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Research article

Integration of host resistance, fungicides, and spray frequencies for managing Fusarium head blight of bread wheat under field conditions in southern Ethiopia

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ABSTRACT

A field experiment was carried out in Adiyo, Bonke, Chencha, Sodo zuriya, and North Ari districts, they are found in Southern Ethiopia, during the 2019 main production season. The objective of the experiment was to evaluate the effectiveness of the integrations of host resistance and application of fungicides with designated spray frequency on Fusarium head blight under natural epiphytotic conditions and to determine the management effects on yield and yield components of wheat. The treatments consisted of wheat cultivars (Shorima and Hidase) and fungicides (Propiconazole and Tebuconazole) with four spray frequencies, including an unsprayed one. The experiment was arranged in a split-split plot design with three replications. Wheat cultivars were assigned to the main plots and fungicides allotted to the sub-plots, while the spray frequencies were appointed to sub-sub plots. Results exhibited that integration of wheat cultivars and fungicides with spray frequencies significantly ($p < 0.001$) reduced disease pressure and increased grain yields across the locations. The highest disease severity (36.46%) and area under disease progress curve (AUDPC) (404.78%-day) and lowest grain yield (2.42 t ha^{-1}) were recorded at North Ari. The lowest severity (7.70%), and AUDPC (130.26%-day), and the highest grain yield (6.68 t ha^{-1}) were recorded in Bonke. The lowest severity (4.78 and 5.74%) and AUDPC (52.86 and 59.78%-day) were recorded from Shorima due to integrated use of Tebuconazole with three and two times spray frequencies, respectively. The highest grain yield of 5.30 t ha^{-1} was recorded on Shorima in combination with Tebuconazole with three times spray frequencies. The grain yield loss of 46.49% was computed on unsprayed plots of Hidase cultivar. Overall, the results exhibited a combination of moderately resistance wheat cultivars supplemented by fungicide with appropriate spray frequencies right at disease onset reduced disease pressure and increased grain yield. Planting of Shorima combined with Tebuconazole with three times spray frequencies was found effective in reducing FHB epidemics and increasing grain yield with the highest monetary advantage. Therefore, this could be recommended to growers in the study areas and similar agro-ecologies to manage *F. graminearum* causing FHB in wheat.

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1. Introduction

Cereal crops are the most significant crops in terms of food security and global market share worldwide (FAO et al., 2018; USDA, 2018; FAO, 2020). These crops furnish indispensable nutrients and energetic yield in the day-to-day human diet via direct consumption and also through beef production since they encompass a key livestock feed. Cereal crops, including rice, wheat, barley, maize, and sorghum, have global importance and together supply nearly 50% of the world's calorie consumption (Dunwell, 2014a; Alicia and Holopainen-Mantila, 2020). Among the cereals, wheat (*Triticum* spp.) is the world's leading crop, which is consumed as a staple food by nearly 1/3rd population of the world (FAO et al., 2018; USDA, 2018). The world's aggregate production of wheat was 809 million tons of grain yields, which was produced from a total of 214 million hectares of land (FAOSTAT, 2018). The world-leading wheat-producing country is China (144 million tons), followed by India (109 million tons), Russia (79 million tons), United States (56 million tons) and France (39 million tons). In this regard, Ethiopia is the major wheat producer next to Egypt and Morocco in Africa, which provides an annual grain production of 4 million tons (CSA, 2018; FAOSTAT, 2018). In Southern Ethiopia, the crop is produced on 151,584 ha of land and contributes more than 400 thousand tons of grain yields (CSA, 2018).

Wheat is cultivated in a broad range of agro-ecologies, including low to high altitudes in Ethiopia. It is the highest crop produced next to Tef (*Eragrostis tef* (Zucc.) Trotter): in terms of production and distribution in the country (CSA, 2018; MoANR and EATA, 2018). In the country, wheat production accounts for 18.23 and 19.80% of all the cereals acreage and production, respectively (CSA, 2018). The crop is potentially grown in Oromiya, Amara, Southern Nation Nationalities and Peoples Region, and Tigray regions in the country. The crop plays great roles in food security, income source, and calorie intake, but its production is constrained by different reasons. Due to this, the average productivity of the crop is low in the country (2.77 t ha^{-1}) as well as in southern Ethiopia (2.66 t ha^{-1}) compared with the world (3.77 t ha^{-1}) (CSA, 2018; FAOSTAT, 2018). However, wheat productivity reached more than 7 t ha^{-1} under research and more than 4 t ha^{-1} under farmers' field conditions reported by MoANR and EATA (2018). The low productivity of the wheat was ascribed to abiotic, biotic, socioeconomic, and those related to crop management worldwide (Zegeye et al., 2001; Dunwell, 2014b; Eshetu and Bedada, 2020). Among the biotic factors, wheat rusts (*Puccinia spp.*), septoria leaf blight (*Septoria tritici*), common bunt (*Tilletia caries*), and barley yellow dwarf virus are important and widely studied diseases in one or another way in Ethiopia as well as in the world (Zewdie and Paul, 2013; Dunwell, 2014b; Tewodros et al., 2016; Eshetu and Bedada, 2020). In addition to the previously reported important diseases of wheat, recently head scab of wheat became an important and destructive disease of wheat in Ethiopia.

Fusarium head blight (FHB) or head scab of wheat, caused by *Fusarium graminearum* Schwabe (Teleomorph *Gibberella zeae* (Schwein.) Petch) is a widespread and destructive fungal disease of wheat and other small grain cereal crops worldwide (Parry et al., 1995; McMullen et al., 1997; Steffenson, 2003). Dean et al. (2012) reported that FHB is an economically significant disease of wheat next to yellow rust (*Puccinia striiformis* f.sp. *tritici*), stem rust (*Puccinia graminis* f.sp *tritici*), and septoria leaf blight (*Septoria tritici*) worldwide. Affected grains are small, light, pre-mature, shriveled, shrunken, and sometimes covered with a white or pink fungal mass (Langseth et al., 1995; Karasi et al., 2016). *Fusarium graminearum* overwinters and survives as asexual (conidia, chlamydospores, and mycelium) and sexual (ascospores) spores within or on seeds, between crops in infected chaff, grass stubble, grains, and stem stalk residues left on the ground, and the soil (Sutton, 1982; Pereira et al., 2004; Gilbert et al., 2008; Dill-Macky, 2010). The weather conditions are known to affect and are to be the main factor affecting the FHB development. The disease regularly occurs in humid wheat-producing areas of the world. The optimum temperature for conidial and ascospores germination and symptom development is 25–30 °C along with high humidity of 90% or higher (Sutton, 1982; Trail et al., 2002; McMullen et al., 2012; Karasi et al., 2016).

Fusarium graminearum is a seed-borne fungus, which is characterized by long-distance dispersal between the fields, the regions, and frequently across the continent. This mode of dissemination is of great practical importance, because a very small proportion of infected seeds have the potential to cause epidemics (Agrios, 2005). Dissemination of the spores from infected to healthy plants within the field driven by the amount of airborne inoculum, rain splashes, and pollinators (Agnès et al., 2004; McMullen et al., 2012; Karasi et al., 2016). Grain yield loss of 50–70% due to FHB was estimated in wheat production. Grain yield losses of 100% have been recorded on the highly susceptible wheat genotypes in severe conditions (Windels, 2000; Pirgozliev et al., 2003). According to the report of the Southern Regional Bureau of Agriculture and respective districts of the office of Agriculture within the region, a remarkable destructive outbreak has occurred in Southern Ethiopia during the 2017 and 2018 cropping seasons. However, practical quantification of yield loss of wheat due to FHB has not been studied under Ethiopian conditions. But, they indicated that the significant damage had been witnessed in the study areas (Adiyo, Bench, and North Ari districts); in some fields of wheat, nearly 100% yield loss has been reported during the growing seasons.

As wheat is an important grain crop utilized for human food, and its safety is pertaining due to FHB. To reduce FHB impairment and mycotoxin contamination, a number of management strategies are reported. Of which, cultural practices including crop rotation with non-host crops, crop residue management, proper tillage practices, early planting, use of early maturing cultivars, and proper post-harvest seed management are mainly practiced (Dill-Macky and Jones, 2000; Jouany, 2007; Wegulo et al., 2015). In addition to this, the use of resistant cultivar and timely application of fungicides with proper rate and spray frequencies had been reported by Ruckenbauer et al. (2001), Gilbert and Haber (2013), Wegulo et al. (2015), and Shude et al. (2020). However, cultural approaches could merely manage FHB to a limited extent since the approach work only lowering the amount of inoculum present in the field and is significantly affected by environmental conditions. These conditions encourage the dispersal of spores through rain splashes and air current (Parry et al., 1995; Trail et al., 2002). The use of resistance cultivars had the most cost-effective and eco-friendly management option for FHB. But, the utilization of resistant cultivar is not assured for a year after year cultivation due to durability of the resistance gene and the wider variability of the pathogen itself, which often breakdown resistance genes making the cultivars vulnerable to the disease (Agrios, 2005).

However, the tendency of many cultivators and the bulk of past research on the disease management strategy of FHB had mainly focused on the use of fungicides worldwide (Shude et al., 2020). Of course, the use of fungicides was the most effective option for FHB management; however, unwise use of fungicides had been reported in several studies (Green et al., 1990; WHO, 2004; Getachew et al., 2018; Getachew, 2020) worldwide, including Ethiopia and the study areas as well. In this regard, WHO (2004), Agrios (2005), and Mostafalou and Abdollahi (2012) indicated that unwise use of fungicide has adverse effects on the crop, human health, and other living organisms, environmental pollution, and development of resistance by the pathogen. For these reasons, Stephen et al. (2013), Dweba et al. (2017), Paul et al. (2019), and Shude et al. (2020) suggested that integrated use of agronomical practices, resistant cultivars, and fungicides with appropriate spray frequencies and time had significant pressure on FHB than using a single approach. In this regard, understanding the epidemiology of plant diseases is necessary for the device of trustworthy and efficient disease management approaches. Jeger (2004) resumed the role of pragmatic approaches in disease progression analysis for evaluating disease management strategies for various pathosystems, host, pathogen, and location interactions. Therefore, devising appropriate management tactics and information regarding factors that influence the intensity of the FHB is a prerequisite for the study areas and the country as well.

Thus, there is a pressing need for experimental data to use fungicides wisely and in an integrated method with other management options such as host resistance under Ethiopian conditions, particularly in the study areas. Stephen et al. (2013) and Paul et al. (2019) reported that a combination of wheat cultivars and fungicide application indicated response of wheat cultivars varied with the different fungicides used. The reasons were the wheat cultivars with various levels of reaction to FHB and the fewer efficacies and resistance of FHB to the fungicides. The wheat cultivar may perform well with one or another fungicide with proper spray frequency and timely application when the first visual symptoms of the disease have appeared. A good combination of wheat cultivar and fungicide (s) with appropriate spray frequency will prefer over a wheat cultivar that demands no or little fungicidal activity. Research on the combined role of host resistance and fungicide applications with appropriate spray frequency against FHB management and grain yield of wheat may generate information suited for use as a practical constituent of integrated disease management strategies for FHB. However, this approach has not been yet evaluated in southern Ethiopia or elsewhere in the country.

A combination of different management tactics are needed to decrease the use of pesticides, environmental pollution, health hazards, and opportunities of resistance development by a pathogen, promising sustainable crop production through effective disease management (Green et al., 1990; Agrios, 2005; Foster et al., 2017). This paper report the results of a multi-location field experiment carried out in southern Ethiopia. The objective of the study was to evaluate the effectiveness of the integrations of host resistance and application of fungicides with designated spray frequency on FHB epidemics under natural epiphytotic conditions and to determine the effects of integrated management of FHB on yield and yield components of wheat.

2. Materials and methods

2.1. Overview of experimental areas

The areas selected for the experiment were Adiyo, Bonke, Chencha, Sodo zuriya, and North Ari districts, they are found in Southern Ethiopia. The experiment deals on the integration of host resistance, fungicides, and spray frequencies was conducted during the 2019 main cropping season, July (2019) to February (2020). The experimental areas are diversified in agro-ecological conditions from midland to highland. These areas are nominated based on the cultivation potential of wheat and the importance of FHB. The experimental areas along with their corresponding geographic positions are displayed in Figure 1. The altitude of 2116, 2391, 2400, 2667, and 2786 m above sea level were recorded at Sodo zuriya, North Ari, Adiyo, Chencha, and Bonke, respectively. The selected areas receive a bimodal rainfall pattern. The short rainy season occurs from March to May, and the main rainy season, July to November. Total rainfall (mm), monthly minimum and maximum temperatures (°C), and relative humidity (%) of the areas during the cropping years were obtained from meteorological stations and displayed in Figure 2. The sites are characterized by different soil properties. In Adiyo, a textural class of clay-loam, strongly acidic pH and organic matter contents of 11.56% are the characteristic features of soil in the

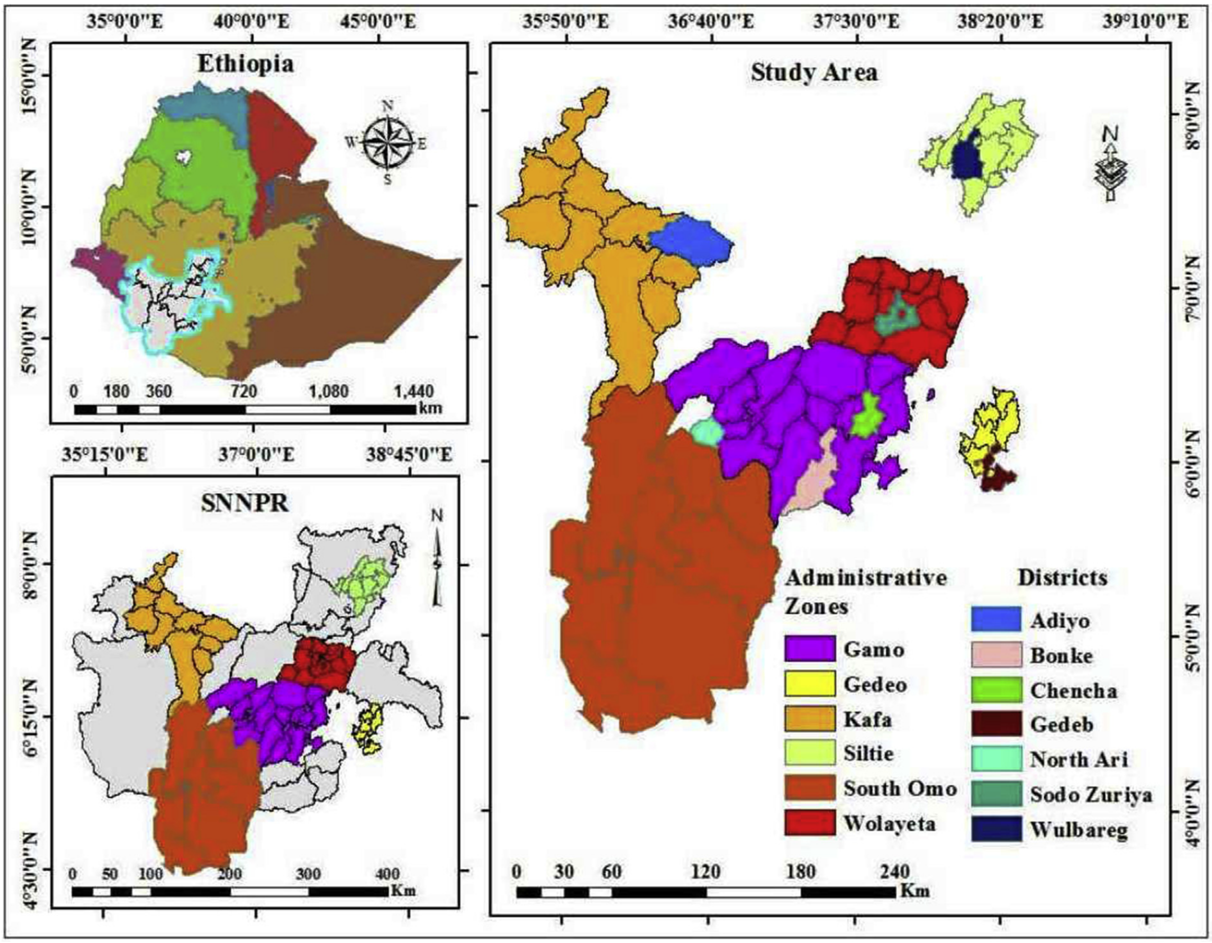

Figure 1. Map of Ethiopian, Southern Nations, Nationality of Peoples' Region (SNNPR), and experimental areas for fusarium head blight during the 2019 cropping season. Source: National Meteorological Agency at Hawassa Branch (2019).

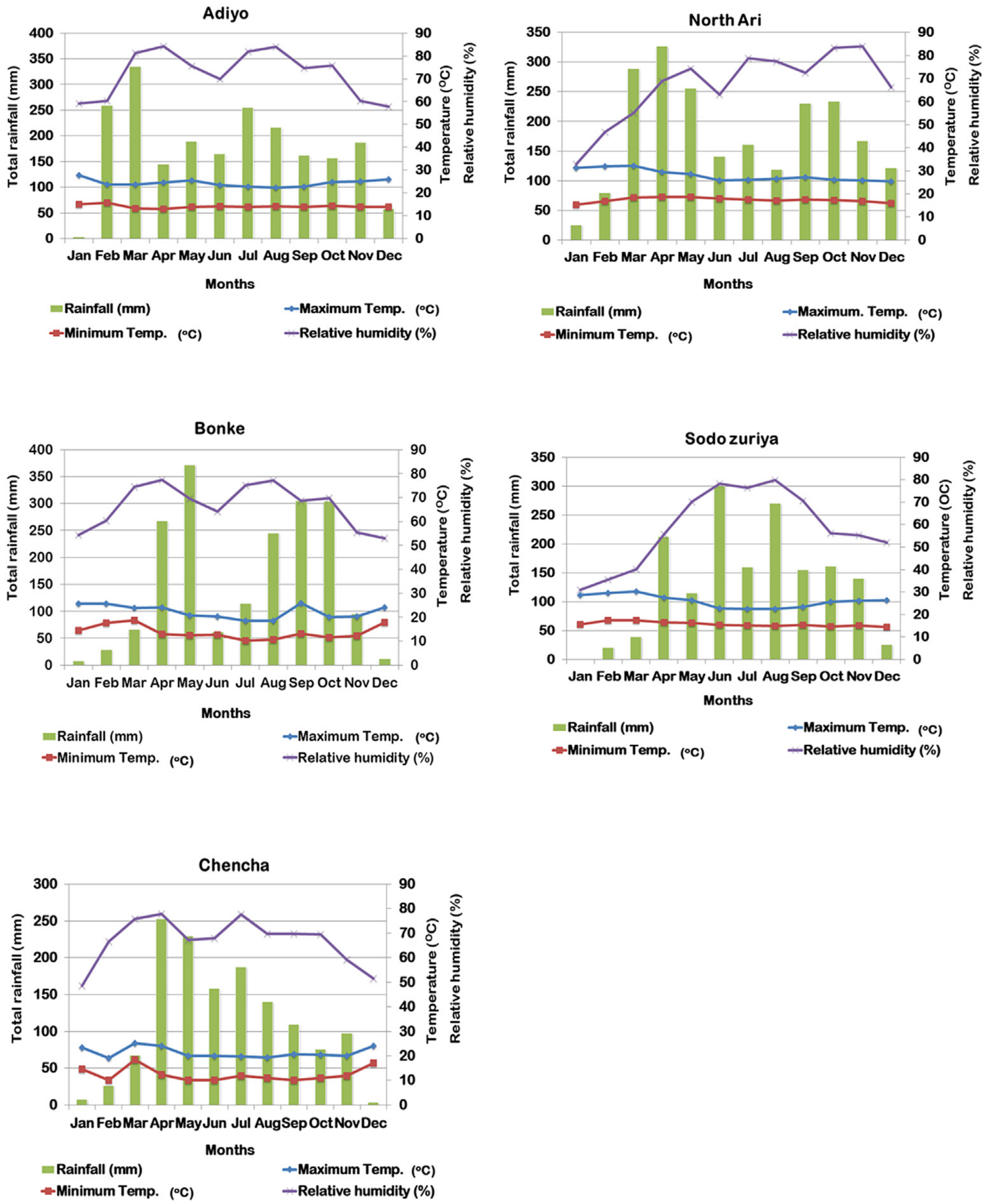

Figure 2. Total rainfall (mm), mean monthly minimum and maximum temperatures (°C), and relative humidity (%) in Adiyo, Bonke, Chencha, North Ari, and Sodo Zuriya districts in Southern Ethiopia during the 2019 cropping season.

area. Moderately acidic pH and organic matter contents of 4.96 and 5.75% are characteristics features of soil in North Ari and Sodo zuriya, respectively. In North Ari and Sodo zuriya, the soil textural class is clay-loam and sandy-loam, respectively. In Bonke and Chencha, the soil is characterized by a strongly acidic pH with low organic matter contents, which are ranged from 0.25% to 1.05%, and sandy-loam (Ministry of Agriculture and Natural Resources [MoANR] and Ethiopian Agricultural Transformation Agency [EATA], 2016).

2.2. Experimental materials, treatments and design

Two wheat cultivars (Shorima and Hidase) currently found under production and differing in their resistance levels to major wheat diseases (MoANR and EATA, 2018; Getachew, 2020) were used as a varietal component of the treatment. Shorima and Hidase correspond as moderately resistant and susceptible to FHB, respectively. Seeds of the wheat cultivars were obtained from Kulumsa Agricultural Research Center, Ethiopian Institute of Agricultural Research, Ethiopia. The chemical Natura 250 EW [Tebuconazole] and Tilt 250 EC [Propiconazole] were utilized as fungicidal components of the treatment. The spray frequencies of zero (0), one time (1), two times (2), and three times (3) were used as the third component of the experimental treatments. Overall, the treatments are comprised of two wheat cultivars, two fungicides, and three spray frequencies. A total of 14 treatment combinations were fashioned, including the unsprayed control plot. The experiment was arranged in a split-split plot design with three replications. To this, wheat cultivars were assigned to the main plots and fungicides allotted to the sub-plots, while the spray frequencies were appointed to sub-sub plots. Each treatment combination was apportioned at random to experimental plots within a block.

2.3. Field management procedures

The study was conducted entirely under natural epiphytotic conditions. Natural infection was used as the source of inoculum. The field design was arranged with a gross field size of 9.4 m width x 41.0 m length. The total field size was 385.40 m^2. The unit plot size was 1.8 m width x 2.0 m length. The space between plots and adjacent replications was 1.0 m and 2.0 m, respectively. The plot was comprised of eight rows with six harvestable middle rows, leaving the two border rows. The seeds were sown in the inter-row spacing of 25 cm at the soil depth of 3 cm as per the recommendations advised by MoANR and EATA (2018). The seeds were drilled along the rows. Seed sowing was done by hand on 28th July (at Sodo zuriya) and 5th of August (at North Ari) 2019 during the cropping season. The sowing date of the other locations was performed between these dates. The fungicides were sprayed at intervals of 15-days on each wheat cultivar, which was adjusted based on the nature of fungicide (systemic) and FHB development. Propiconazole at the rate of 0.5 L ha^{-1} with 250 L water and Tebuconazole at the rate of 0.5 L ha^{-1} with 300 L water were sprayed based on the manufacturer's recommendations. Spraying of Propiconazole and Tebuconazole was started at the first disease symptom of FHB observed on the susceptible cultivar (Hidase) on Zadok growth stage of 59 (heading completed) at Adiyo and North Ari, followed by Sodo, Chencha, and Bonke at Zadok growth stage (ZGS) of 61–69 (during anthesis). The spraying was continued as per programmed spray frequencies for each treatment combination in all locations. The spraying was achieved using a manual knapsack sprayer, which was graduated to convey 500–700 L of water ha^{-1}. The unsprayed plots were left for each wheat cultivar as negative controls to allow for maximum development of FHB.

Regarding field management, NPS fertilizer at the rate of 100 kg ha^{-1} was applied in rows during planting. While N-fertilizer of 200 kg ha^{-1} was applied, of which 1/3rd of it during planting and 2/3rd of it on 35-days after planting. Weeding, earthing up, and regular supervising of the field were done properly and homogeneously as per the recommendations to produce a successful crop production recommended by MoANR and EATA (2018). The fungicides used were not only considered as a treatment for FHB management but were also aimed at managing wheat rusts and septoria leaf blotch. However, before the occurrence of FHB that is before heading, the whole plots, including the control plots, were sprayed with Rex® Duo [Epoxiconazole + Thiophanate-methyl] at the rate of 0.5 L ha^{-1} mixing 300 L water for management of wheat rusts and septoria leaf blotch in all locations.

2.4. Data collection and analysis

2.4.1. Disease monitoring

Fusarium head blight incidence and severity were registered in every 10-days interval beginning from the first disease symptoms that appeared on the spikelet. Correspondingly, the area under the disease progress curve (AUDPC) was computed to determine the effectiveness of the integration of host resistance, fungicides, and spray frequencies against the disease. Zadoks et al. (1974) was used to follow the growth stage of wheat during data collections. The FHB incidence and severity monitoring begun at the Zadok growth stage of 61–69 (during anthesis) at Adiyo and North Ari, followed by Sodo (ZGS of 69, anthesis completed) and Chencha and Bonke at ZGS of 71–73 (post-anthesis), and ceased with the crop attain physiologically mature (Zadok growth stage of 90, soft dough stage). Disease incidence (%) was determined as the ratio of the number of infected plants showing FHB symptoms and the total number of plants considered within the plot and multiplied by 100. Disease severity was appraised from 20 randomly selected plants and tagged once they selected up to the last assessment dates within the central row. The FHB severity was recorded on a rating scale of 1–100% (Stack and McMullen, 2011). A total of five disease severity assessments per location were carried on during the growing season. Mean values of disease severity obtained from 20 assessed plants of each plot were used for data analysis.

The area under disease progress curve (Equation 1), which means the progression and buildup of disease on the whole spike or part of the spike during the epidemic periods, was figured out from severity data recorded at different days after planting for each plot (Campbell and Madden, 1990).

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

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 disease severity of FHB at the i^{th} assessment. AUDPC value was expressed in %-days because severity (x) is expressed in percent and time (t) in days.

2.4.2. Yield parameters

Six middle rows were harvested to determine thousand seeds weight and grain yield. The reason to select these parameters was to determine their association with FHB (Langseth et al., 1995; Gilbert and Haber, 2013; Karasi et al., 2016; Shude et al., 2020). Grain harvesting was carried on 135 and 159-days after planting (ZGS of 100) at Sodo zuriya and Bonke, respectively, while grain harvesting dates of the other locations fell in between. The harvested grain yield was measured in kg on a plot basis initially and changed into t ha^{-1}. A thousand seed weight was also assessed for each treatment. The moisture content tester was used to determine the seed moisture content of the seed during harvesting time. Successively, grain yield was adjusted at 12.5% based on seed moisture content following the procedure advised by Taran et al. (1998). Thousand seed weight was assessed from randomly sampled grains acquired from the total harvested grains of each plot using seed counter and sensitive balance devices.

2.4.3. Data analysis

The disease incidence, severity, AUDPC, and yield-related traits were subjected to the analysis of variance (ANOVA) following the general linear model procedure of SAS version 9.3 (SAS, 2014) to determine the treatment effects. As the five locations are believed to be a different environment, Bartlett's chi-square test was employed to test the heterogeneous error variance (Gomez and Gomez, 1984). Bartlett's chi-square test of the error variances for the parameters showed the parameters considered were heterogeneous of the data ($Pr < \chi2$) across the locations. Even though Bartlett's chi-square test showed heterogeneous data, no separate data analyses were performed per location. Therefore, all data were analyzed as a combined analysis for the studied parameters. To recognize the effects of the treatments against the disease and yield-related traits in each location, the analyzed data were displayed and tabulated with location and interaction effects of the treatments. The mean separations between the treatments were accomplished using Fisher's protected least significant difference at a 5% probability level (Gomez and Gomez, 1984). Correlation and linear regression analysis were carried out to observe the association between disease development and yield loss. The correlation and linear regression analysis were appraised using Minitab® (Release 15.0 for windows® 2007).

2.4.4. Economic feasibility and relative yield loss analysis

Economic feasibility and relative yield loss analysis was determined following the procedures suggested by CIMMYT (1988) and Robert and James (1991). Total input cost of production, gross benefit, net benefit, and the benefit-cost ratio was considered under economic feasibility analysis. The total input cost of production was determined from the sum of all costs of variable and fixed input costs used in the experiment. The fixed cost included expenses of land rent, fertilization, weeding and harvesting wages since they were the same for all treatment combinations. The variable cost included fungicides, knapsack sprayer, and labor for fungicide application. The gross benefit was computed by multiplying of market price and grain yield. The net benefit was obtained as the difference between the gross benefit and the total cost of production. The benefit-cost ratio was determined as the ratio of net benefit and total cost. The statistical significance was tested before economic feasibility analysis to compare the average grain yield received between treatments. The economic feasibility analysis was performed as the departures between treatment means were observed.

The costs of Propiconazole and Tebuconazole were \$31.79 and 38.79 per liter (at the exchange rates of United State \$1 = Ethiopian birr 31.45), respectively. The purchasing price of the Knapsack sprayer was \$38.16 as collected from the central market, Addis Ababa, Ethiopia. The cost of labor per person per day in the areas were \$1.11, 1.58, 1.58, 1.58, and 1.90 around North Ari, Adiyo, Bonke, Sodo zuriya, and Chencha during the 2019 cropping seasons, respectively. The cost of land rent per one growing season was \$78.49, 127.19, 127.19, 143.08, and 174.88 on a hectare basis in North Ari, Adiyo, Bonke, Chencha, and Sodo zuriya during the 2019 cropping seasons, respectively. The purchasing price of NPS and urea fertilizer were \$42.43 and 39.11 per 100 kg of the bundle during planting time, respectively. The unit selling price of wheat grain at Adiyo, Sodo zuriya, North Ari, Bonke, and Chencha was \$0.51, 0.64, 0.67, 0.76, and 0.79 kg^{-1}, respectively. All expense cost, and benefit obtained were changed into a hectare basis for determining the economic feasibility of the additional costs. All costs of production and benefits obtained varied across the locations, except for fertilizer and Knapsack sprayer. The actual grain yield was compensated by 10% downward to appraise the grain yield difference between the experiential research and the farmers' practice. Further, the relative yield loss (Equation 2) for each treatment was ascertained following the approaches advised by Robert and James (1991).

$$\text{Relative yield loss } (\%) = \frac{Y_{bt} - Y_{lt}}{Y_{bt}} \times 100 \qquad (2)$$

where, *Ybt* is the yield of best treatment (maximum protected plot) and *Ylt* is the yield of lower treatment. The economic feasibility and relative yield loss analysis were presented in both treatment and location wise.

3. Results

3.1. Disease incidence

Combined analysis of disease incidence, severity, AUDPC, and yield-related parameters exhibited a significant difference between and among the main plot, sub-plots, and sub-sub plots factors across the locations (Table 1). The characteristic symptom of FHB has first appeared on the wheat cultivar Hidase at Adiyo and North Ari, followed by Sodo zuriya, Chencha, and Bonke during the growing period. The symptoms consisted of water-soaked lesions on spikelets, which later appeared as whitened or bleached, and infected kernels look-alike pre-mature, shriveled and shrunken, production of black spherical structures, and discolored with a whitish-brown appearance of the grain while healthy heads were still green (Figure 3). The ANOVA revealed that there were significant ($P < 0.001$) variations among the evaluated treatments for disease incidence, severity, and AUDPC across the locations (Tables 1 and 2). The crosswise assessment showed that the highest disease incidence (80.71%) was noted from North Ari, whereas, the lowest disease incidence was recorded from Chencha (14.75%) and Bonke (13.31%). Fusarium head blight incidence was lowered by 57.17, 68.59, 81.72, and 83.11% at Sodo zuriya, Adiyo, Chencha, and Bonke compared with North Ari, respectively. At the last date of assessment, the mean highest disease incidence (55.98 and 52.87%) was registered from unsprayed and one-time sprayed of Propiconazole on Hidase cultivar, respectively. The lowest mean disease incidence of 15.94% was recorded on Shorima cultivar in combination with three times foliar spray of Tebuconazole, which was statistically on par with Shorima cultivar in combination with two times foliar spray of Tebuconazole (17.66%) and three times foliar spray of Propiconazole (17.77%) (Table 2).

Table 1. Analysis of variance for mean squares of disease score and yield-related traits across the locations in southern Ethiopia during the 2019 cropping season.

Source of variation	DF	DI_f (%)	DS_f (%)	AUDPC (%-day)	TSW (g)	GY (t ha^{-1})
Main plot factors						
Location	4	38209.79****	6924.05****	965849.55****	304.76****	107.77****
Block (within Location)	10	72.95^{ns}	54.83^{ns}	1208.62^{ns}	15.81^{ns}	1.46^{ns}
Cultivar	1	1681.63ns	332.43***	71428.19***	41.84**	$4.11 \text{ x } 10^{-4}$*
Error	10	97.88	44.82	4855.04	61.13	1.11
Sub-plot factors						
Fungicide	1	101.88^{ns}	492.03*	78236.51*	20.86*	3.80**
Cultivar * Fungicide	1	1089.72***	1977.93*	265844.38**	2.19**	2.53****
Error	40	71.31	35.09	2417.07	29.69	0.1235
Sub-sub plot factors						
FSF	3	373.32^{ns}	301.13^{ns}	56023.84^{ns}	4.45**	0.25*
Cultivar * spray frequency	3	421.44**	794.51*	101468.04*	6.38*	2.53*
Fungicide * spray frequency	3	1750.65***	2171.03**	303575.96**	44.81**	5.06***
Cultivar * Fungicide * FSF	3	453.23***	389.86****	57380.36***	5.32**	1.55*
LOC* CUL * FUN * FSF	12	1358.55^{ns}	1146.77^{ns}	241563.12*	104.23^{ns}	10.74^{ns}
Pooled error	120	60.25	21.57	1760.94	1034.93	5.43
Grand mean		33.94	20.22	252.64	37.02	4.11
CV (%) (Main plot factors)		29.15	32.76	27.58	21.12	25.63
CV (%) (Sub-plot factors)		24.88	29.29	19.46	14.72	18.53
CV (%) (Sub-sub plot factors)		22.87	22.97	16.61	8.69	5.67

DF = Degree of freedom; DI_f = Disease incidence at final date of assessment; DS_f = Disease severity at final date of assessment; AUDPC = Area under disease progress curve; TSW = Thousand seed weight measured in g; GY = Grain yield measured in t ha^{-1}; LOC = Location; CUL = Cultivar; FUN = Fungicide; FSF = Fungicide spray frequency; Cultivar * Fungicide = Interaction effect of cultivar and fungicide application; Cultivar * spray frequency = Interaction effect of cultivar and spray frequency; Fungicide * spray frequency = Interaction effect of fungicide and spray frequency; Cultivar * Fungicide * FSF = Interaction effect of cultivar, fungicide and spray frequency; LOC* CUL * FUN * FSF = Interaction effect of location, cultivar, fungicide and spray frequency; **** = Significantly different at $P \leq 0.0001$; *** = Significantly different at $P \leq 0.001$; ** = Significantly different at $P \leq 0.01$; * = Significantly different at $P \leq 0.05$; ^{ns} = Not significant ($P > 0.05$); CV = Coefficient of variation (%).

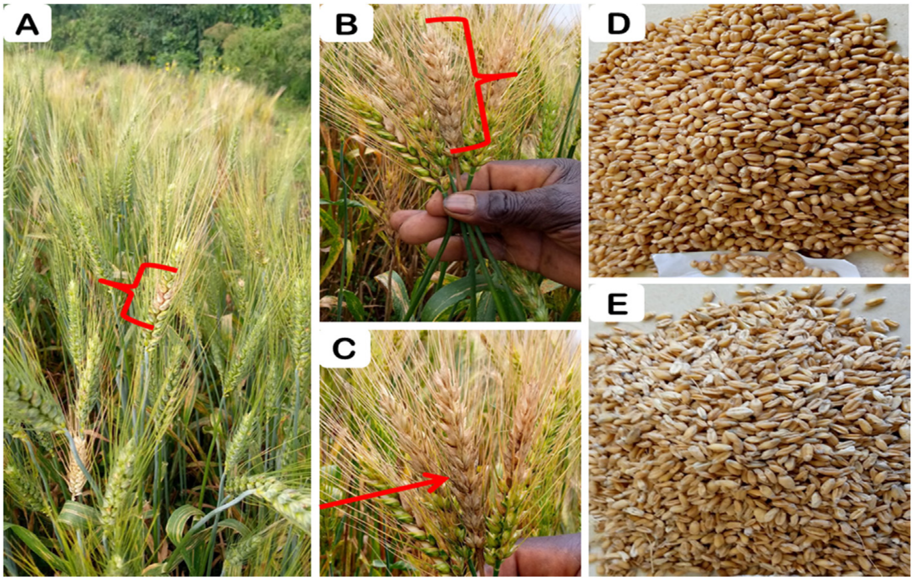

Figure 3. Typical characteristic symptoms of FHB on wheat under field condition. Infected spikelets with water-soaked lesions on Shorima [A], fully infected spike which appeared as whitened or bleached on Hidase [B], production of black spherical structures (perithecia) on Hidase [C], pure and well mature grain of Shorima [D], and pre-mature, shriveled and shrunken grain of Hidase [E].

3.2. Disease severity

The FHB severity was significantly altered by the use of integration of host resistance, fungicides, and spray frequencies across the locations (Tables 1 and 2). Analysis of variance revealed that the mean highest disease severity (36.46%) was recorded at North Ari. The lowest mean disease severity (7.07%) was noted at Bonke. Crosswise comparisons indicated that the overall FHB severity in North Ari was higher than in other locations (Table 2). At Bonke, FHB severity was reduced by 78.88% compared with North Ari. About 25.97, 45.58, and 72.22% FHB severity reductions were observed at Sodo zuriya, Adiyo, and Chencha, respectively, compared with North Ari. The highest mean FHB severity indices were noted from unsprayed plots of Shorima and Hidase cultivars, each with 25.21 and 50.56% at the last assessment date, respectively. The mean lowest FHB severity was recorded on the plot of Shorima cultivar with three times spraying of Tebuconazole, which was not statistically significant with the plot of Shorima cultivar sprayed with two times of Tebuconazole (Table 2). In this regard, the integration of Shorima, Tebuconazole, and three times spray frequencies reduced FHB severity by 81.04% compared with the unsprayed plot of Shorima cultivar. Comparing the two cultivars, the highest mean FHB severity was observed on Hidase (28.41%) than Shorima (12.03%). Regarding the fungicides, the mean highest FHB severity was ascertained on Tebuconazole (13.93%) than Propiconazole (20.62%) under both cultivars evaluations. Comparing spray frequency, the lowest mean FHB severity was noticed on plots sprayed with Tebuconazole three times (4.78%), followed by two times (5.74%) on Shorima cultivar (moderately resistance) compared to unsprayed plots (50.56%) of Hidase cultivar (Susceptible). The overall FHB severity was relatively lower under integrations of host resistances, fungicides, and spray frequencies across the locations (Table 2).

3.3. Area under disease progress curve (AUDPC)

The result obtained from ANOVA showed AUDPC was significantly reduced by the use of integration of host resistance, fungicides, and spray frequencies in all locations (Tables 1 and 2). The AUDPC was as low as 130.26, 158.95, 186.46, 383.74, and 404.78%-day at Bonke, Chencha, Adiyo, Sodo zuriya, and North Ari, respectively, due to the integrated use of host resistances, fungicides, and spray frequencies (Table 2). The highest mean AUDPC was recorded from unsprayed plots of Shorima (294.24%-day) and Hidase (653.36%-day) cultivars. The lowest AUDPC was recorded from plots with a combination of Shorima, Tebuconazole, and three (52.86%-day) and two (59.78%-day) times spray frequencies, respectively. In this instance, the AUDPC on the integration of Shorima, Tebuconazole, and three and two times spray frequencies were reduced by 82.04 and 91.91% (three times), and 79.68 and 90.85% (two times) compared with the unsprayed plot of Shorima and Hidase, respectively, during the epidemic periods. Comparing the two cultivars, the mean highest AUDPC was computed on Hidase (363.47%-day) than Shorima (141.80%-day). Regarding the fungicides, the mean highest AUDPC was received from Tebuconazole (174.42%-day) than Propiconazole (257.13%-day). Regarding spray frequency, the mean highest FHB severity was noticed on plots sprayed three times (148.15%-day) than unsprayed plots (473.80%-day). The overall FHB pressure was comparatively more prominent in North Ari and unsprayed plots of Hidase cultivar than in other locations and Shorima cultivar during the cropping season (Table 2).

3.4. Thousand seeds weight and grain yield

Analysis of variance revealed that there were significant ($P < 0.05$) variations among the evaluated treatments for thousand seed weight and grain yield under crosswise assessment (Tables 1 and 2). The lowest mean thousand seed weight (32.80 g) and grain yield (2.42 t ha^{-1}) were recorded at Adiyo and North Ari, respectively. The highest mean thousand seed weight (40.19 g) and grain yield (6.68 t ha^{-1}) were noted at Bonke than other locations. About 63.77% grain yield gap was observed between the Bonke and North Ari. In this regard, grain yield production at North Ari suffered from disease pressure and reduced by 16.84, 41.12, 45.25, and 63.77% compared with wheat production at Adiyo, Sodo zuriya, Chencha, and Bonke, respectively (Table 2). The mean lowest thousand seed weight of 32.10 g and grain yield of 2.64 t ha^{-1} were recorded on an unsprayed plot of Hidase cultivar. The mean highest thousand seed weight (41.38 g) and grain yield (5.30 t ha^{-1}) were recorded on Hidase and Shorima cultivars, respectively, when the plots were sprayed with a combination of Tebuconazole and three times spray frequencies (Table 2). About 43.96 and 46.45% grain yield advantage was obtained from Shorima and Hidase cultivars, respectively, when they were combined with three times spray frequencies of Tebuconazole. The

Table 2. Effect of cultivar and fungicide application along with spray frequency on Fusarium head blight epidemic developments and yield-related traits of bread wheat across the locations in southern Ethiopia during 2019 main cropping season.

Treatment	DI$_f$ (%)	DS$_f$ (%)	AUDPC (%-day)	TSW (g)	GY (t ha^{-1})
Location					
Adiyo	25.35^{c}	19.84^{c}	186.46^{c}	32.80^{e}	2.91^{d}
Bonke	13.31^{d}	7.70^{e}	130.26^{e}	40.19^{a}	6.68^{a}
Chencha	14.75^{d}	10.13^{d}	158.95^{d}	35.52^{d}	4.42^{b}
North Ari	80.71^{a}	36.46^{a}	404.78^{a}	37.70^{c}	2.42^{e}
Sodo zuriya	34.57^{b}	26.99^{b}	383.74^{b}	38.80^{b}	4.11^{c}
LSD (5%)	3.33	2.00	18.10	0.90	0.15
Wheat cultivar * Fungicide * Spray frequency					
Shorima + Tebuconazole + One time application	26.79^{ef}	12.28^{g}	137.16^{hi}	36.17^{de}	4.15^{d}
Shorima + Tebuconazole + Two time application	17.66^{g}	5.74^{ij}	59.78^{j}	37.14^{cd}	4.90^{b}
Shorima + Tebuconazole + Three time application	15.94^{g}	4.78^{j}	52.86^{j}	38.14^{bc}	5.30^{a}
Shorima + Propiconazole + One time application	29.85^{d-f}	16.24^{f}	193.02^{g}	35.47^{e}	3.70^{f}
Shorima + Propiconazole + Two time application	25.46^{f}	11.30^{gh}	143.57^{h}	36.06^{de}	4.10^{e}
Shorima + Propiconazole + Three time application	17.77^{g}	8.67h^{i}	112.00^{i}	36.96^{de}	4.53^{c}
Shorima unsprayed	31.76^{de}	25.21^{d}	294.24^{de}	33.63^{f}	2.97^{h}
Hidase + Tebuconazole + One time application	38.98^{bc}	21.69^{e}	265.81^{ef}	37.14^{cd}	3.94^{ef}
Hidase + Tebuconazole + Two time application	38.69^{bc}	21.25^{e}	287.48^{de}	39.34^{b}	4.57^{c}
Hidase + Tebuconazole + Three time application	34.38^{cd}	17.89^{f}	243.43^{f}	41.38^{a}	4.93^{b}
Hidase + Propiconazole + application + One time	52.87^{a}	34.11^{b}	417.12^{b}	35.85^{de}	3.32^{g}
Hidase + Propiconazole + Two time application	43.45^{b}	24.46^{de}	315.55^{d}	39.29^{b}	4.04^{e}
Hidase + Propiconazole + Three time application	42.56^{b}	28.93^{c}	361.53^{c}	39.12^{b}	4.40^{cd}
Hidase unsprayed	55.98^{a}	50.56^{a}	653.36^{a}	32.10^{g}	2.64^{i}
LSD (5%)	5.57	3.35	30.28	1.51	0.25
CV (%)	22.87	22.97	16.61	8.69	5.67

Mean values in the same column with different letters represent significant variation at 5% probability level. DI$_f$ = Disease incidence at final date of assessment; DS$_f$ = Disease severity at final date of assessment; AUDPC = Area under disease progress curve; TSW = Thousand seed weight measured in g; GY = Grain yield measured in t ha^{-1}; LSD = Least significant difference at 5% probability level; CV = Coefficient of variation (%).

overall grain yield was comparatively lower in North Ari and unsprayed plot of Hidase cultivar than in other locations and Shorima cultivar during the cropping season (Table 2).

3.5. Relationship between Fusarium head blight attributes with grain yields

The relationship between disease scores (disease severity and AUDPC) and grain yield was performed using correlation and linear regression analysis. Analysis of linear regression for disease scores and grain yield was achieved under the plot-wise condition for each treatment. The results obtained from correlation and linear regression analysis between disease scores and grain yield were depicted in Figure 4. Determined Pearson Correlation Coefficients (r) were used as indices for the strength of the relationship. Significant ($p < 0.0001$) correlation between the disease scores and grain yield were observed. The correlation analysis revealed significant negative relationships between disease severity and grain yield ($r = -0.68$) and AUDPC and grain yield ($r = -0.62$) (Figure 4). In the regression analysis, disease severity and AUDPC were used as explanatory variables, whereas grain yield corresponded for the dependent variable. About 47.90 and 39.50% of R-square (coefficient of determination) was estimated between disease severity and grain yield and AUDPC and grain yield, respectively. The relationship diagram exhibited that when the FHB severity and AUDPC gets higher, the grain yield becomes lower. This indicated that the higher the disease pressure, the lower the capability of treatment suppressing the disease development and, consequently, reducing grain yield. The regression diagram exhibited that for every one-unit increase in disease severity and AUDPC, there was 0.0672 and 0.0048 unit loss in grain yield, respectively (Figure 4).

3.6. Economic feasibility and relative yield loss

The results received from the economic feasibility (net benefit and benefit-cost ratio) and relative yield loss analysis showed significant variation for the evaluated treatments across the locations (Table 3). The highest net benefit of \$4037.77 ha^{-1} and benefit-cost ratio of 7.34 were ascertained at Bonke, while the lowest net benefit (\$616.98 ha^{-1}) and benefit-cost ratio (0.86) was observed at Adiyo under crosswise assessment during the cropping season. The combined analysis of economic feasibility results of the five locations revealed that integration of Shorima cultivar, Tebuconazole, and three times spray frequency, followed by integration of Shorima cultivar, Tebuconazole, and two times spray frequency and Hidase, Tebuconazole, and three times spray frequency exhibited the highest net benefit of \$2593.59, 2373.92, and 2372.75 ha^{-1}, and benefit-cost ratio of 4.55, 4.31 and 4.16, respectively. The lowest net benefit of \$1130.57 and 1327.54 ha^{-1} and benefit-cost ratios of 2.54 and 2.98 were computed from unsprayed plots of Hidase and Shorima cultivars, respectively (Table 3). Overall, variation in relative yield losses was observed among the locations and evaluated treatment

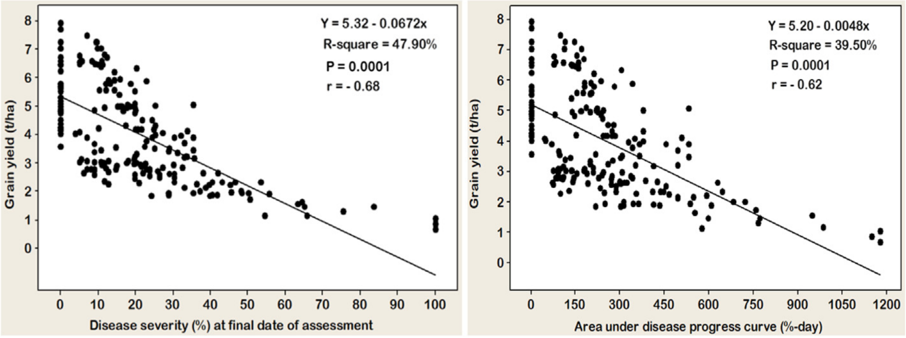

Figure 4. Linear relationships between grain yield losses of bread wheat and severity (left side) and area under disease progress curve (right side) of Fusarium head blight across the locations in southern Ethiopia during the 2019 main cropping season.

Table 3. Economic feasibility and relative yield loss analysis for the management of fusarium head blight using fungicides along with their spray frequency across the locations in southern Ethiopia during the 2019 cropping season.

Treatments	Grain yield (t ha^{-1})	Adjusted yield (t ha^{-1}) 10% down	Total input cost ($ ha^{-1})	Gross benefit ($ ha^{-1})	Net benefit ($ ha^{-1})	Benefit-cost ratio	Relative yield loss (%)
Location							
Adiyo	2.91	2.62	715.42	1332.40	616.98	0.86	56.42
Bonke	6.68	6.01	550.08	4587.85	4037.77	7.34	0.00
Chencha	4.42	3.98	635.93	3162.16	2526.23	3.97	33.81
North Ari	2.42	2.18	429.25	1454.31	1025.06	2.39	63.76
Sodo zuriya	4.11	3.70	581.88	2352.31	1770.43	3.04	38.45
Wheat cultivar * Fungicide * Spray frequency							
Shorima unsprayed	2.97	2.67	445.15	1772.69	1327.54	2.98	43.96
Shorima + Tebuconazole + One time application	4.15	3.74	531.64	2476.99	1945.35	3.66	21.70
Shorima + Tebuconazole + Two time application	4.90	4.41	550.72	2924.64	2373.92	4.31	7.55
Shorima + Tebuconazole + Three time application	5.30	4.77	569.79	3163.38	2593.59	4.55	0.00
Shorima + Propiconazole + One time application	3.70	3.33	528.46	2208.40	1679.94	3.18	30.19
Shorima + Propiconazole + Two time application	4.10	3.69	544.36	2447.14	1902.79	3.50	22.64
Shorima + Propiconazole + Three time application	4.53	4.08	560.25	2703.80	2143.54	3.83	14.53
Hidase unsprayed	2.64	2.38	445.15	1575.72	1130.57	2.54	46.45
Hidase + Tebuconazole + One time application	3.94	3.55	531.64	2351.65	1820.01	3.42	20.08
Hidase + Tebuconazole + Two time application	4.57	4.11	550.72	2727.67	2176.96	3.95	7.30
Hidase + Tebuconazole + Three time application	4.93	4.44	569.79	2942.54	2372.75	4.16	0.00
Hidase + Propiconazole + One time application	3.32	2.99	528.46	1981.59	1453.13	2.75	32.66
Hidase + Propiconazole + Two time application	4.04	3.64	544.36	2411.33	1866.98	3.43	18.05
Hidase + Propiconazole + Three time application	4.40	3.96	560.25	2626.20	2065.95	3.69	10.75

Mean unit price of grain yield per ton was $663.18, the exchange rate of $1 = ETB 31.45, at the time selling of harvested grain during the 2019 cropping years.

combinations. The relative yield loss was as low as 33.81, 38.45, 56.42, and 63.76% at Chencha, Sodo zuriya, Adiyo, and North Ari, respectively, compared with Bonke. The highest relative yield loss of 43.96 and 46.45% was recorded on unsprayed plots of Shorima and Hidase cultivars, respectively, compared to their respective cultivars plots sprayed with Tebuconazole and three times spray frequency (Table 3).

4. Discussion

Wheat production is greatly affected by several abiotic, biotic, and social-economic constraints worldwide (Zegeye et al., 2001; Dunwell, 2014b; Eshetu and Bedada, 2020). Among different biotic factors, Agrios (2005) reported fungal pathogens are the most significant and widespread pathogens that cause damages and economically crucial yield losses to the crop worldwide. In this regard, fungal diseases cause considerable qualitative and quantitative wheat grain yield losses of up to 100% worldwide (CIMMYT, 2005; Murray et al., 2009; Ghimire et al., 2020). Among them, FHB is ranked in the 4th most severe and devastating fungal disease across the globe (Dean et al., 2012). The disease was first fully described in the late 19th Century in England and bears economic consequences in wheat crop (Smith, 1995). Significant yield losses due to FHB are accompanied by flower abortion, grain weight reduction, elimination of damaged grains during threshing, and mycotoxins production (Windels, 2000; Pirgozliev et al., 2003).

Globally, the disease caused to loss 1.3 billion dollars from 1991 to 1996 across the United States (McMullen et al., 1997, 2012). Losses in Canada have been reported as high as 50 million dollars annually during the early 1990s (AFAC, 2012). According to the report of the Southern Regional Agriculture Bureau and respective districts of the office of Agriculture within the region, an exceedingly destructive outbreak has occurred during the 2017 and 2018 cropping seasons in Ethiopia. The harm had been vital in the south and southwest regions of Kafa, Bench, and South Omo administrative zones. Nearly 100% grain yield loss has been reported during the growing seasons, especially in Adiyo, North Bench, and North Ari. The use of host resistance and fungicide in an integrated manner is a cost-effective and efficient method of FHB management as reported by several authors (Stephen et al., 2013; Dweba et al., 2017; Paul et al., 2019; Shude et al., 2020). In this regard, integration of host resistance, fungicide, and spray frequency to FHB and yield-related attributes were evaluated under natural epiphytotic conditions in Southern Ethiopia.

Integration of host resistances, fungicides, and spray frequencies for the management of FHB exhibited significant variations on disease scores and yield-related parameters across the locations. In the present study, typical symptoms of FHB came along at ZGS of 59 at Adiyo and North Ari, succeeded by Sodo zuriya, Chencha, and Bonke (ZGS of 61–69) during the growing periods. The symptoms consisted of water-soaked lesions on spikelets, whitened or bleached spikelets, shriveled, shrunken, and pre-mature kernels, production of pinkish sporodochia and later the black spherical perithecia on the spikelet leaf, and discolored with a whitish-brown appearance of the kernels which was consistently reported across several studies (Gilbert and Tekauz, 2000; Murray et al., 2009; Dill-Macky, 2010; Mills et al., 2016; Ghimire et al., 2020).

The results of the present study demonstrated that mean FHB incidence did not exceed 13.31% at Bonke but reached up to 80.71% at North Ari at the last assessment date. Highly significant variations were also observed in disease incidence among the evaluated treatments at the last date of assessment across the locations. The maximum mean disease incidence was registered from unsprayed plots of Shorima (31.76%) and Hidase (55.98%) cultivars. The mean lowest incidence was recorded from plots sprayed with the application of Tebuconazole for three (15.94%) and two (17.66%) times on Shorima and three times (17.77%) on Hidase cultivars compared with the other sprayed plots. In agreement with the present research findings, Wegulo et al. (2015), Willyerd et al. (2012), and Stephen et al. (2013) reported that the effects of integration of wheat cultivar with various levels of resistance to FHB and three times foliar application of fungicide significantly lowered FHB incidence than untreated controls. Characteristically, as stated by Berger (1981), Campbell and Madden (1990), and Fry and Shtienberg (1990), disease incidence among different cultivars with reaction to diseases progress were variable, due to what follows the management strategy to manage the disease as that time, and increase with time at the rates of epidemic much faster than disease severities for the same pathosystem (host-pathogen-environment interactions) within the same environment. Maximal disease incidence for many pathosystems is nearly 100%, and this highest value frequently is reached early in the season, when disease severity may still be remarkably below. Also, the results of the current study showed similar trends for disease severity and AUDPC across the locations.

Among the locations, disease severity (36.46%) and AUDPC (404.78%-day) were highest at North Ari. This difference might have resulted from the variation in the environmental conditions and the magnitude of disease pressure across the locations, in addition to treatment effects. Planting of wheat at North Ari accrued disease severity and AUDPC by 78.88% and 67.82% compared with the lowest disease pressure recorded at Bonke, respectively. Variation in disease severity and AUDPC might be due to the weather conditions (Figure 2). Campbell and Madden (1990) suggested that disease epidemic is highly affected by the virulent capability of the pathogen, host susceptibility, age of host plant, available host tissue in combination with environmental conditions, including precipitation, relative humidity, temperature, air current velocity, and other factors. In this regard, several studies reported that the occurrence of favorable environmental conditions and the abundance of inoculum before, during, and after anthesis, and the existence of air currents resulted in the development of severe FHB epidemics worldwide (Shaner, 2003; Brown et al., 2011; Lenc, 2015; Reis et al., 2016). However, disease severity and AUDPC were lower at Bonke and Chencha even if there were favorable environmental conditions than in the other locations (Figure 2). This might be due to the low abundance of inocula within the environment or the escape of the cultivars from infection of FHB during critical inoculation and sporulation periods. Infection due to FHB occurs mostly during anthesis (Strange and Smith, 1971; Lacey et al., 1999; Dill-Macky, 2010) when incubation and sporulation are effective under conditions of saturating humidity with a temperature of 14 °C for 12 days, or 20 °C for five days, or 25–30 °C for three days (Sutton, 1982; Caron and Fusarioses, 1993). *Fusarium graminearum* is capable of causing disease in a diversity of conditions, including differences in various climatic demands and genetic and environmental adaptations (Parry et al., 1995; Trail et al., 2002; Lenc, 2015).

The interaction effects of host resistance, fungicides, and spray frequencies varied for disease severity and AUDPC across the locations. They were highest on unsprayed plots of Shorima and Hidase cultivars, relatively higher on Hidase (susceptible) than Shorima (moderately resistant) cultivar. Conversely, they were lowest on the plots of Shorima cultivar planted sprayed with Tebuconazole with three times spray frequencies, followed by application of Tebuconazole with two times spray frequencies for the same cultivar. With the exceptions of unsprayed plots, disease severity and AUDPC were relatively lower on treatment combination of Shorima, Tebuconazole, and three times spray frequency than on treatment combination of Hidase, Propiconazole and three times spray frequency. The trends were similar to the other spray frequencies under the combination of Shorima with Tebuconazole and Hidase with Propiconazole. Also, the application of Tebuconazole under the three spray frequencies, one up to three times application, was effective compared with Propiconazole for similar spray frequencies on the Hidase cultivar. The variation might be due to genetic differences between the cultivar to refuse the epidemic development of FHB in combination with the capability of the fungicide itself. This was explained by the resistance of the pathogen by overpowering the active substances, and the different spray frequencies applied. A number of related studies also reported that integration of moderately resistant cultivar supplemented with an efficient fungicide and frequent application (three to four times) beginning from the disease onset was an effective management strategy to successfully reduce FHB pressure on the wheat crop (Gilbert and Tekauz, 2000; Mesterházy et al., 2003; McMullen et al., 2008; Wegulo et al., 2011; Willyerd et al., 2012; Gilbert and Haber, 2013; Stephen et al., 2013; Reis et al., 2016; Shude et al., 2020). These authors also reported that the highest disease pressure resulted from the highest FHB development on plots that have not sprayed with any combinations of wheat cultivar and applications of fungicide.

The ANOVA also revealed that considerable treatment variations for thousand seed weight and grain yield were observed across the locations. The crosswise assessment showed that the highest (40.19 g) and the lowest (32.80 g) thousand seed weights were recorded at Bonke and Adiyo, respectively. Regarding grain yield, the highest (6.68 t ha^{-1}) and the lowest (2.42 t ha^{-1}) were recorded at Bonke and North Ari, respectively. This difference might have resulted from the variation in the environmental conditions, treatment effects and the magnitude of disease pressure across the locations. In agreement with the present findings, several studies confirmed that variations in yield and yield-related attributes had obtained as a result of the integration of host resistance and fungicide application with right rates and spray frequencies at different environmental conditions for various reasons (Mesterházy et al., 2003; McMullen et al., 2008; Wegulo et al., 2011; Willyerd et al., 2012; Reis et al., 2016).

Concerning treatment combinations, the lowest (32.10 g) and highest (41.38 g) thousand seed weight were obtained from unsprayed and plots treated with integrations of Hidase, Tebuconazole, and three times spray frequency, respectively. In terms of treatment effects for grain yield, the best treatment combinations were integrations of Shorima, Tebuconazole and three times spray frequency, followed by the integrations of Hidase, Tebuconazole and two times spray frequency and the integrations of Shorima, Tebuconazole and three times spray frequency with the mean grain yield of 5.30, 4.94 and 4.90 t ha^{-1}, respectively. Unsprayed plots of wheat cultivars had a lower grain yield than fungicide sprayed plots at different agro-ecologies due to the highest FHB epidemics. This variation might have resulted from the difference in the genetic inheritance of the wheat cultivars supplemented with fungicide application for the FHB management. The overall results revealed it is possible to realize the integrated use of host resistance, fungicide, and a proper number of spray frequency played an important role in increasing grain yield. The phenomenon could be accredited to their auspicious effects on grain yield contributing traits such as thousand seed weight and others while making adverse effects for different metabolic activities of the pathogen and suppress high disease pressure. Thus, cultivar response and fungicides with appropriate spray frequencies and subsequent variation in FHB pressure could be responsible for comparative yield advantages, which were obtained per treatment across the locations, along with other factors. As reported by Mesterházy et al. (2003), McMullen et al. (2008), Wegulo et al. (2011), Willyerd et al. (2012), and Reis et al. (2016), integration of cultivar resistance and fungicide applications with frequent spraying of fungicide reduces FHB pressure and increased yield and yield-related attributes than the unsprayed control plots.

The correlation and linear regression analysis showed a significant relationship between disease scores and grain yield. Higher correlations between disease severity and grain yield, and AUDPC and grain yield were observed. The negative relation between these parameters revealed the high FHB pressure had adverse effects on wheat production. Campbell and Madden (1990) and Agrios (2005) reported that disease parameters had negative and strong links with growth and yield-related characters of the produced crop. In the current study, disease severity and AUDPC were used in predicting the yield losses. The reason was to know which one was more explanatory in high grain yield losses prediction than the other. Disease severity showed a higher (0.0672) grain yield loss explanatory than AUDPC (0.0048) under crosswise assessment. Also, disease severity was better explanatory for grain yield loss predictor, as showed by the higher R-square of 47.90% than AUDPC (39.50%). Comparison of disease severity and AUDPC showed that the higher loss of grain yield was displayed by disease severity than AUDPC, which surpasses 93.33% on the regression examination. The R-square pointed that 47.90% of the yield difference was explained by disease severity. As indicated on the diagram, when the disease severity and AUDPC gets higher, the grain yield becomes lower. As mentioned by the previous researchers, a plant disease was strongly associated with losses of growth and yield-related traits of the crop in every portion of disease progression (Campbell and Madden, 1990; Cook et al., 1999; Agrios, 2005). Likewise, in the integration of host resistance and fungicide application with frequent spray evaluation for FHB studies, Gilbert and Haber (2013), Wegulo et al. (2015), Reis et al. (2016), and Shude et al. (2020) reported variable levels of relationships between the studied parameters in various parts of the world.

The variation in economic feasibility analysis was perceived among the treatment evaluated across the locations. The highest net benefit ($4037.77 ha^{-1}) and benefit-cost ratio (7.34) were observed at Bonke, while, the lowest net benefit ($616.98 ha^{-1}) and benefit-cost ratio (0.86) were observed at Adiyo. The differences in net benefit and benefit-cost ratio across the locations might be influenced by the disease pressure, environmental factors, and total input costs of production (additional costs for disease protection and field management) in the locality. CIMMYT (1988) mentioned the high economic benefits gained from a dedicated crop production was strongly influenced by the total cost of production, time the crop produced, and selling price of the product in the locality during the cropping season. Regarding treatment combinations, the highest net benefit and benefit-cost ratio were observed on integrations of Shorima, Tebuconazole and three times spray frequency ($2593.59 ha^{-1}, and 4.55), followed by Shorima, Tebuconazole, and two times spray frequency ($2373.92 ha^{-1}, and 4.31), respectively. The high net benefit and benefit-cost ratio from the aforementioned treatments could be ascribed to the high grain yield, and the low net benefit and benefit-cost ratios were accredited to low grain yield. As mentioned by CIMMYT (1988) and Foster et al. (2017), the profitability of crop field, nutrient and pest management practices were significantly affected by the choice of the management options, the quality and quantity of products obtained, and the selling price of the product at the time of merchandise. Therefore, from the economic feasibility point of view, it was evident that the uses of the aforementioned treatment combinations were more profitable than all other treatments.

During the growing season, the production of wheat was significantly affected by FHB pressure, especially in North Ari and Adiyo, in which more than 50% grain yield losses were recorded compared to Bonke which has the lowest disease pressure. The reasons might be due to the environmental conditions in these areas being more favorable to FHB development and other factors that lead to high grain yield losses. Likewise, the highest grain yield losses of up to 46.49% were calculated on unsprayed plots of Hidase as compared to the maximum protected plots using the integration of Shorima, Tebuconazole, and three times spray frequency. The losses in grain yield could be ascribed to the severe pressure of FHB on the spikelets, which eventually destroy the spikes and reduced the grain yield through the spikes become uneconomical due to shriveling, shrinking, premature drying, and discoloration, blacking of the grain. The grain yield losses of 50–70% due to FHB and associated mycotoxin productions have been reported in wheat crop in various parts of the world. Under severe conditions, grain yield losses up to 100% had been reported due to FHB on wheat crop (Windels, 2000; Pirgozliev et al., 2003). However, it should be accredited that the grain yield losses computed in the present study could not be solely ascribed to FHB pressure and might have been contributed by the medium levels of yellow rust, stem rust, and septoria leaf blotch. The effects of these factors are not fully explained by the current study, and their confounding effect cannot be underestimated in the grain yield losses. According to CIMMYT (2005), Ayele et al. (2008), Tewodros et al. (2016), and MoANR and EATA (2018), the listed diseases are the most important constraints to wheat production in Ethiopia.

5. Conclusion

Wheat production was seriously restrained by FHB during the growing season. The disease was greatly favored by the host susceptibility, weather conditions, and various other factors. Conversely, it was disfavored by the integrated use of host resistance and fungicide with appropriate spray frequencies across the locations. Results obtained from the current study showed that North Ari and Adiyo were significantly impacted by FHB pressure, and consequently, resulted in the lowest gain yield than the other locations. The current study also revealed that the disease incidence, severity, and AUDPC were greatly reduced by the integrated use of host resistance and application fungicide with appropriate spray frequencies compared with unsprayed ones. Correspondingly, grain yield was increased due to suppression of the disease pressure through the integrated disease management tested in this study. In both wheat cultivars (Shorima and Hidase), application of Tebuconazole with three times spray frequencies during the first visual symptom appearance of FHB showed reduced disease pressure and increased grain yield, followed by application of Tebuconazole with two times spray frequencies. An economic evaluation revealed that the integrated use of wheat cultivars and fungicide with three spray frequencies provided the highest net benefit and benefit-cost ratio. The use of Shorima cultivar in combination with fungicide application with three spray frequencies was proved to be the most cost-effective approach in reducing FHB pressure besides increasing wheat production and productivity. Thus, this could be recommended to the growers in the study areas and elsewhere with similar agro-ecological conditions for efficient management of FHB. However, harmful mycotoxin production, quantification, and its role in grain yield loss were not included in the present study. Therefore, further research focusing on mycotoxin production should be executed for developing effective and reliable FHB management strategies across the wheat growing regions in Ethiopia.

Declarations

Author contribution statement

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

Shiferaw Mekonnen Abebe: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Zerhun Tomas Lera; Kedir Bamud Fedilu; Yosef Berihun Tadesse; Asaminew Amare Mekonnen; Abate G/Mikael Esho; Dizgo Chencha Cheleko: Performed the experiments; Contributed reagents, materials, analysis tools or dat; Wrote the pape.

Misgana Mitku Shertore; Agdew Bekele W/Silassie: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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