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Original Research

Management of Wheat Stem Rust (*Puccinia graminis* f.sp *tritici*) through Fungicides Spray Frequencies in Southern Ethiopia

Metiku Kebede* & Yisahak Tsegaye
Southern Agricultural Research Institute, Werabe Agricultural Research Center, P.O. Box 21 Werabe, Ethiopia

Abstract

*The most impressive wheat disease that causes substantial yield losses in Ethiopia is Puccinia graminis f. sp. tritici stem rust. The 2020 growing season at Mareko and Dalocha examined the influence of fungicide spray frequency on bread wheat disease and yield characteristics under natural infection. Nativo SC 300 (Trifloxystrobin 100 g/l + Tebuconazole 200 g/l) at 0.75 l/ha and Tilt® 250EC (propiconazole) at 0.5 l/ha were field tested with three spraying frequencies in a randomised full block design with three replications. Unsprayed controls were included for maximum rust severity comparisons. Frequent fungicide application significantly reduced terminal rust severity, average infection coefficient, and AUDPC values of stem rust (P<0.05). Compared to untreated check plots, both fungicide-treated plots showed significantly greater thousand kernel weight and grain yield (p < 0.05). Additionally, Nativo SC 300 maximizes grain output and reduces stem rot across sites. TRS, ACI, and AUDPC were negatively correlated with grain yield, TKW, and kernel per spike (r = -0.85** to r = -0.33**). Nativo SC 300 (Trifloxystrobin 100 g/l + Tebuconazole 200 g/l) applied three times at a 10-day interval yields the largest net benefit and is the best management method to increase grain yield or output amount.*

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*Corresponding Author:
Metiku Kebede

E-mail:
metaekebae2014@gmail.com

INTRODUCTION

Modern wheat (Triticum spp.) is one of the world's most productive and important crops (Curtis and Halford, 2014). It provides more than 35% of cereal calories in the developing world, 74% in the developed world, and 41% overall from direct consumption (Shiferaw et al., 2013). Following rice, it is the world's second-most significant cereal crop (Pant et al., 2020). Triticum aestivum L., bread wheat, is an essential African food security crop. In Ethiopia, 4.57 million agricultural households depend on wheat growing for food and income (CSA 2020). Wheat is the main food and revenue source for 4.57 million Ethiopian agricultural households (CSA 2020). Ethiopia produces the most wheat in sub-Saharan Africa (FAOSTAT, 2020). It ranks second in production behind maize (Zea mays L) (CSA 2020). The Ethiopian government prioritizes target crops for food self-sufficiency and export.

Ethiopia produced 5.78 million tonnes of wheat on 1.89 million hectares (CSA 2020). Wheat productivity is 3.04 t/ha (CSA 2020), well below the African and global averages. Several disorders may have reduced product quantity and quality. Wheat stem rust, often known as black rust, is an economically important disease caused by the fungus Puccinia graminis f. sp. tritici Ericks and Henn (Pgt) in most Ethiopian wheat-growing regions. Due to its frequency and spread, the disease reduces annual production. In sensitive wheat types, stem rust outbreaks can reduce output by 100% (Bechere et al., 2000). According to Leppik (1970), Ethiopia's highlands are a stem rust diversity hotspot. The TKTTF stem rust race is the most destructive and prevalent in various major bread wheat varieties in Ethiopia, blocking several resistance genes. Due to a lack of genetic variety and a single Sr-resistant gene in most commercial cultivars, failure resistance and yield losses increased. Stem rust creates enormous, reddish brown oval to elongated spore masses on leaves, leaf sheaths, stems, and heads. Rust illnesses include rubbing spore clumps on the fingers. The illness thrives in humid, warm weather and can cause significant losses (Haldore et al., 1982; Roelfs, 1992). Rust fungi's unique traits make wheat stem rust difficult to treat, making it one of wheat's most common illnesses. The ability to genetically modify and produce new races with increased aggressiveness in resistant wheat cultivars and produce large numbers of spores that can be wind disseminated over long distances and infect wheat under favorable environmental conditions are among these characteristics.

There are various wheat stem rust disease treatments. Wheat rust resistance breeding is the most essential method. Stem rust outbreaks are managed by wheat cultivars with effective stem rust resistance genes (Singh et al., 2006; Jin, 2006). Ethiopia has produced and released numerous rust-resistant wheat cultivars in recent decades. Due to the emergence of new races, resistant cultivars like Ogolcho and Hidase, launched in 2012 and 2012, respectively, are now susceptible to stem rot. In rust-prone Ethiopia, susceptible to moderately susceptible wheat types cannot be grown without fungicides. Fungicides can help manage the disease until genetically resistant cultivars are available (Loughman, 2005). Fungicides reduce corrosion when applied promptly. For these reasons, large-scale commercial wheat growers utilize fungicides to combat rust (Ayele et al., 2008; Badebo, 2002; Hailu & Fininsa, 2009; CIMMYT, 2005). Silte and Gurage zones in southern Ethiopia are best for wheat growing. These farmers grow various bread wheat kinds, but Ogoloch is the most popular. Wheat productivity is threatened by stem rust disease notwithstanding the availability of high-yielding wheat varieties. This study aimed to evaluate fungicide spray frequency responses to wheat stem rust treatment.

MATERIALS AND METHODS

Description of the Experimental Areas

The current investigation took place in the Mareko and Dalocha districts' experimental areas during the 2020 growing season. Mareko is in the Gurage zone, but Dalocha is in the Silte zone. Both experimental locations in the Southern Region are situated in ideal midland ecologies for wheat cultivation. The precise location of Mareko is 08o05'67"N, 38o18'18"E, and an elevation of 1824 meters above sea level. Annual precipitation averages 675 mm and air temperatures hover around 27.5˚C in the region. It is common to find Cromic Luvisole and Haplic Phaeozems soils here. With coordinates

07˚83'62"N, 38˚22'12"E, Dalocha is situated 1925 meters above sea level. The average annual temperature is 22.7 degrees Celsius, and the average annual precipitation is 750 millimeters. The area's soil type is predominantly clay loam, which is also called chromic verticillo. This area is particularly susceptible to stem rust because it experiences a brief wet season from March to May and a main rainy season from June to September.

Methodology and Procedures for Experiments

The study followed the recommended protocol of a randomized complete block design (RCBD) with three replicates. Fungicide treatments included Tilt® 250EC and Nativo SC 300. A total of seven treatment combinations were tested, including three different fungicide spray frequencies for each type and one control group that did not receive any spraying at all. In order to control stem rust, a manual Knapsack sprayer was used with 250 liters of water to apply fungicides to the runoff as soon as the disease severity reached 20% on the examined variety. Both areas were subjected to a total of three successive sprays. The neighboring plots were shielded from fungicide spread by using plastic sheets during the spraying process. High stem rust pressure and extremely hot-spotted testing sites prevented the use of artificial inoculation. The experimental plots used to sow the bread wheat variety under study, Hidase, were 1.2 x 2.5 m (3 m2) in size and had 6 rows with a spacing of 0.2 m. Plots and blocks were separated by half a meter and one meter, respectively. At 125 kg ha1, the appropriate seed rate was used to sow the wheat variety. According to the local crop calendars, plots were planted by hand in rows at specific times. The fertilizer sources used were urea (41 kg N/46 kg P2O5 ha-1) with split application and the appropriate rate of NPS fertiliser (100 kg ha-1) applied at planting. To ensure that the plots were free of weeds, hand weeding was done three times.

Evaluation of Illness

Using the modified Cobb's scale, which was developed by Peterson et al. (1948), the severity of stem rust disease was measured at 10-day intervals, beginning with the development of disease symptoms and continuing until the crop reached physiological maturity. Before each application of fungicide, the degree of stem rust was evaluated. Based on the methods described by Roelf et al. (1985), we multiplied the severity values by the constant number of host responses (i.e., immunity = 0, R = 0.2, MR = 0.4, MS = 0.8, and S = 1), and we converted each observation to a coefficient of infection (CI) after four consecutive disease assessments. The formula mentioned before was used to determine the severity of the disease as well as the average coefficient of infection.

Disease severity

$$\text{Disease severity} = \left(\frac{\text{Area of plant tissue affected}}{\text{Total area of plant tissue examined}}\right) 100$$

$$\text{ACI} = \frac{\text{Disease Severity} * \text{constant for responcs}}{\text{Total number of observation recorded}}$$

Analysis of Disease Progress

Area under disease progress curve (AUDPC): calculated using the CI values from the original rust severity data by using the following formula as suggested by Arama 2000.

$$AUDPC = \sum_{i=1}^{n-1}\left[\left(\frac{x_i + x_{i+1}}{2}\right)(t_{i+1} - t_i)\right]$$

Where xi = the average coefficient of infection of the i^{th} record, X_{i+1} = the average coefficient of infection of the $i+1^{th}$ record, and $t_{i+1} - t_i$ = the number of days between the i^{th} record and $i+1^{th}$ record, and n = the number of observations.

Evaluation of yield parameters

The four middle rows of each experimental unit were used to record all agronomic data. Here are the specifics of the agronomic **Parameters:**

Measurement of spike length (SL) in centimeters: Five plants were selected at random from the four middle rows of each plot, and their average spike length was measured.

The kernels per spike (KPS) was calculated by counting the number of main tillers on five randomly selected plants and then averaging the results.

Weight of a thousand kernels (TKW) in grams: A delicate seed counter, adjusted to a moisture content of 12.5%, and a sensitive balance were used to meticulously count and weigh one thousand kernels.

Grain yield (GY): Grain yield was measured from the four central rows of each plot and translated to kg/ha after being adjusted to a moisture content of 12.5%.

Analyzing costs and benefits and estimating yield loss

To determine the net returns of using fungicides to treat wheat stem rust, we took into account both the fungicide costs and the application expenses. For the CB analysis, the average price of wheat in the local market was utilized. Three chemical businesses and local chemical distribution agencies provided the average prices for fungicides ($ha-1). Table 1 shows the wheat price, fungicide cost, and application cost in detail. Four large-scale commercial farm chemical applicators in the area were surveyed to get information about the cost of fungicide application. Here is how the net return from using fungicide was determined:

$$R_n = Y_i P - (F_c + A_c)$$

Where Rn is the net return from fungicide application ($ ha^{-1}); Yi is yield increase from fungicide application (kg ha^{-1}), obtained by subtracting the yield in the control treatment from the yield in the fungicide treatments; P is the wheat price ($Kg^{-1}); Fc is the fungicide cost ($ ha^{-1}) and Ac is the fungicide application cost ($ha^{-1}).

Table 1

The fungicide costs, fungicide application cost and wheat prices used in cost benefit

Fungicides	Fungicides cost FC ($ha^{-1})	Fungicide application cost (AC) Cost (ha^{-1})	FC + AC ($ha^{-1})	Wheat price (ha^{-1})
Nativo SC 300	40	11.2	55.1	77.4
Tilt 250 EC	33.7	11.2	51.2	77.4

Source: Survey data on Makamba plc, General Chemical & Trading Pvt. Co, and Makubu plc

The relative losses in yield and yield component of each variety were determined as a percentage of those of the protected plots of the respective variety.

$$RL(\%) = \left(\frac{Y1 - Y2}{Y1}\right) * 100$$

where RL = relative loss (reduction of the parameters grain yield and TKW), Y1 = mean of the respective parameter on protected plots (plots with maximum protection), and Y2 = mean of the respective parameter.

Quantitative Evaluation

Use of SAS's General Linear Model Procedure in version 9.3 (SAS Institute, 2004) allowed for independent analysis of data from the two sites. We used the LSD test at the 5% level of probability to compare the means of the treatments. The correlation procedures of Proc-Corr Pearson were used to examine the association between illness parameters and yield components. In order to forecast reductions in grain yield, linear regression was applied to the combined AUDPC data on stem rust.

Findings and Analysis

Grain yield and several agronomic traits were affected differently by the different combinations of fungicide treatments, according to statistical analysis. We were unable to conduct combined analyses of illness and yield components because the data was too inconsistent between locations. Tables 2 and 3 display the data on illness and yield potential metrics.

Death-Decaying Acute

Every one of the test sites had sufficient stem rust epidemic pressures integrated into the experiments. Tables 2 and 3 show that both locations showed a significant effect ($P<0.05$) of individual treatments and combinations of treatments on terminal rust severity (TRS). The untreated plot at Mareko had the highest TRS at 93.3%, while the three-time-sprayed plot treated with Nativo 300 SC had the lowest TRS (Table 2). Table 3 shows that in Mareko, the TRS was 78% in the unsprayed plots and 0% in the three-times-sprayed plots treated with Nativo 300 SC fungicide. After 38 days after planting, stem rust began to show up at Mareko, and after 51 days, it showed at Dalocha. Following both the first and second fungicide treatments, the trend of less severe stem rust persisted. But in the latter case, the cuts were sharper. This led to different levels of resistance in plants, which in turn affected their ability to kill fungus. The degree of stem rust was not sufficiently different between the two sites.

This can be because the two areas where the disease is spreading have comparable agroecological characteristics. On the other hand, compared to Dalocha, the mean terminal rust severity is greater at Mareko due to the longer epidemic duration. The warm and damp weather conditions were bad for wheat growth and development because of stem rust. An individual's predisposition to a certain disease may exert the most influence in either setting. At both sites, stem rust symptoms appeared before the host reached a certain developmental stage, which had an impact on the disease's epidemiology. Similarly, according to Roelf et al. (1985a), there is a direct correlation between the date of sickness beginning and the growth of an epidemic. All of the plant's leaves, even the flag leaves, were severely infected. Necrotic lesions appeared on the plant's stems and leaves, indicating this. Even in the unsprayed areas, green leaf tissues were reduced or destroyed, diseased leaves lost photosynthetic area, leaves withered, and defoliation was significant. The findings of this study align with those of Hepperly (1990), who discovered that when rust infections occur later in the plant's life cycle, there is less assimilate available for grain fill because the pathogen competes with reproductive structures and disrupts photosynthetic capacity earlier. The key active components in the formulation reduced disease infestation to the lowest level when inversely augmented fungicides were used. So far, the most effective method for controlling stem rust infections has been to apply fungicides soon before or shortly after the heads appear.

The typical infection rate

In both sites, there was a significant difference in the average infection coefficients across the treatment combinations (Tables 2 and 3). Table 2 shows that in Mareko, the fungicide Nativo SC had the lowest ACI of 17.3% in plots that were sprayed three times, while the greatest ACI of 86.3% was reported in plots that were not treated. With an ACI of 80%, an unsprayed plot had the best results at Dalocha. Table 3 shows that the plot that was sprayed three times with Nativo SC 300 fungicide had the lowest ACI of 6.3. It appears that fungicide treatments effectively suppressed stem rust at both locations. There was enough rust pressure across both sites with the highest ACI values, as indicated by the severest stem rust at both sites. Possible causes for stem rust's season-long prevalence include weather, pathogen concentration, and infection timing.

The interaction between stem rust and wheat is affected by climatic changes between the two regions. Wheat yields were affected by the disease pressure in each of the environments. Stem rust disease was less severe after using both fungicides. On the other hand, Nativo SC 300 provides superior control over rust pressure as contrasted with Tilt 250 EC. Reason being, they fight stem rust in different ways and use different active substances. Nativo SC 300, when applied once, reduced grain yield loss more effectively than Tilt 250 EC, which required two applications. Potentially contributing to the development of resistance to specific infections, the continued use of Tilt 250 EC over several years may explain this unequal effectiveness. Green et al. (1990), CIMMYT (2005), and Roelfs (1985) all found that the disease had developed a resistance due to the repeated and foolish use of fungicides. The infections' resistance to the active components and variations in the composition of the products can both contribute to the fungicides' varying degrees of efficacy.

Surface area beneath the illness progression curve

Tables 2 and 3 show that the treatment combinations at Mareko and Dalocha considerably varied ($p<0.05$) in the rate of stem rust disease progresses. Table 2 shows that at Mareko, the unsprayed plot had the greatest AUDPC value of 1645.3% days, while the three-times-sprayed plot treated with Nativo 300 SC had the lowest AUDPC value of 478.3% days. Unsprayed plots at Dalocha achieved the highest AUDPC of 1245.2%. Contrarily, a plot that was sprayed three times with Nativo SC 300 fungicide had the lowest AUDPC of 245.1% days (Table 3). Given its correlation with yield loss, the area under the illness progression curve is a more accurate indicator of the disease parameter. The AUDPC value was highest in the untreated plot and was drastically decreased to the lowest level by both fungicides. Consistent with previous research, our study found a greater AUDPC on untreated plots than treated ones (Taddese et al., 2010). Several studies have found that applying fungicides at the right time, when diseases first start to show, can reduce the severity of the illness and help plants produce the most grain possible (Beard et al., 2004; Wubishet and Tamene, 2016; Phillip and Nathan, 2018). Regression analysis of 2020 growing season grain yield and the epidemiological measure AUDPC is shown in Figure 1.

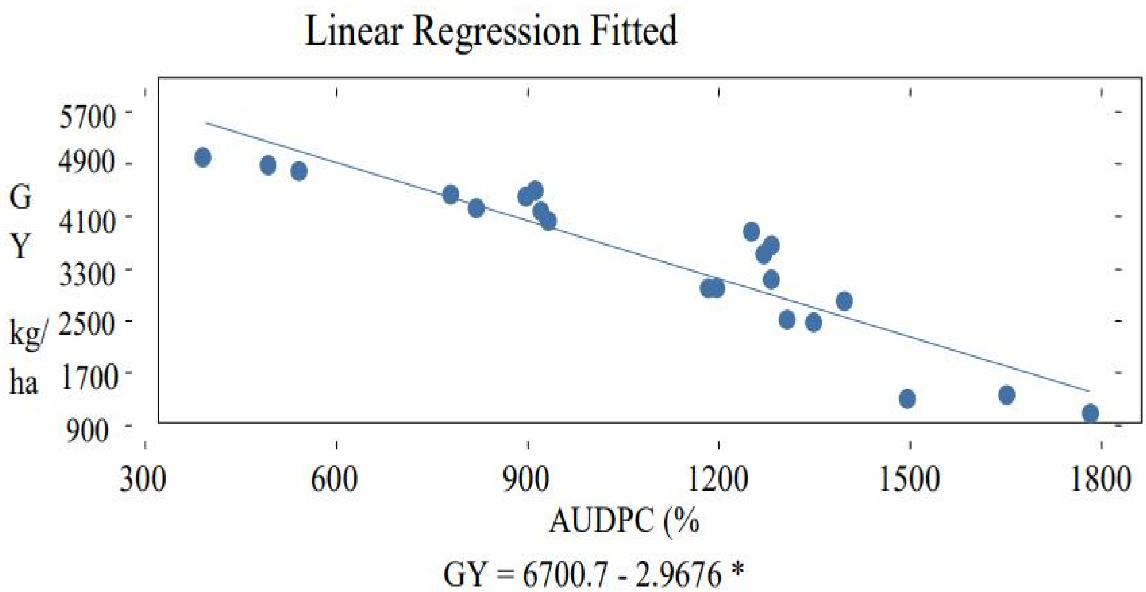

Figure 1. *Liner Regression between Grain yield and rAUDPC at Mareko*

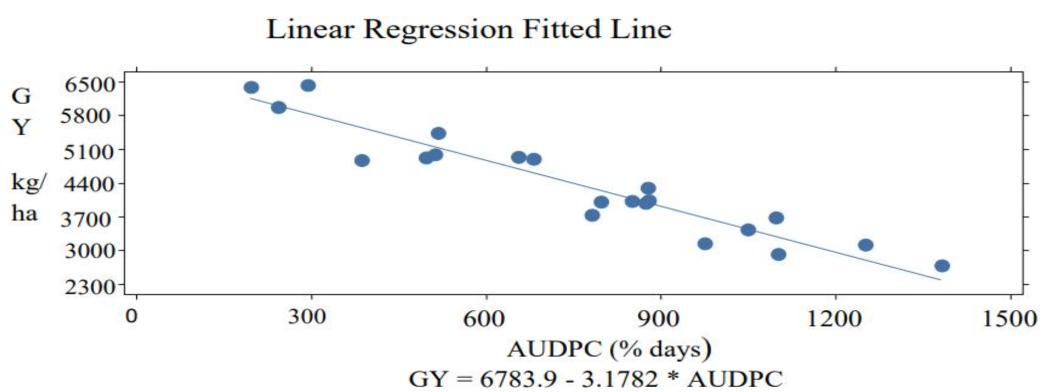

Figure 2 *Liner Regression between Grain yield and rAUDPC at Dalocha*

Figures 1 and 2 show that linear regression of pooled data projected a decrease in wheat grain yield production. At both locations, the correlation between AUDPC and wheat yield was negative and linear. Grain yield dropped in direct proportion to the AUDPC. Figures 1 and 2 show a point around the line, which suggests a higher correlation between the sickness and the loss of grain yield. If the fungicide is ineffective, the grain yield will be decreased, as shown by the increased stem rust of AUDPC. Grain yields are positively correlated with the AUDPC value; a lower value indicates that the fungicide is more effective. In the unsprayed plots, Marko's AUDPC was somewhat greater. The rate of disease progression was significantly impacted by environmental diversity among locales, which in turn influenced the epidemic growth of stem rusts.

Measurement of spike length

Tables 1 and 2 show that there were very significant differences in spike length among treatment combinations, as represented by the analysis of variance. At Mareko, the longest spike length of 8.46 cm was recorded in a plot that was treated three times with Nativo SC 300. The second-longest spike length, 7.76 cm, was recorded in a plot that was sprayed twice with the same fungicide. In contrast, untreated plots yielded the shortest spike lengths of 6.02 at Dalocha and 6.1 at Mareko, respectively (Tables 1 and 2). One essential feature that contributes to yield is spike length. Grain yield was lowest because stem rust reduced spike length. When looking at spike length as a function of treatment combination, there isn't a ton of diversity across sites. However, after applying fungicide treatments, we saw a marked increase in spike length. During the study season, the protected plots had longer spikes than the infected or unprotected plots, according to the data in Tables 1 and 2. Fungicides prevent diseases from spreading and shield the crop canopy, two factors that are critical for the development of dry matter and crop yield (Viljanen-Rollinson et al., 2006).

Shaft for each spike

Tables 2 and 3 reveal that the present investigation found that the kernel per spike at both locations was significantly affected by fungicide spray frequencies and their combinations ($P < 0.05$). In both Mareko and Dalocha, the three-time-treated plots with Nativo SC 300 had the largest kernels per spike (63.3), whereas the untreated plot had the lowest (39.5) and most scattered kernels per spike (29.6).

According to Shah et al. (2006) and Fonseca and Patterson (1968), one of the most significant yield characteristics is the number of kernels per spike. Compared to Dalocha, Mareko had an earlier spike infection onset. Spores accumulated on the surface of the growing grain and on the florets as a result of stem rust attacking the wheat glumes and awns. Because of these factors, the tested variety had the fewest kernels. A significant decrease in yield was seen as a direct consequence of the impact on the sugar supply to the growing seeds caused by the smaller and fewer wheat grains on their dry matter content (Marsalis & Goldberg, 2006; Subba-Rao et al., 1989). Nevertheless, the use of foliar fungicides results in strong and healthy grains, which boosts the overall performance of the grain production. Up until the kernels are full, the flag leaf is protected from infection by fungicide sprays. Spraying with fungicide three times reduced disease pressure to an absolute minimum, which increased the quantity of kernels per spike. Knowing the resistance level of the wheat and bread varieties utilized is crucial, thus such frequency does not reliably enhance grain output. The economic feasibility of the expense of fungicide can be improved by using it less frequently in relatively resistant wheat cultivars, but more frequently in more sensitive cultivars.

Weight of a Thousand Kernel

Significant differences ($P < 0.05$) were seen in the performance of the bread wheat type at two locations as a result of fungicide treatments, as measured by thousand kernel weight (TKW). The highest total potassium content (TKW) of 37.8g was achieved at Mareko in a plot that was treated three times with the fungicide Nativo SC 300. A second plot that was sprayed twice with the same chemical yielded 35.6g. In contrast, the plot treated with Nativo SC 300 at Dalocha achieved a maximum TKW of 36.7g after three sprays with the same 36.4g fungicide and two sprays of the same frequency. When comparing treated and untreated plots, the TKW from the former was 26.6 g and the latter 25.9 g. For both sites, treatment combinations showed the most variation in thousand kernel weight (Tables 1 and 2). The amount and quality of the kernels were both diminished as a result. Everts (2001) found a similar pattern, indicating that flour output decreases as wheat kernels shrink. The fungal overgrowth causes the flag leaves to stop producing nutrients, which prevents those nutrients from reaching the grain and causes the kernels to shrink (Seck et al., 1988; Subba Rao et al., 1989; Hasan et al., 2012). Nevertheless, the quantity of TKW was considerably enhanced by the fungicide application. In a similar vein, Tadesse et al. (2010) found that tilt treatments significantly increased TKW.

Crop Production

According to Tables 1 and 2, the current study's results demonstrated that the grain yield at both sites was considerably ($P < 0.05$) impacted by the combined effect of fungicide treatment frequency. A three-time application of Nativo SC 300 fungicide at Mareko resulted in a maximum grain yield of 4768.9 kg/ha-1, whereas a three-time application of Tilt 250 EC followed with a yield of 4461.6 kg/ha. On the other site (Dalocha), the plot treated with Nativo SC 300 at three time-spray frequencies produced the highest grain yield (6270.6 kg/ha-1), whereas the plot treated with the same fungicide at two time-spray frequencies produced 5092.2 kg/ha-1. In Mareko, untreated plots produced the lowest grain yield at 2767.4 kg/ha, while in Dalocha, the lowest yield was 2915.5 kg/ha.

The greatest disparities in grain yield and losses occurred at both locations because of the intense disease pressure. A similar argument has been advanced, according to Ali (2007), that the level of disease pressure determines the degree of yield fluctuation. Grain yield was shown to be inversely related to disease severity, suggesting that stem rust has a direct impact on kernel quality, causing wheat grains to shrink. In comparison to the untreated control, both experimental fungicides significantly improved grain yield. Disease levels were lowered and grain output was enhanced after using Tilt 250 EC. Similarly, the tilt-protected plots showed minimal stem rust, according to Asmmawy et al. (2013). Native SC 300 was more successful than Tilt

250 EC in controlling stem rust, although the fungicides were not interchangeable. By disrupting the fungal cell wall's structural integrity and, in turn, blocking the respiration, reproduction, and continued growth of stem rust fungi, this chemical decreased grain loss caused by stem rust infection.

Table 2

Effect of fungicides application frequency on diseases and yield components at Mareko in 2021 cropping season

Treatments		TS	ACI	AUDPC	SL	KPS	TKW	GY
Chemical	Frequency	(%)	(%)	(% days)	(cm)		(g)	(kg/ha)
Tilt	1x	65.0[b]	60.3[b]	1353.3[b]	6.46[e]	44.0[de]	29.0[e]	3454.7[e]
	2x	53.3[c]	46.6[cd]	1238.3[c]	7.23[bc]	51.4[b-d]	31.3[d]	3805.0[d]
	3x	43.3[d]	37.3[d]	863.3[d]	7.06[cd]	53.8[bc]	33.7[c]	4446.1[b]
Nativo	1x	60.0[bc]	52.3[bc]	1251.7[c]	6.60[de]	46.5[c-e]	32.2[d]	3549.4[e]
	2x	40.0[d]	23.3[e]	891.7[d]	8.46[a]	59.1[ab]	35.6[b]	4123.2[c]
	3x	35.0[d]	17.3[e]	478.3[e]	7.76[b]	63.6[a]	37.8[a]	4768.9[a]
Control		93.3[a]	86.3[a]	1645[a]	6.10[e]	39.5[e]	26.6[f]	2767.4[f]
CV%		9.8	13.1	15.3	4.4	8.08	1.2	17.5
$LSD_{0.05}$		11.2	15.6	63.8	0.55	8.8	3.21	334.5

$LSD_{0.05}$ = List significant difference at 5%, CV (%) =Coefficient of variation at (%). Means in same column followed by the same letters are not significantly different. TS=terminal rust severity, ACI = average coefficient infections, AUDPC=area under disease progress curve, KPS= kernel; per spick, TKW= thousand Kernel weight, GY= grain Yield

Table 3

Effect of fungicides application frequency on diseases and yield components at Dalocha in 2021 cropping season

Treatments		TS	ACI	AUDPC	SL	KPS	TKW	GY
Chemical	Frequency	(%)	(%)	(% days)	(cm)		(g)	(kg/ha)
Tilt	1x	61.6[b]	61.3	1041.8[b]	6.51[cd]	53.3a[ab]	29.9[c]	3398.3[d]
	2x	46.6[c]	46.6[c]	838.3[c]	6.72[bc]	46.1[bc]	28.3[c]	3989.2[c]
	3x	40.0[cd]	34.8[d]	467.2[c]	6.98[b]	53.0[ab]	34.6[ab]	4908.8[b]
Nativo	1x	56.1[b]	56.6[bc]	851.7[c]	6.69[bc]	49.7[ab]	29.5[bc]	3993.3[c]
	2x	31.6[d]	22.0[e]	618.6[d]	7.31a	53.0[ab]	36.4[a]	5092.2[b]
	3x	13.3[e]	6.3[f]	245.1[f]	7.5[a]	60.7[a]	36.7[a]	6270.6[a]
Control		78.3[a]	80.0[a]	1245.2[a]	6.02[e]	29.6[c]	25.9[c]	2915.5[e]
CV%		10.1	13.3	11.9	5.71	10.9	9.95	8.9
$LSD_{0.05}$		8.42	10.4	147.1	0.49	9.09	5.59	446.7

$LSD_{0.05}$ = List significant difference at 5%, CV (%) =Coefficient of variation at (%). Means in same column followed by the same letters are not significantly different. TS=terminal rust severity, ACI = average coefficient infections, *AUDPC=area under disease progress curve, KPS= kernel; per spike, TKW= thousand Kernel weight, GY= grain Yield*

Correlation Analysis between Disease and Agronomic Variables

We looked for a connection by computing correlations between stem rust and other characteristics. Tables 4 and 5 show that there were statistically significant positive correlations between grain yield and the weights of one thousand kernels (r=0.86**) and one kernel per spike (r=0.61**), respectively, according to the Pearson correlation coefficient analysis. This suggests that the contributors to yield have a significant impact on how much grain a plant produces. Tables 4 and 5 show that stem rust had a negative connection with grain yield (r=-0.87**), total kernel yield (r = -0.78**), and kernel per spike (r = -0.39*). Severity significantly reduced grain yield and had a negative effect on TKW, according to the rather substantial association. The average severity of leaf rust disease, the percentage of thousand kernels lost, and the grain production of bread wheat were all shown to be significantly correlated, according to El-Shamy et al. (2011). The ACI and AUDPC showed a high negative connection with grain yield (r=-0.97** and r=-0.93**, respectively).

Table 4

Correlation between disease parameters and yield and yield components at Mareko

	TRS	ACI	AUDPC	SL	KPS	TKW	GY
TRS							
ACI	0.85**						
AUDPC	0.84**	0.91**					
SL	-0.31*	-0.28*	-0.22ns				
KPS	-0.31*	-0.10ns	-0.07ns	0.26*			
TKW	-0.78**	-0.69**	-0.57**	0.42*	0.45**		
GY	-0.87**	-0.83**	-0.77**	0.49**	0.59**	0.86**	

*** refers to mean values Significant @=0.01, * refers mean square values Significant at @=0.05, ns: refers mean square values not significant at @ = 0.05, TRS= Terminal rust severity, AUDPC= Area under disease progress curve, ACI = Average coefficient of infection, SL = Spike length, KPS= Kernel per spike PH= Plant height, TKW = Thousand kernel weight, GY= Grain yield.*

Table 5

Correlation between disease parameters and yield and yield components at Dalocha

	TRS	ACI	AUDPC	SL	KPS	TKW	GY
TRS							
ACI	0.81**						
AUDPC	0.87**	0.89**					
SL	-0.29*	-0.24*	-0.18ns				
KPS	-0.39*	-0.16ns	-0.06ns	0.28*			
TKW	-0.75**	-0.63**	-0.54**	0.33*	0.38*		
GY	-0.82**	-0.71**	-0.64**	0.40*	0.61**	0.79**	

*** refers to mean values Significant @=0.01, * refers mean square values Significant at @=0.05, ns: refers mean square values not significant at @ = 0.05, TRS= Terminal rust severity, AUDPC= Area under disease progress curve, ACI = Average coefficient of infection, SL = Spike length, KPS= Kernel per spike PH= Plant height, TKW = Thousand kernel weight, GY= Grain yield.*

Cost Benefit and Relative Yield Loss Analysis

Fungicide treatments were significantly linked to an increase in grain output in this study. Results from fungicide applications at Mareko ranged from 792.5 ha-1 in a single treatment with Tilt 250 EC to 2008.4 ha-1 in a three-treatment study with Nativo SC 300 (Table 6). Table 6 shows that post-fungicide net returns varied from 312.6 ha-1 in a one-spray plot with Tilt 250 EC to 2426.43 ha-1 in a three-spray plot using Nativo SC 300 at Dalocha. The cost-benefit analysis revealed that using Nativo SC 300 with three spray frequencies successfully reduced illness and yielded a better financial return. Stem rot caused enormous yield reductions at both sites. In Mareko, untreated plots had the most loss of grain yield at 83.9%, while in Dalocha, it was 64.0%. The main elements that contribute to a decrease in grain output are genetic predisposition, infection timing, disease progression rate, crop developmental stage, and environmental factors (Pretorius 2004; Chen 2005). On the other hand, plots treated with fungicides and improved grains had less relative grain yield loss from stem rust. When contrasted with unsprayed controls, sprayed plots produced higher yields. A single treatment of fungicides was insufficient to completely control the stem rust. Increasing the frequency of fungicide application can help minimize disease re-infection. Nevertheless, there was no continuous increase in grain yield despite such frequency. Economic analysis should, therefore, inform the frequency of applications.

Table 6

Effect of fungicides on net return of bread wheat varieties

Treatment		Mareko					Dalocha			
Chemical	Frequency	FC+AC	GY	GYI	GYIP	Rn	GY	GYI	GYIP	Rn
Tilt	1x	51.2	32.5	10.9	843.6	792.5	33.9	4.7	363.8	312.6
	2x	102.4	38.1	16.5	1278.7	1176.3	39.8	10.6	820.4	718
	3x	153.6	45.4	23.8	1842.1	1689.2	49.1	20.1	1555.7	1402.1
Nativo	1x	55.1	35.4	13.8	1068.1	1013.1	39.9	10.7	828.2	765.1
	2x	111	43.2	22	1709.4	1591.8	50.9	21.7	1679.5	1568.5
	3x	166.5	49.7	28.1	2174.9	2008.4	62.7	33.5	2592.9	2426.4
Control		0.00	21.6	0.00	0.00	0.00	29.2	0.00	0.00	0.00

FC=Fungicide cost ($\$ha^{-1}$), AC = Fungicide application cost, GYI=Grain yield increment from fungicide application ($qtha^{-1}$), P= wheat price ($\$qt^{-1}$), Rn= net return from fungicide application ($\$ha^{-1}$).

CONCLUSIONS

The stem rust disease drastically cut down on spike length, grain yield, and kernel weight. Grain yield losses were inversely related to the severity of stem rust, which was characterized by maximum values of the area under the disease progress curve and average coefficient of infection. There was a notable variation in disease resistance and susceptibility across treatment combinations, and environmental and pathogenic heterogeneity had a substantial impact on the tested variety's yield performance between sites. But this study does suggest that foliar fungicide use is a key tactic for increasing grain yields in the nation. The most cost-effective management technique to prevent grain yield loss caused by stem rust, according to the present study, is to apply Nativo SC 300 three times as much as the prescribed amount at the first sign of disease symptoms. In high-yielding settings, fungicides can be administered regularly and prophylactically with the expectation of a return on investment. In order to effectively manage wheat stem rust disease, farmers in the research areas and those with comparable agro-ecological conditions should apply fungicides at the recommended frequency. To provide a more thorough proposal, however, additional research in other agro-ecological zones is required.

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DECLARATION

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

All data included in the article are available from the corresponding author upon request

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