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Research Paper

# Evaluation of Sorghum Genotypes and Reduced Rates of Fungicide Application against Anthracnose (*Colletotrichum sublineolum*) Management in Arba Minch and Derashe Districts, Southern Ethiopia

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**Abstract**

Anthracnose disease caused by *Colletotrichum sublineolum* is a major constraint that limits the production and productivity of sorghum in Ethiopia. A field experiment was carried out in Arba Minch and Derashe during the 2018/19 cropping season to determine the integrated effects of genotypes and reduced rates of fungicide applications on anthracnose disease, growth and grain yield of sorghum. The treatments were composed of four sorghum genotypes and three different rates of Ridomil Gold MZ 63.5% WP (Ridomil), including unsprayed and laid out in randomized complete block design with the factorial arrangement in three replications. Significant ($p < 0.001$) difference was observed in the magnitude of disease and crop parameters measured among the treatments considered. The disease severities were 22.78, 29.44, 62.22, and 66.11% on Arghiti, Melkam, Seredo and Local cultivar, respectively, because of a combination of Ridomil at the rate of 3 kg ha$^{-1}$. These treatment combinations exceedingly reduced area under the disease progress curve and rates of disease progression as well. No statistically significant difference was observed on the grain yield obtained from plots sprayed with Ridomil at the rates of 2 and 3 kg ha$^{-1}$ at 14 days intervals. A yield loss of 54.41% was recorded on unsprayed plots of the Local cultivar as compared to well-managed plots of other genotypes. The use of Arghiti and Melkam in combination with Ridomil at the rate of 2 kg ha$^{-1}$ was found to be relatively efficient in reducing anthracnose development and gave higher grain yield as compared to the unsprayed plot. Therefore, the use of Arghiti and Melkam in combination with application of Ridomil at the rate of 2 kg ha$^{-1}$ for the management of anthracnose could be suggested to sustain the production and productivity of sorghum for the farmers in the study areas and in similar agro-ecology. Further studies should be conducted in similar and other agro-ecologies in Ethiopia for at least one more year with over location to reach a concrete recommendation.

## 1. Introduction

Sorghum (*Sorghum bicolor* L.) is one of the important cereal crops for a larger section of people in tropical and subtropical countries (FAO et al., 2018; USDA, 2018). It is ranked 5$^{th}$ most important cereal crops grown after wheat, rice, maize, and barley worldwide (FAOSTAT, 2017). It is the staple indispensable food crop for millions of people throughout the arid and semi-arid regions of the world (FAOSTAT, 2017). The crop is a major food and nutritional security for millions of people in Eastern Africa (Gudu et al., 2013) due to its production under the drought-prone condition and other restraints, where other crops can no/little survive (Adugna, 2007; Seyoum et al., 2019). In Ethiopia as well as in the southern region of the country, it is ranked on 3$^{rd}$ and 4$^{th}$ cereal crops grown in terms of the areas of

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land allocated, the volume produced and the number of farmers engaged in its production (CSA, 2018).

However, in the country as well as in the southern region, the production and productivity of sorghum were curtailed by various biotic and abiotic factors. Due to these factors both the national (2.53 t $ha^{-1}$) and the regional (2.23 t $ha^{-1}$) including the study areas (1.54 t $ha^{-1}$) (CSA, 2018) average productivity of sorghum is far very low as compared to the world productivity (5.88 t $ha^{-1}$) (USDA, 2018). Among the biotic factors, diseases are the most important one, of which anthracnose disease caused by *Colletotrichum sublineolum,* is the most important and production bottlenecks, and responsible for low productivity per unit area in sorghum production systems (Casela et al., 1997; Thakur and Mathur, 2000; Binyam et al., 2016). The epidemics cause significant yield loss of 50 to 100% (Thakur and Mathur, 2000; Tesso et al., 2012). Yield losses due to anthracnose infection are typically interconnected with a reduction of grain size due to the interference of normal physiological functions as a result the infection affects the grain development of the crop (Thakur and Mathur, 2000).

Anthracnose had been reported in most sorghum producing areas of the world. However, it was regularly observed in tropical or subtropical environs where it is prevalent and sparingly important under high humid and warm temperatures (Hess et al., 2002; Ngugi et al., 2000). In Ethiopia, anthracnose is prevalent all over the county, particularly in the low and mid-lands of the country (Chala et al., 2010; Binyam et al., 2016; Girmay et al., 2019). The periodic epidemics caused significant yield losses in the country. In spite of being an important disease of sorghum and it has potential to cause significant yield losses, anthracnose management was generally not common in Ethiopia. Particularly in Arba Minch and Derashe areas, a little effort has been made in the use of resistant genotypes as a result of the disease became epidemic year after year in these areas and causes considerable grain yield losses.

However, different management options are available to manage anthracnose and attempts have been made worldwide through different cultural procedures, use of resistance sorghum genotypes and fungicide application (Casela et al., 1997; Marley, 2004). A resistance source to anthracnose is the most preferred management option in sorghum production systems. However, the use of resistant genotype is not guaranteed for a year after year production due to the durability of the resistance gene and the wider variability of the pathogen itself, which are after sometimes may cause to breaking down of the resistance gene and lead the genotype to susceptible for the disease (Agrios, 2005). This phenomenon might probably be associated with climate change and the continuous production of sorghum year after year in the study areas.

Despite continued efforts have been made so far to develop genotypes with either disease escape traits or specific disease resistance genes, fungicides are the only effective method for management of most of the diseases in many crop pathogens (Agrios, 2005; Foster et al., 2017). Management of anthracnose through fungicide application is used in some parts of the country (MoA and EATA, 2018) and the study areas as well, which was done unwisely under field condition, below or over recommended rates and frequency, untimely and indiscriminately whatever fungicide they find in their areas. However, unwise use of fungicide has adverse effects on the crop, health of human and other living organisms found in the kingdom Animalia, pollute the environment and also lead to the development of resistance by the pathogen (Green et al., 1990; WHO, 2004; Agrios, 2005). Therefore, designing appropriate management procedures and information regarding factors that influence the intensity of the anthracnose is a prerequisite for the study areas and the country as well. Use of the integration of host genotypes and fungicide application is the two principal approaches in the integrated management of anthracnose strategy implemented in most sorghum-producing areas of the world (Marley et al., 2005; Gwary et al., 2008). Previous researches on different crops (wheat, maize, sorghum, common bean, potato, tomato, and onion) had been indicated that the use of host resistance in a combination of fungicide application reduced disease suppression and could provide more than a 10% yield increase relative to the untreated ones (Gwary and Asala, 2006b and 2006c; Foster et al., 2017).

Different genotypes respond differently to plant diseases due to the genetic makeup of the genotype and a combination of genotype and appropriate type, rate and time of fungicide application is required to reduce the disease effect and to maximize yield. Reports on the integration of genotypes having a different level of resistance to the disease and fungicide application with different levels of rates indicated that the action of a fungicide might vary with the rates used on the genotype to manage the disease. Similarly, genotypes having different levels of reaction to a given pathogen may respond well with low or medium or higher fungicide rates (Datnoff et al., 2001; Agrios, 2005). A genotype that will perform well with low or medium rates of fungicide will be preferable to a genotype that requires more fungicide rates. No or little recognition of the farmers in managing anthracnose, absence of research works previously in the study areas through a combination of sorghum genotypes and reduced rates of fungicide application and due to the above reasons this study was necessitated. Therefore, the objective of the study was to determine the integrated effects of genotypes and reduced rates of fungicide application on anthracnose, growth and grain yield of sorghum in Arba Minch and Derashe District, southern Ethiopia.

## 2. Materials and Methods

### 2.1. Description of Experimental Areas

A field experiment was carried out in Arba Minch and Derashe district southern Ethiopia during the 2018/19 cropping season. These areas were selected based on the recurrent occurrence of the disease and its importance in sorghum production systems. The geographical position of the specified areas was 06° 06' 841'' N and 037° 35' 122'' E at Arba Minch and 05° 31' 31'' N and 037° 25' 46'' E at Derashe. The areas were far apart from each other with a distance of 80 km, along the accessible vehicle road. The sites are positioned at an altitude of 1216 and 1253 meters above sea levels at Arba Minch and Derashe, respectively. The two locations exhibit a bimodal rainfall pattern from March to April and from August to November. Arba Minch and Derashe receive an average annual rainfall and temperatures for the last decade were 750 mm and 27.50°C and 810 mm and 25.68°C, respectively. The details of weather data during the 2018 cropping season is shown in Table 1. Arba Minch is characterized by moderately alkaline with low organic contents (1.05%) and black sandy-loam in the soil type. Moderately alkaline with high organic content (8.82%) and black clay-loam in the soil type is the basic characteristic features of Derashe (MoANR and EATA, 2016).

### 2.2. Experimental Material

The experiment was entirely executed in an open environment to ensure disease occurrence and augment natural infections at the beginning of the experiment. Four sorghum genotypes (Arghiti, Melkam, Seredo, and Local cultivar) differing in their resistance levels to anthracnose had used as a varietal component. The genotypes are currently under production in the study areas and showed different levels of reactions to anthracnose under natural epiphytotic conditions. Seeds of the sorghum genotypes were obtained from Melkasa Agricultural Research Centre, Ethiopian Institute of Agricultural Research, Ethiopia, and farm-saved (Local cultivar). The genotypes had developed mainly for drought-tolerant with high productivity and quality. The details of agro-ecological, agronomic, and disease reaction characteristic features of the evaluated sorghum genotypes had presented in Table 2. In addition, fungicide, Ridomil Gold MZ 63.5% WP [Metalaxyl 8% + Mancozeb 64% WP] (systemic type) with three spray rates (0.0, 2.0, and 3.0 Kg ha$^{-1}$), was used as fungicidal component. The fungicide was selected due to the systemic effect against anthracnose through translocation within the plant tissues.

**Table 1**: Monthly mean minimum and maximum temperature and total rainfall at Arba Minch and Derashe in southern Ethiopia during the 2018 cropping season

| Location | Weather Variable | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Arba Minch | Maximum(°C) | 29.84 | 30.70 | 28.66 | 26.75 | 26.42 | 24.78 | 25.52 | 26.84 | 28.68 | 27.86 | 28.62 | 28.94 |
| | Minimum (°C) | 15.81 | 15.85 | 17.94 | 17.34 | 17.86 | 17.04 | 18.44 | 18.26 | 17.73 | 17.95 | 16.75 | 17.35 |
| | Rainfall(mm) | 0.00 | 47.60 | 35.50 | 250.70 | 165.0 | 89.00 | 12.80 | 94.40 | 159.40 | 102.6 | 81.00 | 17.76 |
| | RH (%) | 35.84 | 39.32 | 58.77 | 66.12 | 64.13 | 50.56 | 44.12 | 63.35 | 69.11 | 60.34 | 57.45 | 16.34 |
| Derashe | Maximum (°C) | 26.73 | 25.30 | 26.20 | 25.51 | 26.67 | 27.20 | 27.70 | 27.67 | 27.67 | 26.60 | 26.44 | 26.93 |
| | Minimum (°C) | 13.40 | 12.59 | 13.35 | 13.28 | 13.35 | 12.92 | 13.15 | 13.02 | 13.25 | 12.49 | 12.38 | 13.01 |
| | Rainfall (mm) | 37.00 | 28.00 | 48.80 | 204.00 | 170.0 | 164.4 | 85.00 | 96.00 | 96.00 | 319.6 | 186.8 | 32.60 |
| | RH (%) | 36.05 | 35.17 | 50.25 | 60.44 | 59.04 | 46.17 | 36.15 | 48.35 | 56.14 | 48.08 | 37.67 | 30.11 |

Source: The meteorological data were obtained from National Meteorological Agency at Hawassa Branch in the year of 2018. RH = Relative humidity.

**Table 2**: The details of agro-ecological conditions*, agronomic characteristics and breeding center of sorghum genotypes used for the study at Arba Minch and Derashe in southern Ethiopia during the 2018 cropping season

| Sorghum [1] genotypes | Pedigree | Year of release | Flowering dates | Maturity date | Plant height (cm) | Productivity t ha$^{-1}$ | | Reaction to anthracnose |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Research | Farmer | |
| Arghiti | WSV387/P9403 | 2016 | 79 | 125 | 200 | 3.78 | - | R |
| Melkam | WSV387 | 2009 | 76-82 | 118 | 126-163 | 3.70-5.80 | 3.50-4.30 | MR |
| Seredo | Seredo | 1986 | 60-70 | 90-120 | 120-150 | 3.00-5.00 | - | S |
| Local cultivar | - | - | 65-75 | 110-120 | 120-170 | - | - | HS |

[1]Releasing center is Melkassa Agricultural Research Center, Ethiopian Institute of Agricultural Research. * The suitable agro-ecology for the sorghum genotypes are dry lowland with an altitude of < 1600 m.a.s.l., the range of temperature of 27 to 32 $^{O}$C and annual total rainfall of < 600 mm. R = Resistance; MR = Moderately resistant; S = Susceptible; HS = Highly susceptible.

Source: Data were sourced and organized from MoANR (2016) and MoA and EATA (2018).

## 2.3. Experimental Design and Agronomic Practices

The design of the experiment was a randomized complete block design in a factorial arrangement with three replications. A total of 12 treatments have comprised during the experiment, four sorghum genotypes and three rates of Ridomil application. The treatments were assigned randomly to experimental plots within a block. Planting was done with the recommended rates of sorghum (10 kg ha$^{-1}$) on 18 March 2018 for both locations. The layout was designed with 14 m width x 45.30 m length with a unit plot size of 3.0 m width x 2.4 m length. The plots spaced at 1.5 m and blocks separated by a safeguard path of 2.5 m to prevent drifts' effects. There were five rows within plots and spaces between plants and rows were maintained as 15 cm and 75 cm, respectively. Each row consists of 16 plants. NPS (100 kg ha$^{-1}$ for both locations) and N-fertilizers (100 kg ha$^{-1}$ for Arba Minch and 50 kg ha$^{-1}$ for Derashe) had used for nutrient management. Weeding and other cultural practices were implemented to all plots manually as per the recommendations suggested by MoA and EATA (2018) for both locations.

Foliar application of Ridomil had carried out with the prearranged rates for each treatment combination at 14-days intervals. Unsprayed plots were left for each genotype as a control to consent to maximum disease development. The first fungicide spray was taking place at 46 and 42-days after planting (DAP) at Arba Minch and Derashe, respectively. Spraying of fungicide was performed using a manual knapsack sprayer calibrated to convey 500-700 L of water ha$^{-1}$. Three consecutive sprays had practiced for each treatment at both locations.

## 2.4. Disease Assessment

Disease incidence and severity were scored at 14-days intervals before each spray rate of fungicide starting from the first appearance of the disease. A total of six assessments have executed during the experiment at both locations. Disease incidence (PDI) has scored by the rating of diseased plants per total number of plants assessed within the plot in the three central rows and expressed as in percent. Disease severity was scored visually from 15 pre-tagged plants per plot following the scale designated by Thakur et al. (2007), where, 1 = no visible symptoms or presence of chlorotic flecks, 2 = 1 - 10% leaf area covered with hypersensitive lesions without acervuli, 3 = 11 - 25% leaf area covered with hypersensitive and restricted lesions with acervuli in the center, 4 = 26 -50% leaf area covered with coalescing necrotic lesions with acervuli and 5 = $\geq$ 50% leaf area covered with coalescing necrotic lesions with acervuli. Disease severity scales were transformed into percentage severity index (PSI) for analysis following the formula suggested by Wheeler (1969) as below:

$$\mathrm{PSI} = \frac{\text{Sum of numerical ratings}}{\text{No. of plants scored x maximum score on scale}} \mathrm{X}\ 100$$

The area under disease progress curve (AUDPC), the development of disease on a whole plant or part of the plant during the epidemic periods, was figured out from PSI values assessed at different days for each plot using the formula suggested by Campbell and Madden (1990) as below:

$$\mathrm{AUDPC} = \sum_{i=1}^{n-1} 0.5\ (X_i + X_{i+1})\ (t_{i-1} - t_i)$$

Where, $n$ is the total number of disease assessments, $t_i$ is the time of the $i^{th}$ assessment in days from the first assessment date and $x_i$ is the PSI of disease at the $i^{th}$ assessment. AUDPC was articulated in %-days since severity (X) is expressed in percent and time (t) in days.

The rate of disease progress (RDP) was assessed by repetitive assessment of the percentage of leaf area infected by anthracnose in each plot, starting from the beginning of the disease. Logistic, ln [(Y/1-Y)] (van der Plank, 1963), and Gompertz, -ln [-ln (Y)] (Berger, 1981) regression models were compared for the goodness of appropriate in the assessment of disease progression from each treatment. The logistic model showed greater expression as indicated by a higher coefficient of determination ($R^2$) and lower standard errors for most of the parameters. Then, the data were regressed over time, and the apparent rates of disease progression had derived via the following logistic regression equation:

$$Y_t = \frac{1}{1 + \exp^{-\ln\left[\frac{Yo}{1-Yo}\right]+rLt}}$$

Where, $Y_t$: percentage of severity at $t^{th}$ assessment date; $Y_o$: percentage of initial severity at $t^{th}$ assessment date; $t_i$: time of the $i^{th}$ assessment in days from the first assessment date; and $r_L$: the rate parameter determined by the production of inoculum by infected individuals/ lesions per unit area of diseased tissue. The rate of disease progress was expressed in unit $days^{-1}$.

## 2.5. Crop Parameters Assessment

The three central rows of each treatment within the plot were looked over for the determination of growth and yield-related parameters. Numbers of productive plants per plot, grains yield, and thousand seed weight were considered for crop parameters during the experiment. The number of productive plants per plot had measured as counting of the stand productive plants within the plot. Harvesting of sorghum grain was undertaken on 144 and 150 DAP at Arba Minch and Derashe, respectively. The harvested grain yield was converted into t $ha^{-1}$, and a thousand seed weight was also measured in gram (g) for each treatment. The harvested grain yield was adjusted to 12.50% moisture content following the procedure suggested by Taran et al. (1998). Thousand seed weight was measured from randomly sampled grains obtained from the total harvested grains of each plot and adjusted them to 12.50% moisture content.

## 2.6. Data Analysis

Analysis of variance was carried out for the measured disease and yield-related parameters to determine the treatment effects following the general linear model procedure of the SAS software *version* 9.2 (SAS, 2009). The two locations are considered as different environments. As the F-test of the error variances for the studied parameters for the two locations was homogeneous, the data had combined for the analysis. Mean separations between treatments have performed using Fisher's protected LSD at a 5% probability level following the procedure described by Gomez and Gomez (1984). Correlation of disease and yield-related parameters were determined using the Determined Pearson Correlation Coefficient (r). Likewise, the relationship between the disease and grain yield was analyzed using linear regression of the AUDPC and grain yield for estimating the yield loss in sorghum production. Regression was estimated using Minitab (Release 15.0 for windows $^R$, 2007).

## 2.7. Determination of Economic Feasibility and Relative Yield Loss

Before applying partial budget analysis, statistical analysis has done on grain yield of sorghum to relate the mean yield between treatments, as a result, significant differences had observed between treatment means. Economic feasibility and relative yield loss was determined from the pooled data obtained from the two locations following the procedure suggested by CIMMYT (1988) and Robert and James (1991), respectively.

The economic analysis was done based on the fixed and variable cost of production. The fixed cost includes the current value of land rent, whereas the variable cost included current fungicides, labor (fungicide application, weeding practices, sowing, and harvesting), and the market price of sorghum grain. The information was acquired through personal communication with some farmers who told them that the average unit price of land rent $ha^{-1}$ for one growing period was \$ 246.19 across the locations, depending on the crop type produces during the growing time. The unit price of Ridomil was \$ 48.88 $L^{-1}$. The unit cost of the knapsack sprayer was \$ 43.53. Similarly, the cost of labor for fungicide applications was \$ 2.82 man day$^{-1}$. The market average unit price for grain yield of sorghum per ton was \$ 288.50 during the study across the locations. All costs and profits are intended on a hectare basis in the US dollar (\$). The actual grain yield of sorghum was adjusted downward by 10% to estimate the differences between the experimental grain yield and farmers' yield could expect from the same treatment. Besides, relative percent yield loss was determined from each plot as follows:

$$\text{Relative yield loss (\%)} = \frac{Ybt - Ylt}{Ybt} \text{x } 100$$

Where, *Ybt* is the yield of best treatment (maximum protected plot) and *Ylt* is the yield of lower treatments.

## 3. Results and Discussion

### 3.1. Analysis of Variance for the Studied Parameters

The mean square of the combined analysis of variance (ANOVA) for the location, genotypes and rates of fungicide application and the results of their respective interactions of the studied parameters are presented in Tables 3. The combined ANOVA revealed that there was an interaction effect on all the studied parameters across location, genotypes and rates of fungicide application. All parameters of sorghum were significantly affected by the different sorghum genotypes as well as the rates of Ridomil application. This phenomenon indicates the different sorghum genotypes having different levels of reaction to anthracnose similarly affected by different rates of Ridomil application in the two locations.

All the studied parameters, except for TSW, were significantly affected by location by genotype interaction. For all the studied parameters, except for $PSI_f$ and RDP, no interaction effects were observed on location by rates of fungicide applications interaction. The interaction effects of the genotype and rates of fungicide application of the studied parameters showed that there were significant variations on the disease scores ($PDI_f$, $PSI_f$, AUDPC, and RDP), but there were no interaction effects on the growth and yield-related traits (NPP, TSW, and GY). No interaction effects were detected among the treatments tested for the mean squares of the studied parameters on locations by genotypes by rates of fungicide application interaction, except for AUDPC (Table 3). The main effects implied that each sorghum genotype responded differently to the different rates of fungicide application. Likewise, Datnoff et al. (2001); Gwary et al. (2008); Renata et al. (2012) found that significant difference had been observed among the treatments evaluated for the stated and other parameters in their studies on the management of anthracnose through the integration of sorghum genotypes and different fungicide uses under different methods of application.

### 3.2. Effects of Genotype and Rates of Fungicide Application on Disease Development

The disease first appeared on Seredo and Local cultivar at both locations. Symptoms conspicuous for anthracnose were observed on leaves and stalk of the stand sorghum at the two locations during the study period. The infection appeared as elliptical or elongated lesions on leaf and stalk, leaf necrosis, premature drying of a leaf, stalk, and poor grain filling on infected plants (Figure 1). The leaves on unsprayed plots became rigorously infected and gradually produced abundant acervuli. The plants were defoliated and died after the appearance of the disease symptom on those plots severely infected. Similarly, Hess et al. (2002); Thakur and Mathur (2000); Gwary and Asala (2006a); Girmay et al. (2019) reported that symptoms of infected sorghum due to anthracnose, which appeared on the leaf, stalk, panicle and grain with similar features on all the above-ground tissues of the infected sorghum.

**Figure 1**: Symptoms of *C. sublineolum* under field condition on an unsprayed plot of Seredo (left side) and Local cultivar (right side) at Arba Minch in Southern Ethiopia during the 2018 cropping season.

The highest mean disease incidence (100%) was recorded on all rates of Ridomil application on unsprayed plots of Seredo and Local cultivar as compared to unsprayed plots of Arghiti (74.58%) under the integration of sorghum genotypes as well as the rates of Ridomil application. Conversely, the lowest mean disease incidences (55.83%) have recorded on Arghiti

**Table 3**: Mean square of analysis of variance for the studied parameters under the combinations of sorghum genotypes and reduced rates of fungicide applications at the study areas in southern Ethiopia during the 2018 cropping season

| Source of variation | DF | Mean square | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **$PDI_f$ (%)** | **$PSI_f$ (%)** | **AUDPC (%-days)** | **RDP (Unit $day^{-1}$)** | **NPT (Count)** | **TSW (g)** | **GY (t $ha^{-1}$)** |
| Replication | 2 | 18.84 $^{ns}$ | 39.85 $^{ns}$ | 8345.79*** | $1.14 \times 10^{-6}$ $^{ns}$ | 286.72 $^{ns}$ | 13.88 $^{ns}$ | 1.97$^{ns}$ |
| Location | 1 | 1334.72**** | 1291.99**** | 184022.22**** | $1.66 \times 10^{-4}$**** | 13585.01**** | 62.35* | 74.51**** |
| Genotypes | 3 | 6047.57**** | 10966.65**** | 3038706.39**** | $2.01 \times 10^{-4}$**** | 5459.50**** | 333.59**** | 37.88**** |
| Rate of fungicide | 2 | 375.61**** | 1241.01**** | 121740.52**** | $8.56 \times 10^{-5}$**** | 3619.43**** | 435.38**** | 6.53* |
| L * G | 3 | 801.39**** | 113.11*** | 27094.93**** | $2.91 \times 10^{-5}$**** | 883.42* | 10.16 $^{ns}$ | 9.48** |
| L * RoF | 2 | 14.15 $^{ns}$ | 48.26* | 3046.90$^{ns}$ | $6.80 \times 10^{-6}$*** | 108. $^{ns}$ | 4.81 $^{ns}$ | 0.03 $^{ns}$ |
| G * RoF | 6 | 207.90**** | 55.83*** | 15045.79**** | $8.44 \times 10^{-6}$**** | 74.02 $^{ns}$ | 13.07 $^{ns}$ | 0.89 $^{ns}$ |
| L * G * RoF | 6 | 45.75 $^{ns}$ | 17.50 $^{ns}$ | 2847.78* | $2.75 \times 10^{-6}$ $^{ns}$ | 17.56 $^{ns}$ | 2.89 $^{ns}$ | 0.20 $^{ns}$ |
| Error | 12 | 10.50 | 11.08 | 944.35 | $9.80 \times 10^{-7}$ | 178.31 | 11.91 | 0.65 |
| F-value (Pooled) | | 41.28**** | 58.49**** | 176.57**** | 20.28**** | 4.37** | 3.77** | 4.31** |
| Mean | | 84.24 | 51.37 | 978.87 | 0.02 | 62.18 | 28.33 | 2.35 |
| CV (%) | | 3.85 | 6.48 | 3.14 | 17.33 | 21.48 | 12.49 | 34.31 |
| $R^2$ | | 0.99 | 0.99 | 0.99 | 0.99 | 0.96 | 0.95 | 0.95 |

DF = Degree of freedom; $PDI_f$ = Percent disease incidence at final date; $PSI_f$ = Percent severity index at final date; AUDPC = Area under disease progress curve; RDP = Rate of disease progress; NPT = Number of productive tiller; TSW = Thousand seed weight; GY = Grain yield; L = Location; G = Sorghum genotype; RoF = Rates of fungicide application; L * G = Interaction effect of location by genotypes; L * RoF = Interaction effect of location by rates of fungicide application; G * RoF = Interaction effect of sorghum genotypes by rates of fungicide application; L * G * RoF = Interaction effect of location by sorghum genotypes by rates of fungicide application; *SE* = Standard error; CV = Coefficient of variation; $R^2$ = Coefficient of determination; * = Significance difference at $p < 0.05$; ** = Significance difference at $p < 0.01$; *** = Significance difference at $p < 0.001$; **** = Significance difference at $p < 0.0001$;and ns = Not significant.

under the application of Ridomil at the rate of 3 kg ha$^{-1}$ as compared to other genotypes and rates of Ridomil application. Maximum and minimum mean disease PSI$_f$, AUDPC, and RDP were recorded on the genotypes Local and Arghiti cultivar, respectively, unsprayed and sprayed with the rate of 3 kg ha$^{-1}$ (Table 4). Nevertheless, the lowest mean disease PSI$_f$, AUDPC, and RDP recorded on Arghiti as well as the application of Ridomil at the rate of 3 kg ha$^{-1}$ was statistically at par with Ridomil application at the rate of 2 kg ha$^{-1}$. Similar phenomena were observed on the lowest mean disease severity recorded on Melkam integrated with the application of Ridomil at the rate of 2 and 3 kg ha$^{-1}$ (Table 4). This phenomenon might be the level of the genotype to be withstanding the effect of the disease due to little support obtained from the fungicide application. The effects of integration of sorghum genotypes having different levels of resistance and application of different rates of fungicide had similar results in reducing the development of anthracnose on resistant and moderately resistant genotypes under field conditions (Gwary et al., 2008; Resende et al., 2009; Renata et al., 2012).

The high degree of significant difference in AUDPC values among the evaluated treatments might be due to their genotypic resistance characteristics of the genotypes as well as the different rates of Ridomil applications. Campbell and Madden (1990) reported that the highest AUDPC values resulted from the highest disease development on plots that remained unmanaged with any management option in combination or alone during the growing periods. Similarly, Datnoff et al. (2001); Resende et al. (2009); Renata et al. (2012) reported that the effect of moderately resistant and susceptible sorghum genotypes under different fungicide uses resulted in significantly retarded the development of anthracnose during the growing periods. Also, van der Plank (1963); Campbell and Madden (1990); Agrios (2005) reported that the highest RDP resulted from the highest disease development on plots that have not managed with any interference of disease management through the integration of crop genotypes, fungicide application, and other options. Also, Gwary et al. (2008); Resende et al. (2009) reported that the resistant and moderately resistant of given genotypes had retarded the RDP when supplemented with a proper fungicide application.

**Table 4**: Interaction effects of sorghum genotypes and reduce rates of fungicide application on anthracnose incidence and severity at Arba Minch and Derashe in southern Ethiopia during 2018 cropping season

| Treatments | Percent disease incidence at final date (%) | Percent severity index at final date (%) | Area under disease progress curve (%-day) | Rate of disease progress (Unit day$^{-1}$) |
|---|---|---|---|---|
| Location | | | | |
| Arba MInch | 89.93a | 55.60a | 1029.42a | 0.02286a |
| Derashe | 78.54b | 47.13b | 928.31b | 0.01326b |
| LSD (5%) | 1.56 | 1.95 | 22.79 | 0.0017 |
| Genotypes + Rates of fungicide | | | | |
| Arghiti + Unsprayed | 74.58c | 31.67f | 645.56fg | 0.0107ef |
| Arghiti + 2 Kg ha$^{-1}$ | 67.08d | 26.38gh | 604.72gh | 0.0079fg |
| Arghiti + 3 Kg ha$^{-1}$ | 55.83f | 22.78h | 583.33h | 0.0048g |
| Melkam + Unsprayed | 80.42b | 40.00e | 681.53f | 0.0139e |
| Melkam + 2 Kg ha$^{-1}$ | 70.00d | 31.39f | 630.00f-h | 0.0085fg |
| Melkam + 3 Kg ha$^{-1}$ | 62.92e | 29.44fg | 628.06f-h | 0.0071fg |
| Seredo + Unsprayed | 100.00a | 76.94b | 1338.75bc | 0.0335b |
| Seredo + 2 Kg ha$^{-1}$ | 100.00a | 67.22c | 1237.64d | 0.0235cd |
| Seredo + 3 Kg ha$^{-1}$ | 100.00a | 62.22d | 1143.33e | 0.0212d |
| Local + Unsprayed | 100.00a | 88.33a | 1556.53a | 0.0408a |
| Local + 2 Kg ha$^{-1}$ | 100.00a | 73.89c | 1392.22b | 0.0247c |
| Local + 3 Kg ha$^{-1}$ | 100.00a | 66.11cd | 1304.72c | 0.0140d |
| LSD (5%) | 3.83 | 4.79 | 55.82 | 0.0042 |

Means in the same column followed by the same letters are not significantly different at 5% level of significant. LSD = Least significant difference at $p < 0.05$ probability level.

## 3.3. Disease Progress Curves (DPC)

Disease progress curves, PSI versus DAP, drew separately for each sorghum genotype (Figure 2). The symptoms have first appeared on Seredo and Local cultivar at 46 and 42 DAP at Arba Minch and Derashe, respectively. The DPC showed that the disease appeared at varying dates depending on the sorghum genotypes and locations. The severity of anthracnose increased over time on unsprayed plots for all sorghum genotypes, implying that the inoculum built up over time. As a general, each curve for all genotypes revealed that disease severity progressed increasingly starting from the beginning to the final severity irrespective of rates of fungicide application, although the sprayed plots have kept progressively lower as compared to the unsprayed plots during the study periods. The DPC for each sorghum genotype also indicated that the disease progression was not similar for each rate of fungicide application.

For all sorghum genotypes considered, disease on unsprayed plots showed relatively high progressive curves and exhibited the highest levels of anthracnose severity. Thus, severity increased steadily on unsprayed plots of Seredo and Local cultivar, and reached up to 76.94 and 88.33% at the final date of assessment 114 DAT (mean date for the two locations), respectively. Anthracnose severity on Arghiti and Malkam chlorotic specks increased linearly starting from 20% at 44 to (Arghiti) and 40% (Melkam) 114 DAP with lower severity as compared to Seredo and Local irrespective of rates of fungicide application. For all genotypes and rates of fungicide applications significant variations among the evaluated treatments had started afterward of 72 DAP (Figure 2). However, on plots sprayed with Ridomil at the rate of 3 kg ha$^{-1}$ disease severity was elevated from 20% (for Arghiti and Malkam) at 72 DAT to 22.78% (for Arghiti at 100) and 29.44% (for Melkam at 100 DAT) and remained consistently very low with 22.78% (Arghiti) and 29.44% (Melkam) up to final date of an assessment (114 DAT). The sorghum genotypes in combination with the application of Ridomil at the rate of 2 kg ha$^{-1}$ followed similar curves with 3 kg ha$^{-1}$ with slight increments and lied intermediate between unsprayed plots and plots sprayed with Ridomil at the rate of 3 kg ha$^{-1}$ for all sorghum genotypes. Similar trends were observed for Ridomil at the rate of 2 and 3 kg ha$^{-1}$ with the genotypes Seredo and Local cultivars for the assessment dates started from 72 to 114 DAP (Figure 2).

Disease progress curves in a combination of sorghum genotypes with Ridomil at the rate of 2 and 3 kg ha$^{-1}$ slowly increased and showed lower levels of severity as compared to the unsprayed plots for all genotypes. Integration of sorghum genotypes and rates of fungicide application reduced the disease severity as observed on all managed plots; however, unsprayed plots of all sorghum genotypes eventually reached the highest levels of disease severity. This suggested that the management of anthracnose through a combination of genotypes with different levels of resistance and appropriate rates of fungicide application could provide a safeguard for the crop against the disease during the growing periods. Possibly treatment combination could enhance the well-being and vigouristy of the crop that might increase plant chances to endure the pathogen attack and to activate the host defense system through benefits gained from the integrations. In agreement with this study, several researchers reported that a combination of genotypes having different levels of resistance to a given plant disease and supplemented with proper fungicide application could reduce the magnitude of disease severity and enhance the host defense system to withstand the pathogen influence and stabilized towards the end of the epidemic period as compared to the unmanaged ones (Campbell and Madden, 1990; Li et al., 2009; Akwero et al., 2016).

## 3.4. Growth and Yield Related Traits

Evaluation of sorghum genotypes and different rates of Ridomil application revealed significant variations in the Number of productive plants per plot, thousand seed weight, and grain yield (Table 5). The maximum and a minimum number of productive plants per plant, thousand seed weight, and grain yield had recorded at Arba Minch than Derashe. The higher disease severity was recorded at Arba Minch than Derashe, the lower growth and yield parameters recorded at Derashe than Arba Minch (Table 5). This phenomenon might be due to the presence of favorable weather conditions for the growth of the crop at Arba Minch than Derash during the growing periods and these might favor the growth and development of the crop at Arba Minch (Table 1). At Derash, there was erratic rainfall distribution and high

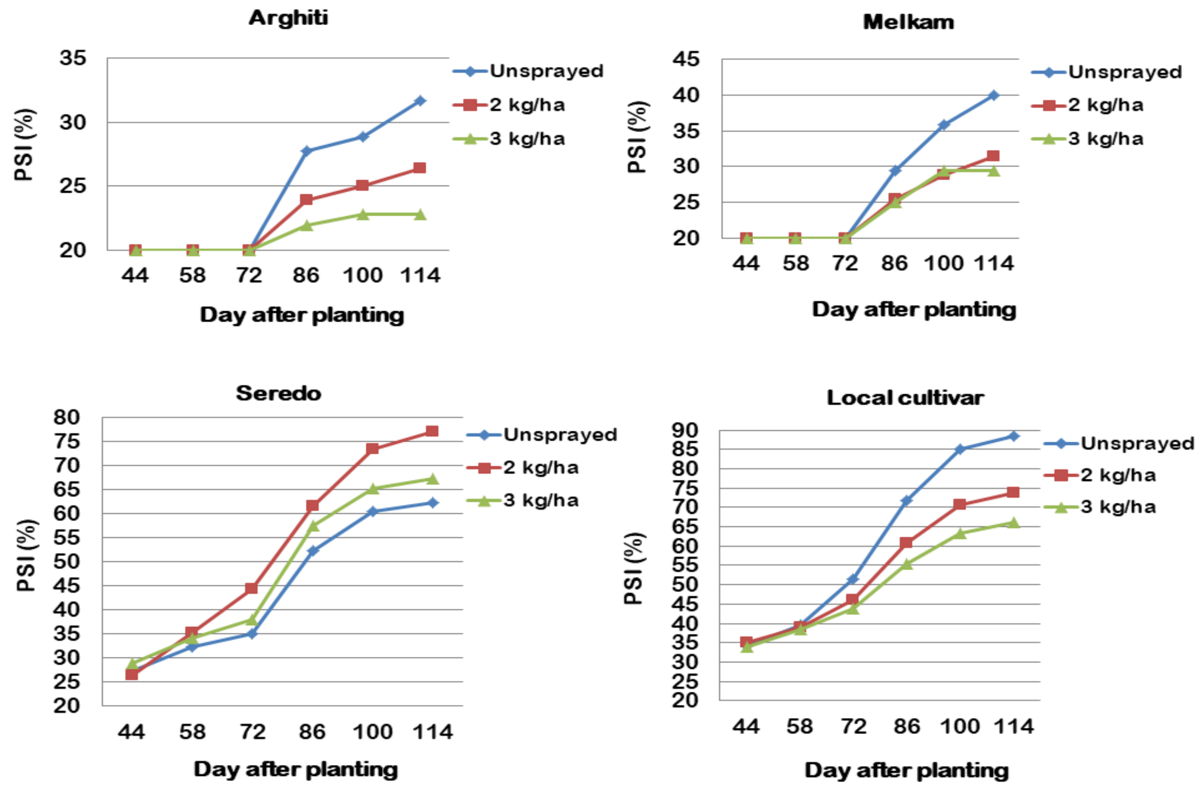


**Figure 2**: Sorghum anthracnose disease progress curve as affected by different rates of fungicide application on four sorghum genotypes at the study areas in southern Ethiopia during the 2018 cropping season.

temperature during the growing periods (Table 1), and this might disfavor the growth and development of the crop and result in a lower number of productive plants per plant, thousand seed weight, and grain yield than Arba Minch (Table 5).

The maximum mean for number of productive plants per plant was found from a combination of Seredo with Ridomil at the rate of 3 kg ha$^{-1}$, which was statistically at parity with the values obtained from Ridomil at the rate of 2 kg ha$^{-1}$ for the same genotype. Contrarily, the minimum mean for number of productive plants per plant was on an unsprayed plot of Local cultivar, which was statistically at parity with the values obtained from Ridomil at the rate of 2 kg ha$^{-1}$ for the same genotype. No statistically significant difference was observed in the number of productive plants per plant for Arghiti with both unsprayed and sprayed ones and Melkam with sprayed of Ridomil at the rate of 2 kg ha$^{-1}$. This phenomenon might be due to the inherent genetic potential of the genotypes to resist the effect of anthracnose than the different rates of fungicide applications. On the other hand, Arghiti and Melkam in combination with the application of Ridomil at the rate of 2 and 3 kg ha$^{-1}$ showed the mean highest thousand seed weight as compared to Seredo and Local cultivar at similar rates of Ridomil applications. The lowest mean for thousand seed weight was for unsprayed plots of all genotypes (Table 5).

Arghiti and Melkam exhibited the highest grain yield as compared to Local cultivar (Table 5). This difference might have resulted from the variation in the genetic makeup of the tested genotypes as well as the different rates of Ridomil applications. Significant variations among sorghum genotypes had observed for growth and yield-related traits and significantly influenced by the genetic makeup of the crop when evaluated for disease management through genotype mixture and fungicide application and gave highest values for these traits over the susceptible genotype and unmanaged plots (Thomas et al., 1996; Gwary et al., 2003; Marley, 2004). Similarly, Gwary et al. (2008); Muhammad et al. (2017); Bunker et al. (2019) reported that significant variations among the evaluated sorghum genotypes and fungicide application for the studied parameters.

**Table 5**: Effect of anthracnose on growth and yield-related traits under the integration of sorghum genotypes and reduced rates of fungicide applications at Arba Minch and Derashe in southern Ethiopia during the 2018 cropping season

| **Treatments** | Number of productive plants per plot, | Thousand seed weight (g) | Grain yield (t $ha^{-1}$) |
|---|---|---|---|
| Locations | | | |
| Arba Minch | 75.92a | 29.26a | 3.36a |
| Derashe | 48.44b | 27.40b | 1.33b |
| LSD (5%) | 5.91 | 1.84 | 0.48 |
| Genotypes + Rates of fungicide | | | |
| Arghiti + Unsprayed | 52.83cd | 26.93cd | 2.48c |
| Arghiti + 2 Kg $ha^{-1}$ | 70.50b | 33.77ab | 4.22a |
| Arghiti + 3 Kg $ha^{-1}$ | 70.17b | 36.43a | 3.78ab |
| Melkam + Unsprayed | 47.00d | 24.90de | 2.63bc |
| Melkam + 2 Kg $ha^{-1}$ | 69.50b | 33.88ab | 4.00a |
| Melkam + 3 Kg $ha^{-1}$ | 71.17b | 35.52a | 3.78ab |
| Seredo + Unsprayed | 63.67bc | 21.62e | 1.56cd |
| Seredo + 2 Kg $ha^{-1}$ | 87.67ab | 27.37cd | 2.11c |
| Seredo + 3 Kg $ha^{-1}$ | 94.83a | 29.60bc | 2.26c |
| Local + Unsprayed | 29.00e | 20.70e | 0.31e |
| Local + 2 Kg $ha^{-1}$ | 42.67ed | 24.13de | 0.37de |
| Local + 3 Kg $ha^{-1}$ | 47.17d | 25.15c-e | 0.67de |
| LSD (5%) | 14.48 | 4.51 | 2.01 |

Means in the same column followed by the same letters are not significantly different at 5% level of significant. LSD = Least significant difference at $p < 0.05$ probability level.

### 3.5. Association of anthracnose Epidemic with the Studied Crop Parameters

A significant correlation between and among the mean values of epidemiological and yield-related parameters had observed (Table 6). Positive and high correlations were observed between final PDI and PSI (r = 0.94), AUDPC (r = 0.92) and DPR (r = 0.0.85). Also, positive and high correlations were detected between final PSI and AUDPC (r = 0.99) and DPR (r = 0.96). Thus, the result demonstrated that these epidemiological parameters were found interconnected to each other and showed the disease had developed at a faster rate on unsprayed plots than sprayed ones of all sorghum genotypes having different levels of resistance and different rates of fungicide application (Table 6).

The correlation between epidemiological and crop parameters was negative; however, their significances are varied among the parameters correlated. The association between the number of productive plants per plant and epidemiological parameters was non-significant when correlated with each other even though it was negatively associated with them. This phenomenon could be partly related to soil infestation and growth suppression by anthracnose and weather conditions in the studied areas. The results indicated that the observed levels of anthracnose cause a substantial adverse effect on crop parameters considered for all sorghum genotypes (Table 6). Campbell and Madden (1990); Thomas et al. (1996); Agrios (2005) noted plant diseases had strongly and negatively correlated with growth and yield-related parameters of a given crop. Renata et al. (2012) also found a highly and significantly negative association of yield-related parameters of sorghum with anthracnose development. The correlation analysis showed that positive associations had observed between and among the number of productive plants per plant, thousand seed weight, and grain yield. Gasura et al. (2015); Andekelile and Zacharia (2018); Seyoum et al. (2019) reported that grain yield had significantly associated with the number of productive plants per plant and thousand seed weight.

A linear regression analysis was made to perceive the relationship of disease parameter and grain yield of sorghum to oversee the loss per each treatment under each plot (Figure 3). The values of AUDPC per plot were used to predict grain yield loss in sorghum production. The estimated values of the coefficient between grain yield and AUDPC was 57.70%. The relationship graph

**Table 6**: Coefficient of correlation between the studied parameters under the integration of sorghum genotypes and reduced rates of fungicide application at the study areas in southern Ethiopia during the 2018 cropping season

| Variable | Final PDI | Final PSI | AUDPC | RDP | NPT | TSW |
|---|---|---|---|---|---|---|
| Final PSI | 0.94**** | | | | | |
| AUDPC | 0.92**** | 0.99**** | | | | |
| DPR | 0.85*** | 0.96**** | 0.93**** | | | |
| NPT | -0.14$^{ns}$ | -0.31$^{ns}$ | -0.30$^{ns}$ | -0.37$^{ns}$ | | |
| TSW | -0.78** | -0.84**** | -0.79** | -0.86** | 0.59* | |
| GY | -0.82** | -0.90**** | -0.91**** | -84*** | 0.56* | 0.88*** |

*, **, *** & **** Correlation is significant at $p < 0.05$, $p < 0.001$, $p < 0.0001$ and $p < 0.00001$, respectively; ns = Not significant ($p > 0.05$); PDI = Percent Disease Index; PSI = Percent Severity Index; AUDPC = Area Under Disease Progress Curve; RDP = Rate of Disease Progress; NPT = Number of Productive Tiller; and TSW = Thousand Seed Weight.

displayed as the influence of AUDPC getting higher, the yield obtained from sorghum genotypes becoming lower suggesting that the higher the AUDPC values, the more susceptible the evaluated sorghum genotypes and the inverse relationship between the disease and grain yield. Distances between the line and all the points inferred whether the regression analysis had taken a relationship i.e. strong or weak, the nearer the line is to the points, the stronger the relationship and vice versa. Similarly, the regression equation tried to determine in every unit of AUDPC brought about 0.00299-grain yield losses on the four sorghum genotypes evaluated (Figure 3).

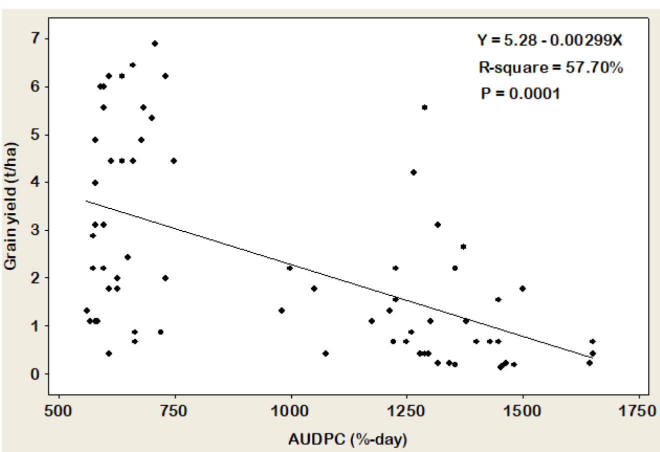


**Figure 3**: Linear regression of grain yield (*Y*) and AUDPC (*X*) at the study areas in southern Ethiopia during 2018 cropping seasons.

### 3.6. Effects of Fungicide Rate on Economic Feasibility of Sorghum Production Relative Yield Loss Assessment

The economic feasibility analysis based on the combined effect of the genotypes and fungicide application against anthracnose management had observed (Table 7). The NB and MRR were figured out based on pooled data obtained from the two locations per genotype versus Ridomil with different spray rates (Table 7). The pooled results of the two locations exhibited that integration of Ridomil at the rate of 2 kg ha$^{-1}$ showed the highest net benefit and MRR from Arghiti and Melkam; however, unsprayed plots of these genotypes were showed the lowest NB and MRR as compared to relatively better-protected plots. Seredo required spraying of Ridomil at the rate of 3 kg ha$^{-1}$ to be economically effective in the sorghum production system against anthracnose management. Nonetheless, the NB and MRR obtained from Local cultivar showed that economically not feasible when it produces through the use of Ridomil due to the negative result obtained from the economic analysis (Table 7). The high NB and MRR from the above treatment combination could be accredited to high grain yield, and the low NB and MRR had attributed to low grain yield. Similar results on the profitability of the use of sorghum genotypes and fungicide applications under integrated management of anthracnose were reported in Nigeria by (Gwary and Asala, 2006b; 2006c).

Relative yield loss was calculated based on a relatively better Ridomil spray rate and the associated grain yield gains or losses in sorghum genotypes (Table 7). The relative yield loss that was obtained by the treatment effect was computed based on pooled values of grain yield obtained from the two locations. The highest grain yield losses were recorded on unsprayed plots of all genotypes as compared to the highly protected plots by Ridomil at the rate of 2 kg ha$^{-1}$ for each genotype. The losses in grain yield of sorghum genotypes could be attributed to the severe infection of

**Table 7**: The economic advantage of using an integration of sorghum genotypes and reduced rates of fungicide application concerning cost-benefit and yield losses at the study areas in southern Ethiopia during the 2018 cropping season

| Treatment | | Grain yield (t $ha^{-1}$) | Adjusted yield (t $ha^{-1}$) 10% down | Total variable cost ($ $ha^{-1}$) | Sell revenue ($ $ha^{-1}$) | Net benefit ($ $ha^{-1}$) | Marginal rate of return (%) | Relative yield loss (%) |
|---|---|---|---|---|---|---|---|---|
| Sorghum genotypes | Rates of fungicide | | | | | | | |
| Arghiti | unsprayed | 2.48 | 2.23 | 312.20 | 715.47 | 403.27 | 0.00 | 41.23 |
| | 2 Kg $ha^{-1}$ | 4.22 | 3.80 | 468.71 | 1217.45 | 748.74 | 2.21 | 0.00 |
| | 3 Kg $ha^{-1}$ | 3.78 | 3.40 | 489.27 | 1089.07 | 599.80 | 1.11 | 10.43 |
| Melkam | unsprayed | 2.63 | 2.36 | 312.20 | 757.30 | 445.10 | 0.00 | 34.25 |
| | 2 Kg $ha^{-1}$ | 4.00 | 3.60 | 468.71 | 1152.54 | 683.83 | 1.53 | 0.00 |
| | 3 Kg $ha^{-1}$ | 3.78 | 3.40 | 489.27 | 1090.52 | 601.25 | 0.88 | 5.50 |
| Seredo | unsprayed | 1.56 | 1.40 | 312.20 | 448.61 | 136.41 | 0.00 | 30.97 |
| | 2 Kg $ha^{-1}$ | 2.11 | 1.90 | 468.71 | 608.73 | 140.02 | 0.02 | 6.64 |
| | 3 Kg $ha^{-1}$ | 2.26 | 2.03 | 489.27 | 652.00 | 162.73 | 0.15 | 0.00 |
| Local | unsprayed | 0.31 | 0.28 | 312.20 | 89.43 | -222.77 | 0.00 | 54.41 |
| | 2 Kg $ha^{-1}$ | 0.37 | 0.33 | 468.71 | 105.30 | -363.41 | -0.90 | 45.59 |
| | 3 Kg $ha^{-1}$ | 0.68 | 0.61 | 489.27 | 194.73 | -294.54 | -0.41 | 0.00 |

The mean unit price of sorghum grain yield per ton was 288.50 $ (at the exchange rate of 1$ = 27.73 ETB) at the time of selling during the 2018 cropping year.

anthracnose at the full-grown stage of the plant, which eventually slew the leaves and reduced the yield obtained from the plants. Grain yield losses computed in the present study could not be only attributed to anthracnose as some effects were noted due to Turcicum leaf blight (*Exserohilum turcicum*) and viral disease of sorghum including environmental conditions and mechanically damaged due to bird. Grain yield losses of 50-100% due to anthracnose had been reported in sorghum production in different parts of the world (Thakur and Mathur, 2000; Tesso et al., 2012).

## 4. Conclusion

Evaluation of sorghum genotypes and different rates of Ridomil exhibited noticeable effects in reducing anthracnose epidemic development and enhance grain yield of sorghum. An economic evaluation of the treatment evaluated revealed that a combination of Arghiti and Melkam with an application of Ridomil at the rate of 2 kg $ha^{-1}$ provided the highest NB and MRR than unsprayed plots but Seredo needed further rates of Ridomil to be economically feasible in the management of anthracnose. However, the Local cultivar showed unprofitable under sorghum production through the use of fungicide. Use of resistant (Arghiti) and moderately resistant (Melkam) in combination with the application of Ridomil at the rate of 2 kg $ha^{-1}$ have proved to be a relatively better and cost-effective mechanism in reducing anthracnose severity, AUDPC and rates of disease progression as well increasing production and productivity of sorghum. Thus, the use of Arghiti and Melkam in combination with Ridomil at the rate of 2 kg $ha^{-1}$ could be suggested to producers in the study areas and elsewhere with similar agro-ecology for effective management of anthracnose and sustain production and productivity of sorghum. Further studies should be conducted in similar and other agro-ecologies in Ethiopia for at least three consecutive years to come up with concrete recommendation on anthracnose management options through a combination of sorghum genotypes and different rates of Ridomil, and to enhance sustainable sorghum production in the country.

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