes were evaluated on field plots during 2014 and 2015 cropping years in Southwestern Ethiopia, respectively. Anthracnose severity was assessed as the proportion of leaf area affected by the disease. 12 consecutive time point anthracnose severity assessments and their mean severity, disease progress rate, AUDPC, grain yield and yield related components were used to evaluate the response of the genotypes. In the year 2014 and 2015, the mean anthracnose severity was varying from 65 to 79 PSI and 54–82 PSI among six and nine sorghum genotypes, respectively. AUDPC varied from 5063 to 6113%-day and 4171 to 6383%-day in the year 2014 and 2015, respectively. BRC-378 and BRC-245 genotypes consistently had the lowest disease levels and highest grain yields during the two experimental years. The disease pressure was reduced, whereas grain yield and 1000-seed weight of the genotypes were increased in 2015 cropping year. Anthracnose severity was strongly correlated with weather variables and showed strong negative associations with grain yield of all tested sorghum genotypes.

1. Introduction

Sorghum (*Sorghum bicolor* L. Moench) is a primary staple food crop in the semi-arid tropics of Africa and Asia for more than 300 million people [1]. Ethiopia is the second largest producer of sorghum in Eastern and Southern Africa after Sudan [2]. It accounts for an average 10% of daily caloric intake of households living in the eastern and northwest areas of the country [3]. However, its production is limited by various constraints, and among others, sorghum anthracnose, caused by a fungal pathogen *Collototrichum sublineolum*, is one of the most destructive sorghum diseases limiting grain production in most sorghum growing regions [4] including Ethiopia [5–8].

Anthracnose disease epidemics are more frequent in tropical and subtropical regions where warm, humid climatic conditions contribute to the rapid development and spread of the disease [9]. Disease epidemics can result in grain yield losses of more than 50% for susceptible cultivars [9–11]. The development of anthracnose in sorghum fields largely depends on host susceptibility, virulence of the fungal strain and prevailing weather conditions [12,13]. Rainfall is a major climatic factor influencing anthracnose development

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[14]. A grain yield loss ranging from 26 to 35% on susceptible cultivar was reported at eastern Ethiopia [6], demanding for immediate management practices.

Several management strategies towards limiting the effect of anthracnose of sorghum have been used with different achievements on the basis of patho-systems. More diverse types of foliar biocontrol agents need to be evaluated for developing an eco-friendly and sustainable approach for management of sorghum anthracnose [15]. The use of fungicides to protect sorghum against anthracnose poses risk to both workers and the environment and reduces the producer's profit margin; making cultivation of anthracnose resistant sorghums is the preferred way of safeguarding the crop [16]. The choice of cultivars were found to influence the development of anthracnose in the field [17]. In addition, shifting of planting dates is also found to significantly affect the development of the disease [10,17] and hence could play a role in reducing anthracnose severity. Genetic resistance has been the main strategy for the control of this disease, but host-specific resistance is often unstable because of the high variability [18] and rapid evolution of new races or pathotypes in the pathogen populations [19]. Breeding for resistance, which has been found to be the most practical, economical and feasible method for plant disease management is not able to match with the development of more virulent pathogens. It is well known that pathogenic variability creates difficulty for the identification of an effective host resistance and its deployment, which is a reliable and economic practice of plant disease management [20].

Furthermore, understanding the temporal dynamics of the disease is an essential task to identify the proper planting time, which in turn contributes towards developing effective, affordable, safe and sustainable management strategies [21]. Hence, understanding the interaction effect of genotypes with the main weather factors that prevail in the cropping season on sorghum anthracnose leads to successful management schemes through selection and breeding in Ethiopia. Therefore, the objective of this research was to evaluate the reaction of sorghum genotypes and influence of weather variables on anthracnose under field conditions at Jimma, Southwestern Ethiopia.

2. Materials and methods

2.1. Description of the study site

The field experiment was conducted at Jimma University Research Field (*Eladale*) during the 2014 and 2015 main cropping seasons. The research site is located at '36°48′ East-longitude, 7°42' North-latitude and at an altitude of 1821 m. a.s.l. It is situated in Southwestern Ethiopia and characterized by a humid type of climate with average annual rainfall of about 1616 mm, annual mean minimum and maximum temperature of 12.4 °C and 28.4 °C, respectively. The soil type is clay with average pH of 5.5 [22].

2.2. Land preparation, experimental materials, experimental units and design

2.2.1. Land preparation

The land was prepared by plowing two times in each cropping seasons. Recommended rates of fertilizer DAP and urea at a rate of 100 kg ha^{-1} was applied [23]. It was performed by applying DAP at the time of sowing and urea was applied when the sorghum plants reached at knee height (0.50 m). Cultivation and weed managements were carried out three times after planting.

2.2.2. Experimental materials

Five released sorghum genotypes (Sartu, ACC-BRC-18, BRC-378, ACC-BRC-5 and BRC-245) with different level of resistance (Table 1) and one local check genotype were evaluated for their reaction to anthracnose in 2014. In addition to the above six sorghum genotypes, ETS-3931, ETS-2416 and BTx623 (universally susceptible) were evaluated in 2015 cropping year (Table 1).

2.2.3. Experimental units and design

The experimental units were six sorghum genotypes tested in 2014 cropping season and nine sorghum genotypes tested in 2015

Table 1
Agronomic characteristics of released sorghum genotypes used in the field studies at Jimma, Southwestern Ethiopia during 2014 and 2015.

Sorghum genotype	Pedigree name	Year of release	Disease reaction	Production area (m)	Days to maturity	Yield (tonnes ha^{-1})		Released by*
						Research center	Farmer field	
Aba-Melko	Sartu	2001	R	1600–1800	160–180	7.5	5	JARC
Chemeda	ACC-BRC-18	2013	R	1500–1900	180	3.2	2.5	BARC
Gemedi	ACC-BRC-5	2013	R	1500–1900	175	3.3	2.8	BARC
–	ETS-3931	–	R	–	–	–	–	–
Dano	BRC-378	2006	MR	1500–1900	198	4.-5	3–4.8	BARC
Lalo	BRC-245	2006	MR	1500–1900	199	4–5.2	3.5–4.8	BARC
–	ETS-2416	–	MR	–	–	–	–	–
Local check	–	–	NA		–	–	–	–
–	BTx623	–	HS	–	–	–	–	–

Source [24–27]: * JARC = Jimma agricultural research center, BARC = Bako agricultural research center, R = Resistant, MR = Moderately Resistant, NA = not available, HS = highly susceptible.

cropping season. The experiment was arranged in randomized complete block design (RCBD) with three replications. The experiments were conducted under naturally infected fields (no artificial inoculations). Spacing between blocks and plots were 1.5 m and 1 m, respectively. Each plot had 2 m×3.75 m (7.5 m^2) areas with five-rows. The inter row and intra-row spacing of 0.75 m and 0.20 m were used, respectively [23]. In each plot 50 plants were grown and each row had 10 sorghum plants. Sowing was done on April 12th and May 4th in 2014 and 2015 cropping seasons, respectively. The variation in date of sowing between the two years happened due to the late appearance of rainfall in 2015 cropping season. Two seeds per hill were sown and plants were thinned to one plant per hill at 21 days after sowing.

2.3. Data collection

2.3.1. Weather data

Monthly weather data (rainfall, minimum and maximum temperature) of two consecutive years of 2014 and 2015 main cropping seasons of the area were obtained from the National Meteorological Agency of Jimma Station [28]. The data for 2014 and 2015 were summarized and used for correlation analysis with severity records of anthracnose.

2.3.2. Disease assessment

Anthracnose severity was assessed as the proportion of leaf area affected by the disease on 15 randomly selected and pre-tagged plants in the middle three rows. In this study, the onset of the disease was observed at 1st and 4th week of July in 2014 and 2015, respectively. Anthracnose disease was scored in twelve consecutive time points at 7-day intervals starting from 12 weeks (84 days) after sowing of each cropping year. It was started from the onset of clear symptoms of the disease on the Local check and BTx623 (universally susceptible) sorghum genotypes in 2014 and 2015, respectively. Finally severity grades were converted into percent severity index (PSI) for analysis using the following formula (equations −1) suggested by Ref. [29]:

$$\mathrm{PSI} = \frac{\mathrm{Snr}}{\mathrm{Npr} \times \mathrm{Mss}} \times 100$$

Where Snr = sum of numerical ratings, Npr = number of plants rated, Mss = the maximum severity scale of sorghum anthracnose.

The disease progress rates (r) were calculated basing on the linearized logistic model (equations −2) [30] and the calculated value were analyzed by using SAS software:

$$\mathrm{r} = \frac{\left(\ln \frac{\mathrm{X}}{1-\mathrm{X}}\right) - \left(\ln \frac{\mathrm{X_o}}{1-\mathrm{X_0}}\right)}{\mathrm{t}}$$

Where: r = disease progress rate, Xo = initial disease severity, X = final disease severity, t = the duration of the epidemic and ln = Natural logarithm.

Area under the disease progress curve (AUDPC) was calculated from the percent severity index (PSI) data following the method (equations −3) proposed by Ref. [31].

$$\mathrm{AUDPC} = \sum_{i=1}^{n-1} \left[\frac{(\mathrm{X_i} + \mathrm{X_{i+1}})}{2}\right] (\mathrm{t_{i+1}} - \mathrm{t_1})$$

Where: X_i = percent leaf area covered by anthracnose at ith observation, t_i = time in days of the ith assessment from the first assessment date and n = total number of disease assessments.

2.3.3. Yield and yield related traits

Sorghum genotypes were also evaluated for their performance in terms of grain yield and yield related traits. Plant height was recorded by measuring the height of the plants from the above ground to the tip of the panicle of 15 plants in the middle three rows. Panicle length was recorded by measuring the length of each panicle from the base to the tip of the panicle. Grain yield (kg/plot) and 1000-seeds weight were recorded from plants in the middle three rows of each plot at harvest. Grain yield was determined from harvested areas. Finally the grain yield per hectare (tonnes ha^{-1}) was calculated by converting the grain yield obtained from harvested middle three rows in each plot into hectare. Moisture content of the grains were adjusted to 12.5%.

2.4. Data analysis

The data of all anthracnose severity assessments, mean anthracnose severity (MAS) of all assessments in PSI, disease progress rate (r), AUDPC, grain yield and yield related traits were analyzed by using SAS software version 9.2 [32]. For treatments having significant differences, LSD test at $p < 0.01$ probability level was used for mean comparisons among treatments. Correlation tests were conducted between the disease components and grain yield, weather variables with disease severity, disease severity with grain yield and, AUDPC with grain yield and yield related traits of the tested sorghum genotypes in the two cropping years were analyzed using SAS software. Regression analysis between AUDPC with grain yield and 100-seed weight was performed using Microsoft Office Excel 2007.

3. Results

3.1. Weather conditions

The research area generally received high but variable rainfall during 2014 and 2015 main cropping seasons. Overall the total annual rainfall was higher during 2014 (1565.7 mm) than in 2015 (1350.6 mm) experimental year. The total monthly rainfall of the research area varied from 126.4 to 265.6 mm during 2014 and from 81 to 308.6 mm during 2015 (Fig. 1). In general, 2014 cropping season received more total rainfall than 2015. High rainfall was recorded in the last experimental month (October) in 2014 as compared with 2015. This high rainfall resulted in spoilage of grains under field condition and lowest grain yields of all tested sorghum genotypes in that year as compared to 2015 (Fig. 4 a and c). On the other hand, the mean maximum temperature showed an increase of∽1 °C in 2015 as compared to the 2014 year mean maximum temperature. Except this, the minimum and average temperature of the area showed small or no variability during all experimental months. The reduction of rainfall and slight increase of temperature during 2015, could be due to the effect of "El Nino weather changes" that happened in Ethiopia as well as in the world. Overall, the area was found to have favorable climatic condition for sorghum anthracnose development. The weather change clearly showed its effects on severity of anthracnose and grain yield of all tested genotypes. The present finding confirmed the significant interaction effect of weather variables and genotypes on anthracnose severity under the field conditions.

3.2. Response of sorghum genotypes to anthracnose disease

All tested sorghum genotypes significantly differed ($p < 0.01$) in disease severity in both experimental years. In the year 2014, mean anthracnose severity varied between 65.2 and 78.5 PSI. The Local check sorghum genotype was found susceptible (78.5 PSI) while BRC-378 genotype was the most resistant (65.2 PSI) followed by BRC-245 (68.8 PSI). In the year 2015, mean anthracnose severity varied between 53.8 and 81.6 PSI (Table 2). BTx623 was found susceptible (81.6 PSI) while BRC-245 genotype was the most resistant (53.8 PSI) than others. Overall the disease pressure was lower in 2015 than in 2014 on the six commonly tested sorghum genotypes. This indicated that 3–15 PSI reductions in MAS were observed on the six commonly tested sorghum genotypes during 2015. The lowest anthracnose severity assessment scores were recorded on BRC-245 and followed by BRC-378 genotype.

Disease progress rate was calculated to all sorghum genotypes in the two cropping years and highly significant ($p < 0.01$) difference among some of the tested sorghum genotypes were observed (Table 2). In the year 2014, disease progress rate was varied between 0.04 and 0.09 (logit day^{-1}). The fastest rate of disease development (0.09) was recorded on the Local check, while the slower rate of disease development (0.037) was obtained from BRC-378 genotype than other genotypes. In the year 2015, disease progress rate varied between 0.04 and 0.06. The faster rate of disease development (0.06) was recorded on BTx623, Local check and ETS-2416 genotypes. The slower disease progress rates were recorded on the six sorghum genotypes. The disease showed slower rates of development on BRC-378 and BRC-245 genotypes in both cropping seasons than the rest of the genotypes tested. Generally, the disease development was slow in 2015 on the commonly tested sorghum genotypes. The disease was rapidly developed on susceptible rather than resistant genotypes.

AUDPC was computed from severity records and showed highly significant ($p < 0.01$) differences among the tested sorghum genotypes within the two cropping years. In the year 2014, AUDPC varied between 5062.9 %-days to 6112.6 %-days. The highest AUDPC value (6112.6 %-days) was calculated on the Local check which was found susceptible genotype, while the lowest AUDPC value (5062.9 %-days) was calculated on BRC-378, followed by Sartu and BRC-245 genotypes, which were found resistant to the disease (Table 3). In the year 2014, the second highest AUDPC value (5843.1 %-days) was calculated on ACC-BRC-18 genotype which was previously reported as resistant to anthracnose. But, in the present study it was susceptible with the lowest grain yield in the same cropping year (Table 4). In the year 2015, AUDPC was varied between 6382.8 and 4170.8 %-days. The highest AUDPC of 6382.8 %-days was calculated on BTx623 which is highly susceptible genotype (universally susceptible), followed by the Local check. On the

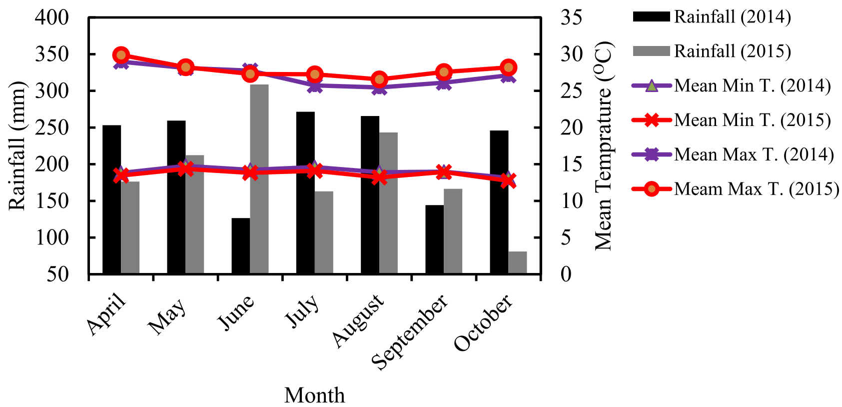

Fig. 1. Monthly rainfall, mean minimum and maximum temperature of the research area during the 2014 and 2015 main cropping seasons [28].

Table 2
Response of sorghum genotypes to anthracnose severity (PSI) and disease progress rate (logit day^{-1}) at Jimma, Southwestern Ethiopia in 2014 and 2015.

Genotype	Mean anthracnose severity (PSI)		Disease progress rate (logit day^{-1})	
	2014	2015	2014	2015
Sartu	66.6 ± 0.8^{de}	63.0 ± 3.2^{c}	0.06 ± 0.00^{b}	0.05 ± 0.00^{b}
ACC-BRC-18	75.0 ± 2.1^{b}	63.5 ± 2.4^{c}	0.06 ± 0.00^{b}	0.04 ± 0.01^{b}
BRC-378	65.2 ± 1.6^{e}	61.3 ± 1.5^{c}	0.04 ± 0.01^{c}	0.04 ± 0.00^{b}
ACC-BRC-5	71.8 ± 1.6^{c}	63.6 ± 2.6^{c}	0.06 ± 0.01^{b}	0.05 ± 0.01^{b}
BRC-245	68.8 ± 1.6^{d}	53.8 ± 1.4^{e}	0.05 ± 0.01^{b}	0.04 ± 0.01^{b}
Local check	78.5 ± 2.9^{a}	75.2 ± 0.3^{b}	0.09 ± 0.00^{a}	0.06 ± 0.01^{a}
BTx623	–	81.6 ± 1.3^{a}	–	0.06 ± 0.01^{a}
ETS-2416	–	72.8 ± 0.3^{b}	–	0.06 ± 0.02^{a}
ETS-3931	–	57.5 ± 1.9^{d}	–	0.04 ± 0.01^{b}
CV (%)	12.1	13.0	11.5	13.8

CV = Coefficient of variation, Mean values with the same superscript letters are not significantly different from each other at $p<0.01\%$.

Table 3
Response of sorghum genotypes to area under disease progress curve (AUDPC) (%-days) at Jimma, Southwestern Ethiopia in 2014 and 2015.

Genotype	Mean AUDPC (%-days)	
	2014	2015
Sartu	5144.6 ± 52.91^{de}	4883.7 ± 245.75^{c}
ACC-BRC-18	5843.1 ± 170.71^{b}	4922.2 ± 200.64^{c}
BRC-378	5062.9 ± 50.16^{e}	4758.8 ± 125.68^{c}
ACC-BRC-5	5570.8 ± 124.14^{c}	4945.5 ± 188.06^{c}
BRC-245	5339.8 ± 112.61^{d}	4170.8 ± 119.94^{d}
Local check	6112.6 ± 240.15^{a}	5855.5 ± 26.42^{b}
BTx623	–	6382.8 ± 113.75^{a}
ETS-2416	–	5688.7 ± 43.48^{b}
ETS-3931	–	4446.2 ± 148.70^{d}
CV (%)	2.24	3.11

CV = Coefficient of variation, Mean values with the same superscript letters are not significantly different from each other at $p<0.01\%$.

Table 4
Reactions of sorghum genotypes on plant height, panicle length, TSW and grain yield within two cropping years in Jimma, Southwestern Ethiopia.

Sorghum Genotype	Plant height (cm)		Panicle length (cm)		TSW (g)		Grain yield tonnes ha-1	
	2014	2015	2014	2015	2014	2015	2014	2015
Sartu	289.8 ± 3.9^{c}	240.9 ± 3.6^{c}	33.3 ± 0.8^{a}	29.9 ± 1.1^{b}	25.0 ± 0.6^{a}	26.5 ± 0.8^{bc}	3.9 ± 0.3^{b}	6.9 ± 0.4b
ACC-BRC-18	364.1 ± 20.2^{b}	350.9 ± 14.7^{b}	23.9 ± 1.0^{c}	28.5 ± 1.5^{bc}	17.9 ± 0.4^{c}	20.6 ± 0.2^{de}	1.0 ± 0.1^{d}	7.5 ± 0.8b
BRC-378	460.7 ± 14.9^{a}	449.2 ± 1.3^{a}	23.6 ± 0.8^{c}	29.7 ± 0.5^{b}	25.0 ± 0.6^{a}	27.8 ± 1.3^{b}	5.2 ± 0.2^{a}	10.4 ± 0.3a
ACC-BRC-5	375.7 ± 6.0^{b}	359.9 ± 14.8^{b}	28.2 ± 0.7^{b}	36.3 ± 1.4^{a}	21.9 ± 0.2^{b}	25.8 ± 1.4^{bc}	1.1 ± 0.3^{d}	6.8 ± 1.1b
BRC-245	469.3 ± 14.9^{a}	464.1 ± 7.4^{a}	23.7 ± 0.8^{c}	30.0 ± 0.6^{b}	22.6 ± 0.6^{b}	25.3 ± 0.7^{c}	5.1 ± 0.8^{a}	10.9 ± 0.3a
Local check	276.0 ± 8.4^{c}	263.8 ± 8.9^{c}	22.4 ± 1.7^{c}	26.0 ± 0.5^{c}	15.8 ± 0.5^{d}	20.4 ± 0.1^{de}	2.5 ± 0.7^{c}	6.9 ± 0.4b
BTx623	–	133.8 ± 7.6^{e}	–	28.1 ± 0.7^{bc}	–	22.4 ± 0.2^{d}	–	2.8 ± 0.3d
ETS-2416	–	253.4 ± 30.8^{c}	–	19.6 ± 1.6^{d}	–	31.3 ± 2.7^{a}	–	3.9 ± 1.2c
ETS-3931	–	184.7 ± 4.7^{d}	–	13.4 ± 0.9^{e}	–	20.1 ± 1.0^{e}	–	2.9 ± 0.6d
CV (%)	3.8	4.7	4.4	6.4	2.6	5.2	16.6	8.0

CV = Coefficient of variation, TSW = 1000-seed weight, Mean values with the same superscript letters are not significantly different from each other at $p<0.01\%$.

other hand the lowest AUDCP values (4170.8 and 4446.2 %-days) were calculated on BRC-378 and ETS-3931 genotypes which were found resistant genotypes (Table 3). Even-though the disease pressure was lowest on ETS-3931 genotype, it performs with the lowest grain yield in 2015 (Table 4). This could be due to its shortest panicle length and smallest TSW. However, this genotype showed resistant reaction to the disease under field conditions. Therefore, ETS-3931 sorghum genotypes could be serving as a good source of resistant gene to be bred with these genotypes having good yielding ability but susceptible reaction to anthracnose disease. The results of this analysis in line with those obtained from different severity assessments. Overall, results of the two year experiments indicated a differential but stable reaction by the genotypes to natural infection by anthracnose at Jimma Southwestern Ethiopia.

3.3. Temporal dynamics of anthracnose

Both the onset and progress rate of anthracnose varied among the tested sorghum genotypes and cropping years. The disease started earlier and progressed very rapidly on Local check and BTx263 genotypes in 2014 and in 2015 cropping years, respectively. While it showed a relatively late appearance and slower developments on BRC-245, Sartu and BRC-378 in 2014 and, ETS-3931 and BRC-245 genotypes in 2015. ACC-BRC-5 had showed relatively intermediate anthracnose severity in both 2014 and 2015. During the first assessments, the severity of anthracnose on Local check was around 38 and 34 PSI in 2014 and 2015, respectively. Data collected at seven days interval showed a significant increase in anthracnose severity (0.1–14.2 PSI in 2014 and 0.2–14 PSI in 2015) on Local check, with the highest severity increase occurring during early flowering stages of the plants. This period coincided with the 2nd to 3rd week of August in both cropping years (Figs. 2 and 3).

This could be related to the interaction of the plant growth stage and the highest rainfall period, lowest minimum and average temperatures of the cropping years (Fig. 1). Similarly 0.3–13.6 PSI increase was recorded on BTx623 in 2015 with the highest increase also occurred at the 1st to 3rd weeks of August. On the other hand, the resistant genotypes BRC-245 and BRC-378 exhibited anthracnose severity of 31 and 32 PSI in 2014 and 25 and 29 PSI in 2015 at the first assessment, respectively. The increase in anthracnose severity for those resistant genotypes at seven days interval was 0.9–14.2 PSI and 1.8–10.6 PSI in 2014, and 1.6–13 PSI and 0.3–17 PSI in 2015, respectively. The highest severity increase on both genotypes and cropping seasons occurred from early August to end of September. This period coincide with flowering to panicle formation stage of the sorghum genotypes. The remaining genotypes were showed intermediate increases on anthracnose severity (PSI). Generally the result of this study suggests the time frame from August to September as the most important period for anthracnose development on sorghum in Southwestern Ethiopia.

3.4. Yield related traits of sorghum genotypes

The yield related components of all tested sorghum genotypes showed a highly significant ($p < 0.01$) difference among each other, within the two cropping rears and their interactions (Table 4). The height of all commonly tested sorghum genotypes showed taller appearance in 2014 as compared to 2015. The prolonged raining season in 2014 might have delayed flowering and increasing vegetative growth of the genotypes. On the other hand panicle lengths of most of the commonly tested genotypes showed increments in the year 2015. The 1000-seed weight (TSW) also showed higher increments on these commonly tested sorghum genotypes in 2015. This directly showed strong positive correlations and highest grain yield increments of these genotypes in 2015 (Table 4). This clearly showed that how much the weather condition of 2015 was favorable for sorghum production and how the plants converted their photosynthetic product to store in a grain form. The lowest TSW was recorded during 2014 which resulted in lowest grain yield as compared with 2015.

3.5. Grain yield of sorghum genotypes

Grain yield showed a highly significant ($p < 0.01$) difference among the six and nine tested sorghum genotypes, within the two cropping years and the interaction between year and commonly tested genotypes (Table 4). In the year 2014, grain yield varied between 1.0 and 5.1 tonnes ha^{-1}. The highest grain yield (5.1 and 5.1 tonnes ha$^{-1)}$ was measured on BRC-378 and BRC-245 resistant genotypes, respectively (Table 4). Even though ACC-BRC-18 and ACC-BRC-5 genotypes were previously released as resistant to the disease, but, in the present study they are susceptible with the lowest (1.0 and 1.1 tonnes ha^{-1}) grain yield. In the year 2015, grain yield varied between 2.8 and 10.9 tonnes ha^{-1}. The highest grain yield of 10.9 and 10.4 tonnes ha^{-1} was measured on BRC-378 and BRC-245 resistant genotypes, respectively. Meanwhile, the lowest grain yield of 2.8 and 2.9 tonnes ha^{-1} was measured on BTx623

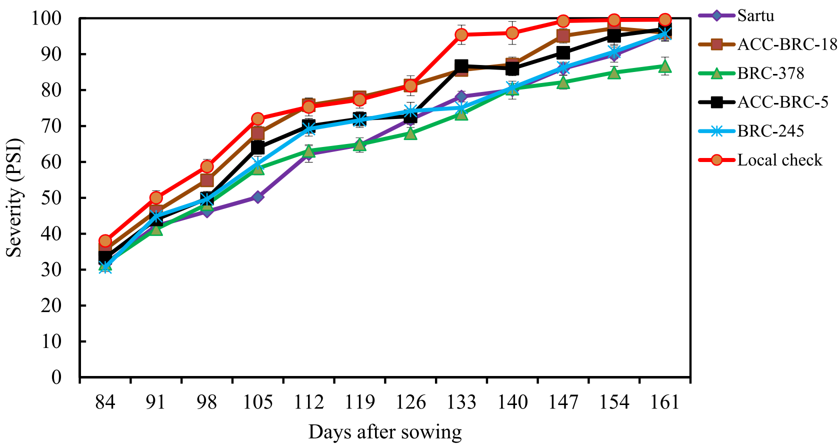

Fig. 2. Disease progress curves of anthracnose epidemics on six sorghum genotypes tested in 2014 cropping season at Jimma, Southwestern Ethiopia.

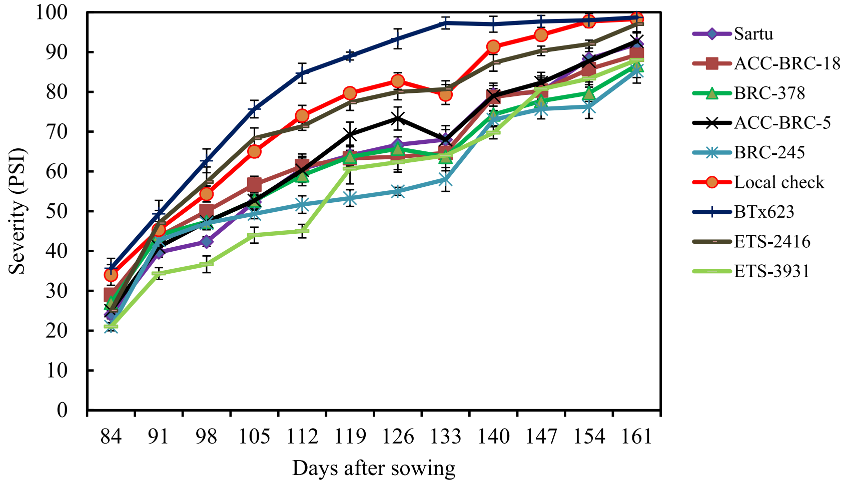

Fig. 3. Disease progress curves of anthracnose epidemics on nine sorghum genotypes tested in 2015 cropping season at Jimma, Southwestern Ethiopia.

Fig. 4. Sorghum head of ACC-BRC-18 in 2014 (a), 2015 (b) and ACC-BRC-5 in 2014 (c), 2015 (d) experimental years.

(universally susceptible) and ETS-3931 genotypes, respectively (Table 4).

Overall higher grain yield was recorded in the year 2015 than 2014. The highest grain yield increase (6.7 and 4.7 tonnes ha^{-1}) was recorded on ACC-BRC-18 and ACC-BRC-5 genotypes in the year 2015, respectively. This is due to the effect of high anthracnose severity and unfavorable weather condition in 2014 resulting in a very poor grain-filling of the genotypes (Fig. 4a and c). Meanwhile, due to conducive weather for growth of the same genotypes in the year 2015 happened resulted in good panicle stand and grain size of these genotypes (Fig. 4b and d). The present study showed a strong interaction effect of genotype and weather factors on disease development that indirectly affect grain yield of sorghum crop. However, great variations were observed among tested sorghum genotypes in responding to the disease. This variation indicates that Ethiopian sorghum germplasms have a great potential for resistant sources to sorghum anthracnose diseases.

Generally grain yield of all sorghum genotype increased at a very fast rate in 2015 than 2014. This could be due to changes in weather condition that resulted in delayed sowing time and reduced anthracnose severity in that year. From this result, we suggested

Table 5
Correlation coefficient between weather variables and anthracnose severity (PSI) recorded at a weekly interval in Jimma, Southwestern Ethiopia.

Weather variables	Genotype					
	Sartu	ACC-BRC-18	BRC-378	ACC-BRC-5	BRC-245	Local check
WTRF	0.73***	0.68***	0.72***	0.67***	0.68***	0.69***
Min To	−0.46*	−0.51*	−0.51*	−0.52**	−0.51*	−0.49*
Max To	−0.36^{ns}	−0.27^{ns}	−0.29^{ns}	−0.259^{ns}	−0.31^{ns}	−0.23^{ns}
Ave To	0.51*	0.55**	0.52**	0.5*	0.61**	0.45*

WTRF: Weekly total rainfall, Min To: minimum temperature, Max To: Maximum temperature, Ave To: Average temperature, ***Significant at $p < 0.001$, **Significant at $p < 0.01$ *Significant at $p < 0.05$, ns: no significant difference.

Table 6
The correlation coefficients of weekly anthracnose severity and grain yield of sorghum genotypes tested in 2014 and 2015 cropping years at Jimma, Southwestern of Ethiopia.

Grain yield tonnes ha^{-1}	Anthracnose severity at days after sowing (PSI)											
	84	91	98	105	122	129	136	133	140	147	154	161
2014	−0.64^{ns}	−0.40^{ns}	−0.61*	−0.59**	−0.60**	−0.65**	−0.53*	−0.74***	−0.54*	−0.72***	−0.73***	−0.51*
2015	−0.18^{ns}	−0.33^{ns}	−0.46*	−0.40*	−0.34*	−0.57**	−0.60***	−0.61***	−0.51**	−0.45***	−0.63***	−0.62***

PSI = Percent severity index, ***Significant at $p < 0.001$, **Significant at $p < 0.01$, *Significant at $p < 0.05$, ns: not significant.

that the year 2015 was unfavorable to anthracnose development, whereas very conducive for sorghum crop production. BRC-245 and BRC-378 genotypes performed the best grain yield in both experimental years with resistant reaction to anthracnose. In addition these two genotypes had a good quality as well as tallest height of stalk which resulted to high harvestable biomass which is very important to farmers due to its multiple purposes.

3.6. Correlation analysis

3.6.1. Correlation analysis between weather variables and anthracnose severity

The correlation coefficient analysis among the 12 round anthracnose severity assessment records and weakly weather variables conducted only for the six commonly tested sorghum genotypes. Anthracnose severity showed a positive significant ($p < 0.01$) and negative significant ($p < 0.05$) relationship between weather variables (weekly total rainfall and average temperature, and mean minimum temperature, respectively) on the six sorghum genotypes (Table 5). However, the interaction of the maximum temperature and anthracnose severity showed a negative none significant relationship. This result indicates that rainfall, mean minimum and average temperature are the best indicators of anthracnose development in the field than maximum temperature.

3.6.2. Correlation analysis between anthracnose severity and grain yield

All except the 13 weeks after sowing in the year 2014, and the 17–20, 22 and 23 weeks after sowing in the year 2015 of anthracnose severity assessment records showed strong negative significant ($p < 0.01$) and none significant associations with grain yield of sorghum genotypes. In the year 2014, the strong negative ($p < 0.01$) association between the disease and grain yield was occurred at 14 to 22 weeks after sowing, respectively (Table 6). Which mean the time frame from early August to end of September was critical for the disease development on the sorghum genotypes in 2014 cropping year. In 2015 cropping year, the strong negative ($p < 0.01$) associations between the disease and grain yield of sorghum genotypes was also observed from 17 to 20, 22 and 23 weeks after sowing (Table 6). The time frame coincided from end of August to mid of October. This variation in critical time of the disease development in the two cropping years clearly showed that the disease becomes extra sever when the plants are at their grain-filling to maturity stages. In both cropping years, the 1st and 2nd round anthracnose severity assessments had negative but not significant impact on grain yield of all sorghum genotypes.

3.6.3. Correlation analysis between AUDPC, grain yield and yield related traits

The yield related components (plant height and TSW) showed a strong negative correlations at $p < 0.001$significant level with AUDPC during 2014 and 2015 cropping seasons, respectively (Table 7). Panicle length showed weak negative correlation with AUDPC in both cropping years. On the other hand, plant height and panicle length showed a strong positive correlations at $p < 0.01$ with grain yield of sorghum genotypes in the year 2014 (Table 7). TSW also showed strong positive correlation at $p < 0.001$ with grain yield in the year 2015. This showed how much the disease affect grain filling of sorghum genotypes in 2014 cropping year. The negative association between AUDPC, grain yield and yield related traits also showed the magnitude of anthracnose damages in sorghum production in that area.

3.6.4. Regressions analysis between AUDPC and grain yield

Linear regression of the AUDPC was used for predicting the grain yield loss on the six and nine sorghum genotypes tested in 2014 and 2015 cropping years (Figs. 5 and 6), respectively. AUDPC linear regression better indicated the relationship of yield loss and disease than severity linear regression. On the other hand, disease progress curves are highly sensitive to fluctuations in epidemiological factors during disease development so they are not good predictors of the relationship of yield and disease severity. The AUDPC accounts for all these factors [33] as the crop yield loss depends upon severity as well as on duration of the disease. The relation was used by Ref. [34] to see the relationship between yield loss and faba bean (*Vicia faba* L.) chocolate spot in sole and mixed cropping

Table 7

The correlation coefficients of sorghum anthracnose AUDPC, grain yield and yield related components of sorghum genotypes at Jimma, Southwestern of Ethiopia.

	Cropping year							
	2014				2015			
	Plant height (cm)	Panicle length (cm)	TSW (gm)	Grain yield tonnes ha^{-1}	Plant height (cm)	Panicle length (cm)	TSW (g)	Grain yield tonnes ha^{-1}
AUDPC (%-days)	−0.62***	−0.02^{ns}	−0.02^{ns}	−0.54**	−0.50*	−0.44^{ns}	−0.95***	−0.70***
Plant height (cm)	1	0.46*	0.30^{ns}	0.90***	1	0.35^{ns}	0.45^{ns}	0.47*
Panicle length (cm)		1	0.15^{ns}	0.58**		1	0.53*	0.33^{ns}
TSW (g)			1	0.18^{ns}			1	0.63**

AUDPC = area under the disease progress curve, TSW = 1000-seed weight, ***Significant at $p < 0.001$, **Significant at $p < 0.01$, *Significant at $p < 0.05$, ns: not significant.

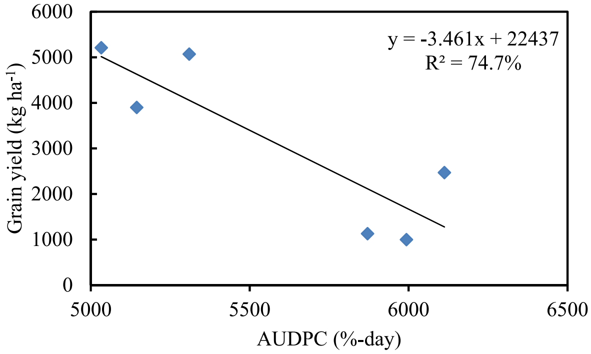

Fig. 5. Linear regression relating AUDPC (%-days) of sorghum anthracnose with grain yield (kg ha^{-1}) on six sorghum genotypes tested in 2014 cropping year.

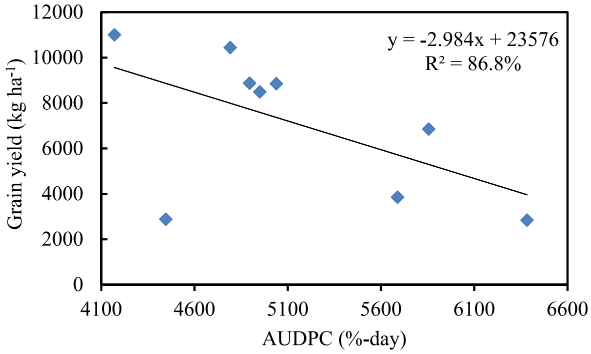

Fig. 6. Linear regression relating AUDPC (%-days) of sorghum anthracnose with grain yield (kg ha^{-1}) on nine sorghum genotypes tested in 2015 cropping year.

systems under Ethiopian conditions.

The relationship between anthracnose AUDPC and grain yield indicated by the model accounted for 74.7 and 86.8% of variance (Figs. 5 and 6) in 2014 and 2015 cropping years, respectively. The estimated slope of the regression line observed for 2014 cropping year was greater than 2015 cropping year, with the estimated regression coefficients of $b_1 = -3.46$ and -2.98 kg ha^{-1}, respectively. Based on the estimates, for every percent per day AUDPC increase of sorghum anthracnose resulted in 3.5 and 3.0 kg ha^{-1} grain yield losses on different sorghum genotypes in 2014, 2015 cropping years, respectively.

The relationship between sorghum anthracnose AUDPC and TSW of different sorghum genotypes in two cropping years indicated by the model also accounted for 97.5 and 82.5% variance (Figs. 7 and 8) in 2014 and 2015 cropping years, respectively. The estimated slope of the regression line observed for 2014 was greater than 2015 cropping year. The estimated regression coefficients are $b_1 = -0.009$ and -0.006 g in 2014 and 2015 cropping years, respectively. Based on these estimates, for every percent per day AUDPC increase of sorghum anthracnose resulted in 0.009 and 0.006 g TSW losses on six and nine sorghum genotypes tested in 2014 and 2015 cropping year, respectively. The higher TSW loss was observed during 2014 than 2015 cropping year. This happened due to the high disease pressure of anthracnose in that cropping year.

4. Discussion

Sorghum is commonly produced by small scale farmers throughout the world and its production is highly affected by anthracnose. Since chemical control of anthracnose is not practical and economic in sorghum production areas, genetic resistance has been established as the most acceptable and economical approach for successful management of the disease [18,35]. The present research confirmed that different sorghum genotypes responded differently to anthracnose disease in different cropping seasons and the disease pressure in 2014 was higher than 2015. This could be due to the variations in weather variables in those cropping seasons. The different reaction of genotypes could play a significant role in developing resistant variety thought resistant breeding program. Using resistant varieties is one of the most effective and number one management strategies of sorghum anthracnose under field conditions. High severity reduction was observed during 2015. This may be due to weather changes and delay of sowing that happened in 2015. In addition, anthracnose severity showed a significant positive correlation with weekly total rainfall and average temperature, and significant negative correlation with mean minimum temperature and non-significant negative correlation with maximum temperature during 2014 cropping season. Similarly, Rana et al. [20] also reported maximum temperature, minimum temperature and evening

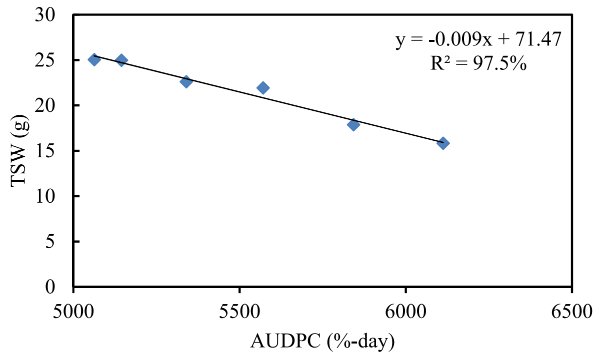

Fig. 7. Linear regression relating AUDPC (%-days) of sorghum anthracnose with 1000-seed weight (TSW) (g) on six sorghum genotypes tested in 2014 cropping year.

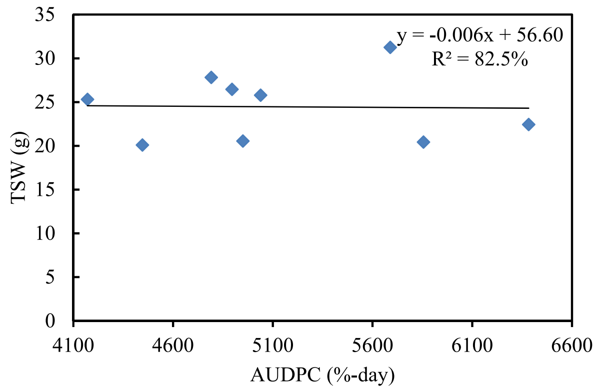

Fig. 8. Linear regression relating AUDPC (%-days) of sorghum anthracnose with 1000-seed weight (TSW) (g) on nine sorghum genotypes tested in 2015 cropping year.

relative humidity were negatively correlated with percent severity index of anthracnose during 2014 cropping season. Tsedaley et al. [7] Also reported percentage severity index of sorghum anthracnose showed strong negative correlation with different altitude ranges and this could be related with the differences in relative humidity and temperature variations across different altitudes.

Previously ACC-BRC-18 and ACC-BRC-5 sorghum genotypes were released as resistant to anthracnose, but in the present study they become susceptible with the low grain yield. This could be due to the variable nature of the pathogen and the ability to break down the resistant gene in the genotypes. Prom et al. [36] Also reported that the variable nature of the pathogen offers challenges to breed for resistance and to deploy available cultivars effectively. In addition [8] also confirmed five *C. sublineolum* isolates collected from major sorghum growing areas of Southwestern and Western Ethiopia, showed considerable variation in pathogenic characteristics such as virulence and level of aggressiveness on ten known sorghum differentials tested under greenhouse conditions. Consequently, long-term control of anthracnose depends on the management of host resistance genes, manipulation of the host-pathogen environment and reduction of inoculum sources [19]. Epidemics of the disease were found frequent in the study area. That could be due to warm and humid climatic conditions of the study area that contribute to the rapid development and spread of the disease. We also observed great variations in severity of anthracnose among the tested sorghum genotypes, within cropping years and their interactions. These variations may be depending on host pathogen interaction, the changes in the physiological stage of the host and environmental conditions [4]. Our observations agreed with [4] findings, in which the pathogen is capable of infecting all aboveground parts of the plant including the stalk, foliage, panicle, inflorescence and grain/seed, thereby degrading not only the quantity but also the quality of both grain and stalk. Infection of foliar tissues reduces photosynthetic accumulation while infection of the stalk leads to stalk rot followed by lodging, a detriment to maximizing harvestable biomass [36]. Anthracnose is most severe on mature plants, especially during the formation of the panicle [37]. Even thought farther researches are needed to confirm our results, based on our two years 12 findings, we recommend to the farmers in Jimma zone to use BRC-245 (Lalo) and BRC-378 (Dano) sorghum genotypes and delay the time of sowing with one month particularly at early May is important in reducing anthracnose severity on sorghum crop.

In this study the disease was developed differently on the tested sorghum genotypes per two consecutive experimental years in the study area. Similar findings are also reported by Refs. [11,12]. This could largely be dependent on susceptibility of the host and prevailing weather conditions of the study area. It is also influenced by inoculum density, pathogenicity of the strains and cultural practices [21,38,39]. While infected plant debris, seeds and alternate hosts serve as sources of the primary inoculum [40,41], shifts in planting dates and the choice of cultivars were found to influence the development of anthracnose in the field [17]. From the results of the present study, sorghum anthracnose was more severe during 2014 than 2015 cropping season. This could be due to favorable weather condition such as high rainfall that happened in 2014. Frederiksen [42] also reported, the disease is most severe during extended periods of cloudy, warm, humid and wet weather, especially when these conditions occur during the early grain-filling period. In the present study the highest grain weight losses and the smallest TSW was observed in the year 2014. This is due to the highest anthracnose severity effect that was recorded on all sorghum genotypes in that year. Casela, Ferreira[18] reported that when the conidia of *C. sublineolum* are inside the plant they interfere in water and nutrient movement in the vascular tissues, resulting in poor development of the panicle and grain. Ali et al. [43] also reported grain yield losses due to fungal infection are commonly associated with a reduction in grain size.

Most of the time, management of sorghum anthracnose largely depends on the development of resistant varieties. In addition, the choice of planting dates is also found to significantly impact on the development of the disease [10,12], and hence could play a role in reducing anthracnose severity in the field. Furthermore, understanding the temporal dynamics of the disease is an essential task to identify the proper sowing time, which in turn contributes towards developing effective, affordable, safe and sustainable management strategies [21]. However, for sowing date to be used as one option on anthracnose management, first the life cycle of the disease and the optimum time to reach its peak should be identified. Our current findings also showed the differential impact of genotypes with varying levels of resistant and weather conditions on the timely development of anthracnose. Variations in disease progress were significant among the genotypes with anthracnose development showed slower progress on BRC-245 and BRC-378. The authors identified, the time from August to September was found to be a peak time for anthracnose development and strong negatively affects grain yields of sorghum genotypes in southwestern Ethiopia. Chala et al. [21] also reported the disease reaches its peak in this time in south Ethiopia. This could be related with favorable weather condition, the developmental stage of the crop and the peak time of the pathogen. Therefore, taking management measures which mismatches the pick time of the disease development and susceptible stage of the crop is critical and more effective in reducing severity of the disease and increasing grain yield. Furthermore, altering sowing date could be used as important options in reducing the severity of sorghum anthracnose and finally in increasing sorghum grain yield. Our result is in agreement with the ideas of [39,44,45].

As it is clearly known that for every disease development three thinks should be synchronized (the weather should be conducive, the host should be susceptible and the pathogen should be virulent). From this perspective, the weather in 2014 is more favorable than 2015 for anthracnose development on the tested sorghum genotypes under field condition in Southwestern, Ethiopia. Weather factors had a significant effect on the development of anthracnose disease and grain yield of different sorghum genotypes under field conditions. Weather conditions, in particular rainfall, have been shown to play a critical role in the incidence and severity of sorghum anthracnose. Cumulative and frequency of rainfall, and relative humidity are critical factors for anthracnose disease development 15, 19,42,46. Anthracnose is a polycyclic and epidemic disease, is favored by high rainfall and humidity, moderate temperatures and the presence of large amounts of inoculum [19]. In both cropping years, the 1st and 2nd round anthracnose severity assessments had negative but not significant impact on grain yield of all sorghum genotypes. This could be due to the lower contributions of the lower leaves in grain-filling (converting photosynthetic products to grain). This clearly showed that the top leaves are more important in grain development and the more severity at grain-filling to maturity stage resulted in high yield reduction. The flag leaf contributes the largest proportion of photosynthate to grain filling [47, 48]. The strong positive relationship between grain yield and TSW showed, as grain size increased grain yield also increase and vice versa. Grain size is highly affected by severe anthracnose infection and weather condition (related to photosynthesis) and the amount of food stored in the grains. Therefore, selecting more resistant genotypes and adjusting sowing date could play an important role in reducing anthracnose severity and increasing grain yield of sorghum crop around Jimma, Southwestern Ethiopia.

5. Conclusion and recommendation

Under field condition anthracnose severity was strongly affected by different resistant levels of sorghum genotypes and weather variables specially rainfall, mean minimum and average temperature. Disease pressure had strong negative impacts on grain-filling which resulted in large amounts of yield losses on susceptible sorghum genotypes throughout the world. Therefore, understanding these variables could play an important role in the management of this major disease of sorghum thought out the world. The findings also showed Ethiopian germplasms have high potential sources of resistant genes. The two local sorghum genotypes BRC-245 (Lalo) and BRC-378 (Dano) are also recommended to be used by farmers around Jimma and similar areas in southwestern Ethiopia as they had good performances such as moderate resistance to anthracnose, vigorous growth and high grain yield. Since delaying in date of sowing had shown some positive impacts in reducing anthracnose severity and increasing grain yield, additional research is needed to find the date of sowing which mismatch the peak time of the pathogen and more susceptible growth stage of the crop in the study area.

Author contribution statement

Binyam Tsedaley: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Girma Adugna: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Fikre Lemessa: Conceived and designed the experiments; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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