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Research Article

Effect of Stripe Rust (*Puccinia Striiformis F. p. ritici*), Variety and Fungicide Application Time on Yield and Yield Components of Bread Wheat

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Abstract

The study was conducted to evaluate effects of bread wheat variety and fungicide application time on stripe rust epidemics under natural field conditions at Banja and Aneded in the main cropping season of 2019/2020 year. Four different fungicide application time (7, 14, 21, 28), including fungicide unsprayed combined with three wheat varieties (Wane, Danda'a and Kubsa) with different level of resistance to stripe rust were used in the experiment and the experiment was laid out in RCBD design with factorial arrangement and replicated three time. Disease data's severity, AUDPC, incidence and Disease progress rate and also yield component and grain yield data were recorded. The maximum disease incidence (100%), on unsprayed plots of the susceptible Kubsa and moderately resistant Danda'a varieties in both locations was recorded. Additionally, 100% SRI was recorded on Kubsa variety plots applied 14, 21, and 28 days at Banja. But SRI was recorded in both the susceptible and resistant varieties when fungicide was sprayed 7 days after the initial symptoms appeared. Moreover, the maximum grain yield (4648.8kg/ha) was obtained from combination of Wane variety (Resistant and 7 days fungicide sprayed time at banja location. While the minimum yield (609.7 kg/ha) was obtained from fungicide unsprayed Kubsa variety (susceptible) at banja location. 7 days after initial symptom appeared fungicide sprayed varieties were effective to against Stripe rust and gave the highest values of yield over unsprayed plots and other fungicides application times. However, Combination of Wane variety and 7 days after initial symptom appeared fungicide application time was more feasible than other treatment combinations.

Keywords

AUDPC, Bread Wheat, Incidence, Severity, Stripe Rust

1. Introduction

Wheat (*Triticum aestivum* L) is a widely cultivated cereal grain serves as a staple food for over one-third of the world's population [23]. It is grown in various agro-ecological and crop management systems and serves as the primary source of food for humans, supplying 40% of the world's food and accounting for 25% of calories consumed in developing countries [24]. The global average wheat productivity is around 5t/ha, although this varies significantly among countries and regions. East African (including Ethiopia), North African, and Middle Eastern countries consume more than 150% of their own wheat production and heavily rely on imports to meet their food security needs [27].

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Many diseases can affect wheat, but one of the most serious diseases affect Ethiopia's wheat is stripe rust [22, 25]. Three environmental factors temperature, altitude, and moisture affect the development of stripe rust. [6] Reported that low nighttime temperature is more conducive to stripe rust infection than daytime temperature due to moisture present in the cold air. Epidemics of stripe rust have been documented all across the world, primarily in East and North Africa, Central and West Asia. These regions have experienced high disease pressure with Morocco being particularly affected [5]. The presence of a primary host, such as wheat or grasses, and an alternative host, such as Berberis or Mahonia species, favors the presence of Pst, the fungus that causes stripe rust.

In Ethiopia, there have been previous occurrences of stripe rust epidemics, which were accompanied by the emergence of virulent strains. These strains have made popular bread wheat cultivars like Lakech and Dashen susceptible to the disease [33]. Severe infestations of stripe rust can lead to significant reductions in yield and grain quality, up to 60% [8]. Stripe rust outbreaks are occurring more frequently and extensively due to cultivar susceptibility and favorable weather conditions, leading to significant yield and quality losses [16]. For instance, stripe rust caused bread wheat cultivars in the Bale highlands lose up to 71% of its yield [1]. In severe cases, highly susceptible varieties have reported a 100% yield loss [4].

The primary approach for managing stripe rust in Ethiopia has been the use of resistant varieties. This led to significant progress in the development of wheat varieties with different levels of resistance. However, many of these resistant varieties have become susceptible over time due to the introduction of new races or changes in environmental factors [3]. Additionally, resistance failure has been observed due to changes in pathogen virulence, which has increased interest in chemical control of the disease [12].

Chemical fungicides are preferred when resistant wheat varieties fail, as they provide practical and rapid disease control. Foliar fungicides have been widely used to manage stripe rust, preventing million-dollar losses and significantly reducing crop loss [19]. [16] Reported that the sprayed plots had a relatively better yield compared to the unsprayed plots. Furthermore, their study demonstrated that the timing of the spray application is a significant factor in reducing disease severity and the rate of epidemic development. Another study by [38] highlighted that the significance of timely and appropriate fungicide application is effectively preventing substantial yield losses and the dissemination of stripe rust to other areas.

The use of fungicides has played a crucial role in preventing potential significant nationwide yield losses. The 2010 yellow rust epidemic showed a significant reduction in crop loss due to the use of chemicals [12]. In East Africa, all current commercial wheat cultivars are susceptible to the new race, which makes it impossible to grow a profitable crop without the application of fungicides [18]. While resistant varieties and fungicides are the most effective management options against wheat stripe rust, only a small number of farmers in the study area utilize fungicides to combat the disease, and they have limited knowledge regarding the response of their chosen variety to stripe rust. Many farmers also remain unaware of the economic benefits of applying fungicides to maximize their yield. Therefore the Objectives of this study were to evaluate the effects of stripe rust, variety and fungicide application time on yield and yield Components of bread wheat under natural field conditions.

2. Materials and Methods

The study was conducted at Pawe Agricultural Research Center in Banja substation and Debremarkos Agricultural Research Center in Aneded station, located in northwestern Ethiopia, during the main cropping season of 2019. Based on the potential for wheat production and the hotspots for outbreaks of wheat stripe rust, the locations were purposively selected. The locations that were tested, along with their geographic coordinates, are shown in Figure 1.

2.1. Description of Study Sites

Table 1. *Study sites description.*

Mean parameters	Aneded	Banja
Altitude (masl)	2471	2511
Rain fall (mm)	1341	1344
Temperature (Min and Max)	11°C and 15°C	10.3°C and 22.5°C
Soil PH	4.9	5.2

Source: Western Amhara Metrological Center, 2019.

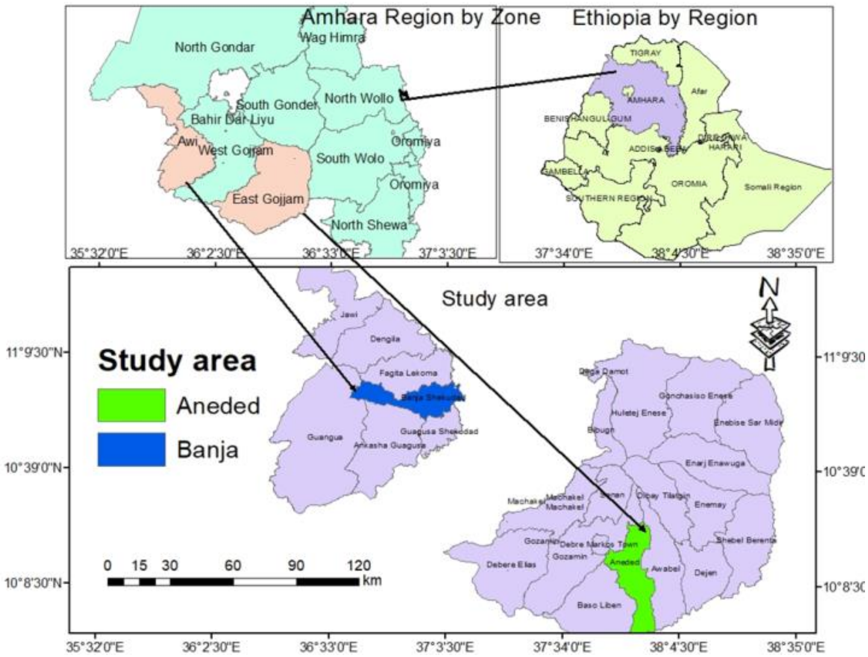


Figure 1. Map showing Ethiopia, the Amhara region, and the experimental districts for stripe rust diseases in northwestern Ethiopia.

Table 2. Profiles of bread wheat varieties used in the field experiments.

No	VN	Pedigree	YR	RGA (masl)	Reaction to stripe rust	Yield (ton/ha)
1	Wane	ETBW6130	2016	2100-2700	Resistant	5.0 - 6.0
2	Danda'a	DANPHE#1	2010	2000-2600	Moderately resistant	3.5-5.5
3	Kubsa	HAR1685	1995	2000-2600	Susceptible	3.0 - 5.0

VN: Variety name, YR: Year of release, RGA: Recommended growing altitude, masl: meters above sea level.
Source: Ethiopian Ministry of Agriculture, Animal and Plant Health Regulatory Directorate Crop Variety Register 1995-2016, Addis Ababa, Ethiopia.

2.2. Treatments and Experimental Procedures

Three bread wheat varieties with varying levels of resistance to stripe rust which are currently under production were used as a varietal component. Seeds of these varieties (Table 2) were obtained from Kulumsa Agricultural Research Centre. 150 kg of seeds per hectare were sown for each variety on a properly prepared seedbed. Manual seeding was conducted in rows on June 24th and June 28th, respectively, at Aneded and Banja locations during the main rainy season of the 2019 cropping season. During sowing, the recommended NPS fertilizer at a rate of 150 kg/ha and urea at a rate of 200 kg/ha (split application; one-third during sowing and two-thirds during crop booting stage) were applied. At both locations, weeds were manually removed three times. The first weeding was done at the tillering stage (21 days after sowing); he second weeding was done at the booting stage (20 days after the first weeding); and the third weeding was done at the flowering stage (one month after the second weeding).

2.3. Description of the Tested Fungicide

Foliar application of the fungicide (Rex® Dou table 3) was performed at the rate recommended by the company. Spraying was performed using a manual knapsack sprayer, with a mixture of 0.5L/ha fungicide and 250L/ha water. The spraying was performed weekly.

Table 3. Specifications of the commercial fungicide used in the field experiments.

Parameters	Description
Trade Name	Rex® Dou
Year of registration	2010
Active Ingredient	Epoxiconazole + Thiophanate-methyl

Parameters	Description
Product Formulation	Emulsifiable wettable
Mode of Action	Systemic
Product Rate (L/ha)	0.5
Amount of dilution water (L/ha)	200-300
Registrant Company	BASF, Ludwigshafen, Germany

Data were sourced and organized from the Ministry of Agriculture (MoA, 2015) and the product package booklet.

There were a total of 15 treatment combinations (Table 4) derived from two factors 3 wheat varieties x 4 fungicide spraying dates, plus the unsprayed plots as a control. Randomized Complete Block Design with 3 replications in a factorial arrangement was used.

The treatments were randomly assigned to the experimental plots within a block. The size of the unit plot was 2m x 4m (8m²), consisting of 10 rows with 8 harvestable rows spaced at 0.02m. The space between blocks and plots was 1.5m and 1m, respectively.

Table 4*. The treatment combinations used at both locations.*

Treatments			
No.	**Variety**	**FAT* Days***	**Designation**
1	Wane	Unsprayed	W0
2	Wane	7	W7
3	Wane	14	W14
4	Wane	21	W21
5	Wane	28	W28
6	Danda'a	Unsprayed	D0
7	Danda'a	7	D7
8	Danda'a	14	D14
9	Danda'a	21	D21
10	Danda'a	28	D28
11	Kubsa	Unsprayed	K0
12	Kubsa	7	K7
13	Kubsa	14	K14
14	Kubsa	21	K21
15	Kubsa	28	K28

FAT: fungicide application time. "*": Application of fungicide time x days following the onset of the first symptoms

2.4. Disease Assessment

Strip rust incidence: ten randomly pre-tagged plants were taken from the central 8 rows. Plants exhibiting symptoms of stripe rust were counted and expressed as a percentage.

Strip rust severity: was assessed using the modified Cobb scale [26]; which takes into account the percentage of the plant infected and the type of disease reaction. This assessment was conducted using the same plants that were used for the incidence assessment. Specifically, ten plants were randomly selected and previously tagged from the central 8 rows of each plot. The assessment was performed weekly for five times, starting from the occurrence of the first disease symptoms up to the early maturity stages.

Table 5*. Tripe rust rating scale.*

NO.	Index	Category	Description of Infection Type
1	0	0	No visible symptoms
2	1	VR	Necrotic/chlorotic flecks; no sporulation
3	2	R	Necrotic/chlorotic stripes; no sporulation
4	3	MR	Necrotic/chlorotic stripes-trace; sporulation
5	4	LM	Necrotic/chlorotic stripes; light sporulation
6	5	M	Necrotic/chlorotic stripes; intermediate sporulation
7	6	HM	Necrotic/chlorotic stripes; moderate sporulation
8	7	MS	Necrotic/chlorotic stripes; abundant sporulation
9	8	S	Chlorosis behind sporulating area; abundant sporulation

NO.	Index	Category	Description of Infection Type
10	9	VS	No necrosis/chlorosis; abundant sporulation

Note, 0 = Immune, VR = Very Resistant, R = Resistant, MR = Moderately Resistant, LM = Light Moderate, M = Moderate, HM = Highly Moderate, MS=Moderately Susceptible, S = Susceptible, VS =Very Susceptible. Source: [20].

Area under the Disease Progress Curve (AUDPC)

The Area under Disease Progress Curve (AUDPC) was computed using the following formula, based on the mean disease severity recordings [36]:

$$\text{AUDPC}=\sum 0.5(xi+1+xi)(ti+1-ti)$$

Where n is the total number of observations, ti is the time (in days after planting) at the ith observation, and xi is the cumulative disease severity expressed as a proportion at the ith observation.

Disease progress rate: was determined by repeatedly assessing the percentage of leaf area affected by stripe rust, starting from the onset of the disease. The logistic model was used for temporal analysis of disease progress, as it is the most appropriate model [10].

2.5. Evaluation of Yield and Yield Components

A number of agronomic characteristics that contribute to the impact of stripe rust on wheat were evaluated. Ten randomly selected plants from the middle eight rows were used for all measurements.

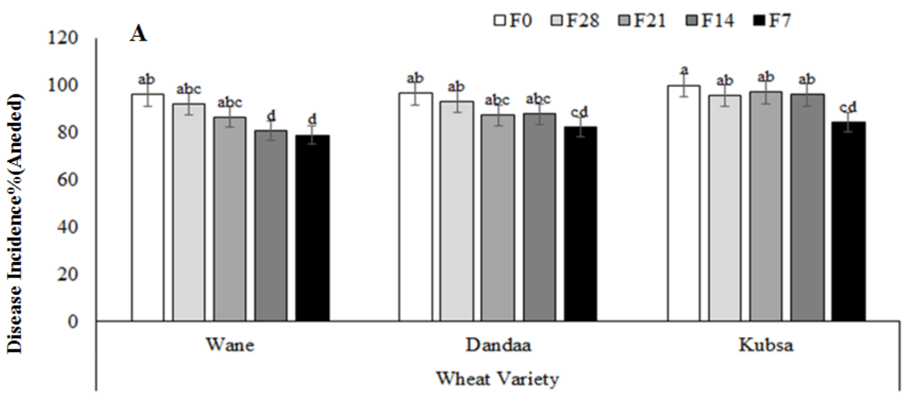
2.6. Data Analysis

The statistical software package SAS version 9.4 (SAS, 2013) was used to perform mean comparisons and analysis of variance. The two locations were considered as different environments due to variations in weather, edaphic and disease pressure. For example, there was a shortage of rain at Anede location during the study period. The variation in error variance between the two locations was high, so a combined analysis across locations was not done. Therefore, the data was analyzed separately for each location. Analysis of variance (ANOVA) was used to determine the treatment effects based on data of disease severity at the terminal assessment, disease progress rate, area under the disease progress curve, yield, and yield components obtained from three replications were used for analysis of variance (ANOVA) to determine treatment effects.

3. Results and Discussion

3.1. Effect of Variety and Fungicide Application Time on Disease Parameters

The ANOVA results indicated that variety, fungicide application time, and their interaction at both locations had a significant effect on stripe rust incidence (SRI) ($P \leq 0.0001$). The unsprayed plots of the susceptible Kubsa and moderately resistant Danda'a varieties in both locations recorded the highest SRI (100%). Additionally, a 100% SRI was observed in Kubsa variety plots 14, 21, and 28 application days at Banja. In unsprayed plots, the SRI for the resistant variety Wane was 98.8% at Banja and 96.1% at Aneded (Figure 1).



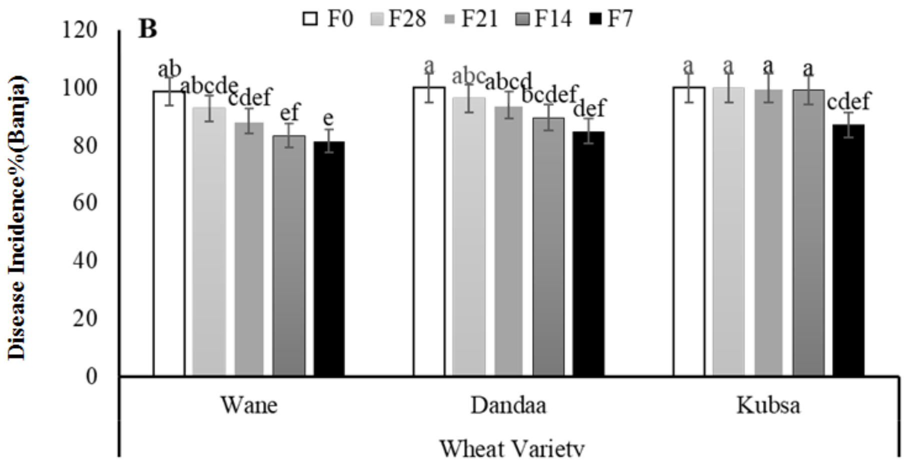


Figure 2. *tripe rust disease incidence on each treatment at Aneded (A) and Banja (B) locations. Bars with the same letters are not significantly different at P ≤ 0.05.*

The above results showed that, although the difference was slight, there was a varying degree of response between the resistant and susceptible varieties. Regardless of the locations, a significant reduction in SRI was observed in both the susceptible and resistant varieties when fungicide was sprayed 7 days after the initial symptoms appeared. Moreover, a significant difference was observed between the resistant and susceptible varieties only when fungicide was sprayed 14 days after the initial symptoms appeared at Anede and 14 and 21 days after the initial symptoms appeared at Banja. Besides, when compared to Anede, a greater degree of differences between the resistant and susceptible varieties in Banja was observed (Figure 1).

Previous research have demonstrated that stripe rust disease develops faster on susceptible varieties than on resistant varieties [31]. Once it is established in the field, the chance of its spread depends on several factors, including variety [12], wind [11], and fungicide spray [38], which determine the percentage of disease incidence under field conditions. The notable variations in SRI between sprayed and unsprayed plots in the current study were clearly caused by the effectiveness of the fungicide in managing the disease. More importantly, when fungicide was sprayed 7 days after the appearance of initial symptoms; its effect on reducing SRI was significant; regardless of variety and location.

Regarding terminal stripe rust severity (TSRS), significant difference has shown by ANOVA (P≤0.0001) among varieties, fungicide application time, and their interaction at both locations. Application of fungicide 7 days after the initial symptoms appeared the severity was reduced on Wane, Danda'a, and Kubsa varieties by 8.9%, 18.5%, and 54.6%, respectively, at the final assessment date in Aneded. Similar treatments at Banja reduced by 8.7%, 18.8%, and 68.5% on Wane, Danda'a, and Kubsa varieties. At both locations, the fungicide application time has a stronger effect on the susceptible variety compared to the resistant variety.

Both the susceptible and resistant varieties showed a significant reduction in TSRS when fungicide was sprayed 7 days after the initial symptoms appeared. Furthermore, in almost every fungicide application time in Anede and Banja, a noticeable difference in response between the resistant and susceptible varieties was observed (Figure 2). Furthermore, when compared to Anede, Banja exhibited significantly larger differences between resistant and susceptible varieties, as well as a more pronounced impact of fungicide application time. This indicates that the location plays a crucial role in determining the effectiveness of both fungicide treatment and variety selection in preventing stripe rust disease in wheat.

Despite the variations in disease resistance levels among the three varieties, none of them exhibited complete resistance (0% infection) without the use of fungicide. This suggests that the varieties tested in the current experiment do not possess immunity or complete resistance. This aligns with the research conducted by [2]. Therefore, it is clear that the effectiveness of the fungicide in managing the disease caused the notable differences in TSRS between the sprayed and unsprayed plots in the current study.

More importantly, when fungicide was sprayed 7 days after the appearance of initial symptoms, its effect on reducing TSRS was significant, regardless of the wheat variety and location suggesting this time as a potential recommendation for management of stripe rust disease on bread wheat. This is in agreement with the work done by [21], who reported higher TSRS on unsprayed plots than sprayed plots across different locations and varieties.

In general, the efficacy of fungicide is much stronger on the susceptible variety Kubsa compared to the moderately resistant variety (Danda'a) and the resistant variety (Wane). More interesting is the gradual reduction of TSRS, which is dependent on application time, observed across all varieties regardless of the level of disease resistance. However, there is a significantly higher degree of efficacy in the case of the susceptible variety (Figure 3).

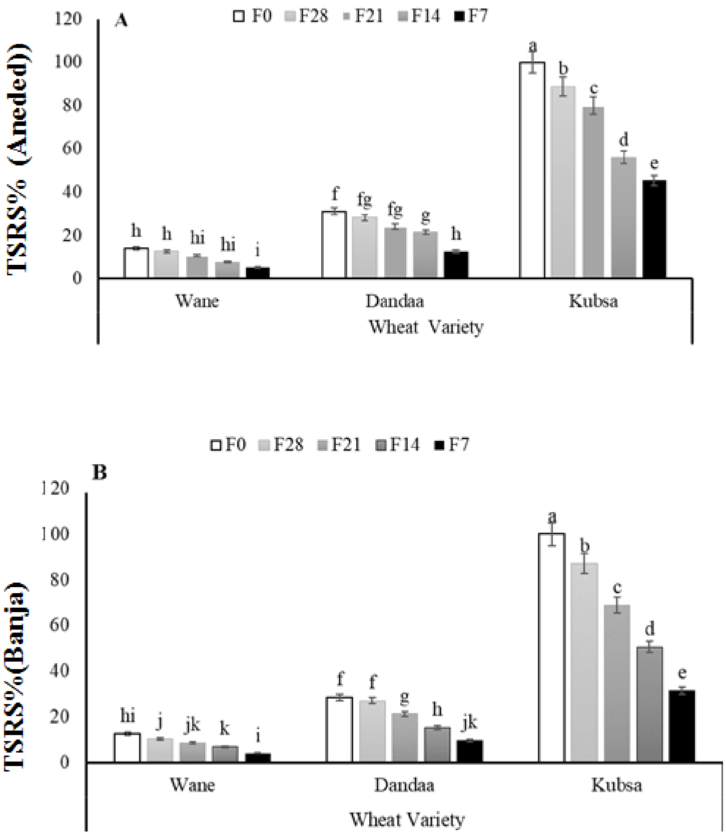


Figure 3. *Terminal Strip Rust Severity on each treatment at Anede (A) and Banja (B) locations. Bars with the same letters are not significantly different at P ≤ 0.05*

Therefore, based on the findings of this study, it is necessary to conduct an economic feasibility study before making a decision or recommendation regarding the use of fungicides for managing stripe rust in areas where resistant or moderately resistant varieties are employed. The results of the current study, which clearly showed a significant difference in TSRS between the resistant and susceptible varieties when no fungicide was applied, provide strong evidence for this claim (Figure 3).

Similar to the previously mentioned disease parameters, analysis of variance (ANOVA) on the stripe rust disease progress rate (SRDPR) showed significant differences (P≤0.0001) between varieties, fungicide application time and their interaction at both locations. Compared to Anede, a relatively higher rate of disease progression was observed at Banja location.

Even though there was disease progression in all treatment combinations, the extent of progress varied depending on the resistance level of the varieties. Previous research by [1] revealed similar findings, showing significant variations in the rate of disease progression among cultivars with different levels of disease resistance.

In the current investigation, the average daily rate of disease progression on unsprayed plots of Wane, Danda'a, and Kubsa varieties was 0.03, 0.031 and 0.036, per day at Anede, respectively. The comparable values at Banja were 0.04/day, 0.043/day, and 0.045 per day for the respective treatments. Regardless of location, the variety Wane showed the lowest disease progression, while Kubsa variety showed the highest (Table 6). In general, the above variation in disease progress rate between the two locations indicates effect of location/agro ecological factors on the efficacy of varieties and fungicide in the management of strip rust disease on wheat.

ANOVA on AUDPC showed significant (P≤0.0001) variations in fungicide application time and the interaction between them at both locations. In comparison to Aneded (AUDPC=186), the mean AUDPC of the unsprayed plots of the susceptible variety Kubsa was slightly higher at Banja (AUDPC=190). However, compared to the susceptible variety, the mean AUDPC value in the unsprayed plots of the resistant variety (Wane) was significantly lower at 129.0 and 105.2 at Aneded and Banja, respectively. More significantly, the resistant variety consistently responded even in the absence of fungicide spray. This was evidenced by its distinct response across locations, which differed from that of the susceptible variety.

Table 6. *Effect of variety and fungicide application time on Disease progress rate.*

Treatment factors		Treatment	Stripe rust disease progress rate	
Variety	FAT Days *	designation	Aneded	Banja
Wane	7	W7	0.000[f]	0.000[f]
Wane	14	W14	0.008[e]	0.016[e]
Wane	21	W21	0.020[cd]	0.027[d]
Wane	28	W28	0.027[ba]	0.038[c]
Wane	Unsprayed	W0	0.030[ab]	0.040[bc]
Danda'a	7	D7	0.000[f]	0.000[f]
Danda'a	14	D14	0.014[de]	0.017[e]
Danda'a	21	D21	0.020[d]	0.029[d]
Danda'a	28	D28	0.027[bc]	0.039[bc]
Danda'a	Unsprayed	D0	0.031[ab]	0.043[ab]
Kubsa	7	K7	0.000[f]	0.000[f]
Kubsa	14	K14	0.014[de]	0.017[e]
Kubsa	21	K21	0.024[bc]	0.030[d]
Kubsa	28	K28	0.030[ab]	0.039[bc]
Kubsa	Unsprayed	K0	0.036[a]	0.045[a]
CV (%)			13.3	5.9
LSD (0.05)			0.007	0.0045

FAT: fungicide application time. "*": Fungicide application time x days after the appearance of initial symptoms *LSD (0.05)*: List significant difference at *5%, CV (%)*: Coefficient of variation, means with the same letters are not significantly different.

Whenever the fungicide was sprayed 7 days after the appearance of initial symptoms, the AUDPC value on the resistant variety wane was significantly reduced to 64.4 and 49.5 at the Anede and Banja locations, respectively. Interestingly, fungicide sprayed 7 days after the initial symptoms appeared has also reduced the Area under the Disease Progress Curve (AUDPC) on the susceptible variety Kubsa to 114.3 and 112.0 at the Anede and Banja locations, respectively.

Nevertheless, this study showed that, regardless of location, the efficacy of fungicide used for managing stripe rust is significantly higher when resistant varieties are used, as compared to susceptible varieties (Figure 3). The findings of this study are consistent with reports from [33], [7] and [21]. These reports indicated that untreated plots had higher AUDPC values than fungicide treated plots. Additionally, [31], who showed that faster development of stripe rust disease on susceptible variety than resistant variety.

Moreover, it has been noted that fungicides reduced subsequent disease progression on plant parts that were slightly infected at the time of fungicide application. However, it is not effective on heavily infected plant parts as indicated in a previous study by [9], the timing of symptom onset, early disease detection and early fungicide application should all be taken into consideration in the stripe rust management strategy when using fungicides, if economic control of the disease to be achieved. In this study, the fungicide treatments were effective in significantly slowing down the progression of the disease. This effect was observed regardless of the wheat variety and location.

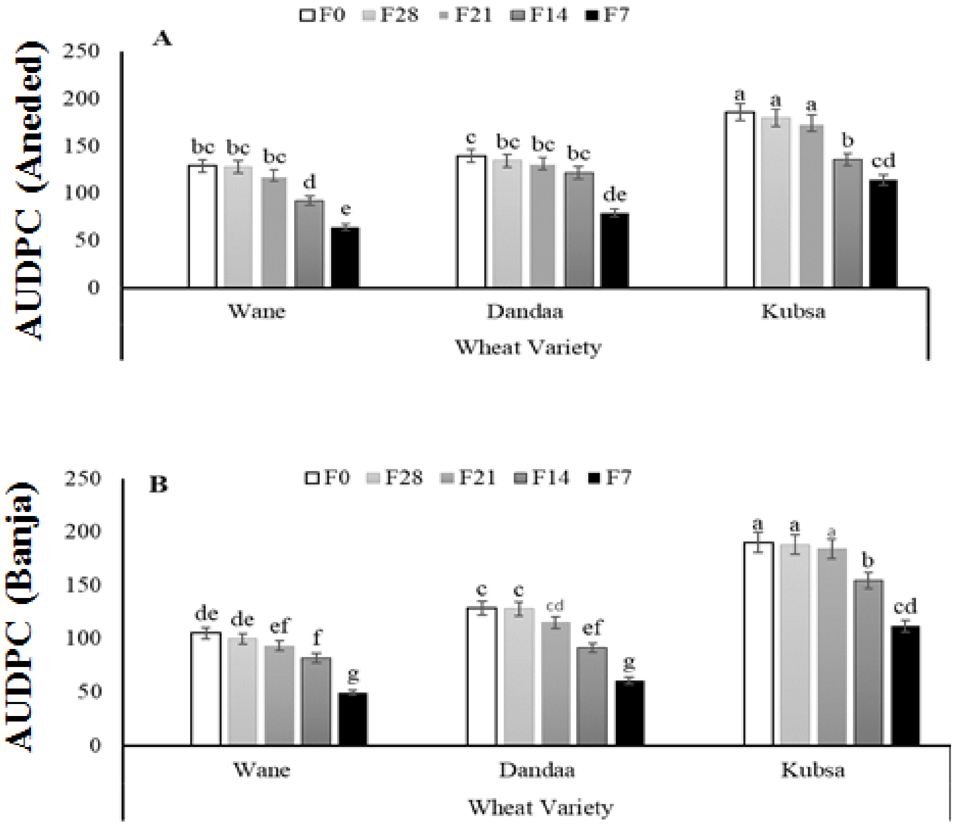


Figure 4. *Area under the disease progress Curve on each treatment Aneded (A) and Banja (B) locations. Bars with the same letters are not significantly different at P ≤ 0.05.*

3.2. Effect of Variety and Fungicide Application Time on Agronomic Traits

In this study, multiple agronomic traits that best explain the reactions of wheat varieties to stripe rust were examined. These included stand count, days to 50% of heading, days to 90% of physiological maturity, plant height, and spike length (Table 7). Accordingly, the ANOVA results revealed that, except stand count, all the agronomic variables showed significant differences (P≤0.01) among varieties at both locations. The ANOVA result also indicated that at Anede, fungicide application time significantly (P≤0.05) influenced days to 90% of physiological maturity, plant height, and spike length. At Banja, only days to 50% of heading and spike length were affected. On the other hand, the number of days to reach 90% physiological maturity and plant height were significantly influenced by its interaction at Banja. However, only the interaction significantly affected plant height at Aneded.

In terms of physiological maturity, except for variety Danda'a, the two varieties showed no significant delay in physiological maturity compared to untreated plots with fungicides (Table 7). It could be due to a reduction in the level of disease pressure, which can be attributed to a timely application of fungicides. Different justifications exist for the variability in the number of days between physiological maturities, as documented by various authors. According to [13], fungicides prolong the time that leaves remain on plants during late developmental stages and accelerate the ripening period, which causes late maturation. They also slow down the breakdown of chlorophyll and leaf protein. Conversely, according to [5], *Puccinia striiformis f.* sp. *Tritici,* as biotrophic pathogen, is characterized by reduction in green leaf area which accelerates leaf senescence and cause early maturity of wheat. [30], who studied physiological maturity of wheat cultivars also revealed variations in maturity days of wheat varieties due to inherent differences between cultivars. In the present study, plots that were not treated with fungicide reached 90% physiological maturity earlier (Danda'a 97 days) compared to the plots that were treated in a timely manner (Danda'a 104 days).

Table 7. Effect of variety and fungicide application time on agronomic traits.

Treatments		Agronomic variables							
		Aneded				Banja			
Variety	FAT	DTH	DTM	PH (cm)	SL (cm)	DTH	DTM	PH (cm)	SL (cm)
Wane	W7	66.7^{cd}	100.3^{bc}	72.4^{ef}	7.3^{a}	50.7^{bc}	87.7^{cd}	79.3^{de}	6.8^{cd}
	W14	66.0^{d}	97.7^{bcd}	76.1^{c}	6.97^{abcd}	51.0^{bc}	88.0^{c}	80.0^{cd}	6.6^{cdef}
	W21	66.0^{d}	97.7^{bcd}	75.3^{cd}	6.7^{bcd}	50.7^{bc}	88.0^{c}	80.3^{cd}	6.3^{defg}
	W28	66.0^{d}	96.7^{cd}	74.6^{cd}	6.3^{e}	51.3^{b}	87.7^{cd}	77.7^{de}	6.2^{efg}
	W0	66.0^{d}	97.3^{cd}	75.3^{cd}	6.7^{cde}	51.3^{b}	87.0^{de}	77.6^{ed}	5.7^{g}
Danda'a	D7	70.0^{a}	104.3^{a}	82.0^{a}	7.1^{abc}	53.7^{a}	97.0^{a}	86.4^{b}	7.8^{a}
	D14	69.7^{ab}	100.3^{bc}	79.1^{b}	7.2^{ab}	53.0^{a}	97.3^{a}	87.4^{b}	7.6^{ab}
	D21	69.7^{ab}	99.3^{bc}	81.6^{a}	6.9^{abcd}	54.0^{a}	97.0^{a}	86.1^{b}	7.6^{ab}
	D28	68.3^{abc}	101.3^{ab}	79.0^{b}	6.5^{de}	53.7^{a}	96.0^{b}	92.3^{a}	7.0^{bc}
	D0	67.7^{bcd}	97.0^{cd}	80.4^{ab}	6.9^{abcd}	54.0^{a}	97.0^{a}	84.0^{bc}	7.5^{ab}
Kubsa	K7	67.0^{cd}	98.7^{bcd}	75.4^{cd}	6.9^{abcd}	50.3^{bc}	86.3^{ef}	73^{fg}	6.7^{cde}
	K14	69.3^{ab}	98.3^{bcd}	71.0^{f}	6.6^{de}	50.0^{c}	87.0^{de}	72.1^{fg}	6.4^{cdef}
	K21	70.0^{a}	97.3^{cd}	73.9^{de}	6.4^{e}	50.0^{c}	87.0^{de}	79.3^{de}	6.2^{defg}
	K28	68.0^{abcd}	96.7^{cd}	74.3^{cd}	6.5^{de}	50.0^{c}	86.7^{ef}	69.8^{g}	5.8^{g}
	K0	67.0^{cd}	95.0^{d}	68.7^{g}	6.4^{e}	50.0^{c}	86.0^{f}	75.5^{ef}	6.0^{fg}
CV (%)		1.99	2.33	1.42	4.5	1.34	0.46	3.3	5.81
LSD (0.05)		2.26	3.83	1.8	0.5	1.15	0.7	4.42	0.65

FAT: Fungicide application time; 7, 14, 21 and 28 days after the appearance of initial symptoms, respectively. *W0*: Unsprayed; *DTH*: Days to heading; *DTM*: Days to maturity; *PH*: Plant height; *SL*: Spike length; *LSD* (0.05): Least significant difference at 5%. *CV*: Coefficient of variation. For each parameter, means followed by the same letter are not significantly different at P≤0.05.

Regarding plant height, the ANOVA results revealed significant differences (P≤0.0001) among varieties, fungicide application time and their interaction at Anede location. But at Banja location, the ANOVA result revealed significant differences (P≤0.0001) among varieties and their interaction, but not in fungicide application time.

Plant height showed significant variation not only due to varietal differences but also because of fungicide application time and disease pressure. The results of this study indicate that the time of fungicide application, along with varietal differences, contributes to the observed variation in plant height. Fungicide treated plots demonstrated a significant increase in plant height compared to untreated plots. Plant height exhibited significant variation as a result of varietal differences and the time of fungicide application. This is in contrast to the findings of [17] and [29], who reported that the plant height of wheat varieties is mainly influenced by genetic factors and environmental conditions.

Spike length, which determines potential yield, showed significant variation not only due to genetic differences, but also because of fungicide timing and disease pressure. Genetically, on untreated plots, the variety Danda'a exhibits a significantly taller spike length compared to the other two varieties. Regardless of the variety, spike length increased when fungicide was sprayed. When comparing treated and untreated plots of susceptible (Kubsa) and resistant (Wane) varieties with the intermediate material (Danda'a), statistically significant differences were observed (Table 7).

3.3. Effect of Variety and Fungicide Application Time on Yield Traits

Multiple parameters for evaluating number of kernels per spike (NKPS), thousand kernels weight (TKW), and grain yield (GY). The ANOVA results showed that there was a significant interaction effect (P≤0.01) between the wheat variety and fungicide application time for all parameters at both locations (Table 8).

Regardless of location, Wane and Danda'a varieties had significantly higher NKPS (number of kernels per spike) compared to the susceptible variety Kubsa. This clearly indicates the higher susceptibility of Kubsa to stripe rust and the significant impact of this disease on yield parameters. Interestingly, fungicide application significantly increased NKPS, regardless of the different response of the varieties to stripe rust (level of disease resistance) at both locations. However, compared to the resistant variety, the susceptible variety exhibited a significantly higher level of response to the time of fungicide application in terms of yield increase (Table 8). This could be due to the genetic makeup of the varieties. Varietal differences in response to fungicide application have been reported previously; where relatively higher NKPS (number of kernels per spike) were observed in sprayed plots compared to unsprayed plots [34, 16]. Similar trends have been observed at grain yield (GY) in both locations, in the absence of fungicide, grain yield (GY) was significantly lower on the susceptible variety Kubsa (891.0 kg/ha) compared to Danda'a (1737.1 kg/ha) and Wane (1957.9 kg/ha).

There is a higher effect of fungicide application time on the susceptible variety compared to the resistant variety on grain yield (GY). For instance, the application of fungicide on variety Kubsa increased the grain yield (GY) from 891.0 kg/ha in unsprayed plots to 2454.2 kg/ha in plots sprayed 7 days after the appearance of initial symptoms in Aneded. Similarly, in Banja, the GY increased from 609.7 kg/ha in unsprayed plots to 4055.7 kg/ha in plots sprayed 7 days after the appearance of initial symptoms. For the resistant variety Wane, the grain yield increment was from 1957.9 kg/ha (unsprayed plots) to 2711.8 kg/ha (plots sprayed 7 days after the appearance of initial symptoms) in Aneded, and from 3698.6 kg/ha (unsprayed plots) to 4658.8 kg/ha (plots sprayed 7 days after the appearance of initial symptoms) in Banja. This clearly indicates the effectiveness of fungicide application time in reducing the impact of stripe rust on wheat and consequently increasing yield. The other important point regarding the GY is the variation in yield between the two locations. i.e., Banja had a yield that was more than 50% higher compared to Aneded (Table 8). Nevertheless, this difference was not due to potential genetic variation among the varieties. It was rather due to the shortage of rainfall at Aneded during the experimental period.

It should be noted that in the case of managing plant diseases with fungicides, there are direct benefits in terms of yields and yield components [28]. In addition, it is important to determine whether the effectiveness of fungicide use as a disease management tool can be assessed not only in terms of disease control but also in terms of increasing final crop yields. Fungicides inhibit the breakdown of chlorophyll, which allows plants to retain their leaves for a longer period and absorb more nutrients during late developmental stages. This, in turn, helps protect the potential yield of wheat [37]. Fungicides have also stabilized and increased the yield of cereals by reducing disease pressure and helping plants maintain vegetation throughout the grain filling stage [35]. To that end, the use of Rex Duo Fungicide has been shown to increase wheat grain yields in several trials conducted in various areas [7, 21].

Table 8*. Effect of variety and fungicide application time on yield traits.*

Treatments		Yield variables in two locations					
		Aneded			Banja		
Variety	FAT	NKPS	TKW (g)	GY (kg/ha)	NKPS	TKW (g)	GY (kg/ha)
Wane	W7	41.2[a]	39.04[a]	2711.8[a]	50.7[a]	48.70[a]	4648.8[a]
	W14	39.1[abc]	38.20[ab]	2291.4[bcd]	49.3[ab]	45.82[ab]	3999.7[abc]
	W21	38.1[abc]	36.40[abc]	2077.1[def]	47.0[abc]	42.70[bcd]	3943.9[abc]
	W28	37.4[bcd]	34.60[bcd]	2029.0[def]	43.9[bc]	39.20[cd]	3903.9[bc]
	W0	35.8[bcde]	30.30[ef]	1957.9[defg]	41.86[c]	39.10[cd]	3698.6[c]
Danda’a	D7	40.3[ab]	38.14[ab]	2552.6[ab]	49.8[ab]	45.98[ab]	4556.4[ab]
	D14	38.8[abc]	36.90[abc]	2126.5[cde]	46.03[abc]	45.10[ab]	4071.5[abc]
	D21	38.3[abc]	36.70[abc]	1876.2[efg]	43.9[bcd]	44.80[ab]	3965.2[abc]
	D28	38.7[abc]	33.20[cdef]	1783.3[efg]	42.1[cd]	38.30[d]	3893.5[bc]
	D0	31.3[ef]	29.60[f]	1737.1[fg]	38.3[de]	29.30[e]	2938.6[d]
Kubsa	K7	35.6[cde]	36.90[abc]	2454.2[abc]	46.4[abc]	43.00[bc]	4055.7[abc]
	K14	32.2[ef]	35.30[abcd]	2068.3[def]	41.9[c]	41.43[bcd]	3878.[5bc]

Treatments		Yield variables in two locations					
		Aneded			Banja		
Variety	FAT	NKPS	TKW (g)	GY (kg/ha)	NKPS	TKW (g)	GY (kg/ha)
	K21	29.4^{f}	34.40^{bcde}	1864.8^{efg}	35.57^{d}	38.98^{cd}	3765.6^{c}
	K28	33.2^{def}	31.60^{def}	1637.0g	29.9^{d}	32.89^{e}	2408.2^{d}
	K0	24.7^{g}	19.80^{g}	891.0^{h}	7.77^{e}	23.80^{f}	609.7^{e}
CV (%)		4.2	3.98	5.9	5.95	3.9	6.6
LSD		4.5	4.1	357.6	4.8	4.71	719.8

FAT: Fungicide application time; *W7, W14, W21* and *W28* sprayed every 7, 14, 21 and 28 days after the appearance of initial symptoms, respectively. *W0*: Unsprayed; *NKPS*: Number of kernels per spike; *TKW*: Thousand kernel weight; *GY*: Grain yield. *LSD (0.05)*: Least significant difference at 5%. *CV*: Coefficient of variation. For each parameter, means followed by the same letter are not significantly different at P=0.05.

The results of the current study provide clear evidence that fungicides are becoming essential for wheat production in Ethiopia, especially when susceptible and/or moderately susceptible varieties are grown in areas where stripe rust is a significant issue. The integration of crop variety and fungicide application has been found to suppress disease and increase crop yield attributes, as reported by [14], and [21] in their studies. The application of the fungicide significantly decreased the severity of the disease and increased the yield parameters when compared to unsprayed plots, as reported by [15] and [32].

4. Conclusion

All three wheat varieties supplemented with foliar spray application fungicides had distinct effect in reducing stripe rust disease epidemics at the study area. In the present study, stripe rust disease resulted in a significant reduction in grain yield, thousand kernel weight, and the number of kernels per spike in untreated plots. The study not only quantified the impact of stripe rust on grain yield but also confirmed the importance of fungicide application timing and its combination with host resistance in reducing stripe rust pressure on wheat. The most effective management approach involves using varieties with varying levels of resistance to stripe rust diseases and promptly applying Rex® Dou after the appearance of disease symptoms. Unsprayed plots of all varieties exhibited the highest rust severity and AUDPC, leading to lower yields compared to the sprayed ones. Therefore, establishing a vigilant disease monitoring system and promptly applying fungicides will be crucial for improving crop productivity.

Abbreviations

AUDPC	Area Under Disease Progress Curve
CV	Coefficient Variance
GY	Grain Yield
LSD	Least Significant Difference
NKPS	Number of Kernels per Spike
TKW	Thousand Kernel Weight

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Conflicts of Interest

The author declares no conflicts of interest.

References

[1] Abdennour, S., Sahbi, F., & Houcine, B. (2018). Yellow rust effects on grain yield, and yield components of some spring bread wheat cultivars under rainfed conditions. *World J. Agric. Res*, *6*(2), 65-69.

[2] Ahmed, A. U., Bakr, M. A., Chowdhury, J. A., & Sarkar, M. A. (2006). Efficacy of six fungicides in controlling rust (Uromyces fabae) disease of lentil (Lens culinaris). *Bangladesh J. Plant Pathol*, *22*(1&2), 39-40.

[3] Alemu, W., & Fininsa, C. (2016). Effects of environment on wheat varieties' Yellow Rust resistance, yield and yield related traits in South-Eastern Ethiopia. *Science Publishing Group. Plant*, *4*(3), 14-22.

[4] Alemu, W., & Mideksa, T. (2016). Verification and evaluation of fungicides efficacy against wheat rust diseases on bread wheat (Triticum aestivum L.) in the Highlands of Bale, Southeastern Ethiopia. *International Journal of Research*, *2*(9), 35-40.

[5] Ali, S., Gladieux, P., Rahman, H., Saqib, M. S., Fiaz, M., Ahmad, H., Leconte, M., Gautier, A., Justesen, A. F., & Hovmøller, M. S. (2014). Inferring the contribution of sexual reproduction, migration and off‐season survival to the temporal maintenance of microbial populations: A case study on the wheat fungal pathogen P uccinia striiformis f. sp. tritici. *Molecular Ecology*, *23*(3), 603-617.

[6] Asnakew, A. (2021). Assessment for the distribution of yellow rust at lemo, misha and Duna districts of Hadiya zone. *Int. J. Adv. Res. Biol. Sci.*, *8*(9), 65-71.

[7] Ayele, A., Chala, A., & Shikur, E. (2019). Effect of varieties, fungicides and application frequencies to wheat yellow rust disease (Puccinia striiformis f. sp. tritici) management in Arsi highlands of Ethiopia. *American Journal of BioScience*, *7*(6), 113-122.

[8] Badebo, A., Fehrmann, H., & Yahyuoui, A. (2008). Status of Wheat Yellow Rust (Puccinia striiformis) Races and their Virulences in major Wheat Growing areas of Ethiopia. *Pest Managment Journal of Ethiopia*, *12*, 1-7.

[9] Beard, C., Jayasena, K., Thomas, G., & Loughman, R. (2006). Managing stem rust of wheat. *Managing Stem Rust of Wheat.*, *73*.

[10] Campbell, C. L., & Madden, L. V. (1990). Temporal analysis of epidemics II: Advanced topics. *Introduction to Plant Disease Epidemiology*, 203-251.

[11] Chen, X. (2013). *High-temperature adult-plant resistance, key for sustainable control of stripe rust*.

[12] Dembel, W. (2014). Epidemics of pucciniastriiformis f. Sp. Tritici in arsi and west arsi zones of ethiopia in 2010 and identification of effective resistance genes. *Journal of Natural Sciences Research*, *4*(7), 2224-3186.

[13] Dimmock, J., & Gooding, M. J. (2002). The influence of foliar diseases, and their control by fungicides, on the protein concentration in wheat grain: a review. *The Journal of Agricultural Science*, *138*(4), 349-366.

[14] Foster, A. J., Lollato, R., Vandeveer, M., & De Wolf, E. D. (2017). Value of fungicide application in wheat production in Southwest Kansas. *Kansas Agricultural Experiment Station Research Reports*, *3*(5), 3.

[15] Gomes, C., Costa, R., Almeida, A. S., Coutinho, J., Pinheiro, N., Coco, J., Costa, A., & Maçãs, B. (2016). Septoria leaf blotch and yellow rust control by: fungicide application opportunity and genetic response of bread wheat varieties. *Emirates Journal of Food and Agriculture*, 493-500.

[16] Hailu, D., & Fininsa, C. (2007). Epidemics of stripe rust (Puccinia striiformis) on common wheat (Triticum aestivum) in the highlands of Bale, southeastern Ethiopia. *Crop Protection*, *26*(8), 1209-1218.

[17] Jemal, A., Tamado, T., & Firdissa, E. (2015). Response of bread wheat (Triticum aestivum L.) varieties to seeding rates at Kulumsa, south eastern Ethiopia. *Asian Journal of Plant Sciences*, *14*(2), 50-58.

[18] Jin, Y., Szabo, L. J., Rouse, M. N., Fetch Jr, T., Pretorius, Z. A., Wanyera, R., & Njau, P. (2009). Detection of virulence to resistance gene Sr36 within the TTKS race lineage of Puccinia graminis f. sp. tritici. *Plant Disease*, *93*(4), 367-370.

[19] Line, R. F. (2002). Stripe rust of wheat and barley in North America: a retrospective historical review. *Annual Review of Phytopathology*, *40*(1), 75-118.

[20] McNeal, F. H., Konzak, C. F., Smith, E. P., Tate, W. S., & Russell, T. S. (1971). *A uniform system for recording and processing cereal research data. Agricultural Research Service bulletin 34-121*. United States Department of Agriculture Washington.

[21] Mengesha, G. G. (2020). Management of yellow rust (Puccinia striiformis f. sp. tritici) and stem rust (Puccinia graminis f. sp tritici) of bread wheat through host resistance and fungicide application in Southern Ethiopia. *Cogent Food & Agriculture*, *6*(1), 1739493.

[22] Mengistu, H., Getaneh, W., Yeshi, A., Rebka, D., & Ayele, B. (1991). Wheat pathology research in Ethiopia. *Wheat Research in Ethiopia: A Historical Perspective. Addis Ababa. IAR/CIMMYT*, *173217*.

[23] Nigus, M., Shimelis, H., Mathew, I., & Abady, S. (2022). Wheat production in the highlands of Eastern Ethiopia: opportunities, challenges and coping strategies of rust diseases. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, *72*(1), 563-575.

[24] Olana, A. (2022). *Screening of bread wheat (Triticum aestivum L.) genotypes resistance to yellow rust along with grain yield*.

[25] Olivera, P., Newcomb, M., Szabo, L. J., Rouse, M., Johnson, J., Gale, S., Luster, D. G., Hodson, D., Cox, J. A., & Burgin, L. (2015). Phenotypic and genotypic characterization of race TKTTF of Puccinia graminis f. sp. tritici that caused a wheat stem rust epidemic in southern Ethiopia in 2013-14. *Phytopathology*, *105*(7), 917-928.

[26] Peterson, R. F., Campbell, A. B., & Hannah, A. E. (1948). A diagrammatic scale for estimating rust intensity on leaves and stems of cereals. *Canadian Journal of Research*, *26*(5), 496-500.

[27] Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L., & Chookolingo, B. (2018). An open-access dataset of crop production by farm size from agricultural censuses and surveys. *Data in Brief*, *19*, 1970-1988.

[28] Rodrigo, S., Cuello-Hormigo, B., Gomes, C., Santamaria, O., Costa, R., & Poblaciones, M. J. (2015). Influence of fungicide treatments on disease severity caused by Zymoseptoria tritici, and on grain yield and quality parameters of bread-making wheat under Mediterranean conditions. *European Journal of Plant Pathology*, *141*, 99-109.

[29] Shahwani, A. R., Baloch, S. U., Baloch, S. K., Mengal, B., Bashir, W., Baloch, H. N., Baloch, R. A., Sial, A. H., Sabiel, S. A. I., & Razzaq, K. (2014). Influence of seed size on germinability and grain yield of wheat (Triticum aestivum L.) varieties. *Journal of Natural Sciences Research*, *4*(23), 147-155.

[30] Shahzad, A., Ahmad, M., Iqbal, M., Ahmed, I., & Ali, G. M. (2012). Evaluation of wheat landrace genotypes for salinity tolerance at vegetative stage by using morphological and molecular markers. *Genetics and Molecular Research*, *11*(1), 679-692.

[31] Singh, R. P., William, H. M., Huerta-Espino, J., & Rosewarne, G. (2004). Wheat rust in Asia: meeting the challenges with old and new technologies. *Proceedings of the 4th International Crop Science Congress*, *26*, 1-13.

[32] Sylvester, P. N., & Kleczewski, N. M. (2018). Evaluation of foliar fungicide programs in mid-Atlantic winter wheat production systems. *Crop Protection*, *103*, 103-110.

[33] Tadesse, K., Ayalew, A., & Badebo, A. (2010). Effect of fungicide on the development of wheat stem rust and yield of wheat varieties in highlands of Ethiopia. *African Crop Science Journal*, *18*(1). https://doi.org/10.4314/acsj.v18i1.54194

[34] Tesfaye, Y., Teshome, G., & Asefa, K. (n. d.). *Evaluation of Fungicide Efficacy against Stripe Rusts (Puccinia Striiformis F. Sp) at Guji Zone Southern Ethiopia*.

[35] Wiik, L., & Rosenqvist, H. (2010). The economics of fungicide use in winter wheat in southern Sweden. *Crop Protection*, *29*(1), 11-19.

[36] Wilcoxson, R. D., Skovmand, B., & Atif, A. H. (1975). Evaluation of wheat cultivars for ability to retard development of stem rust. *Annals of Applied Biology*, *80*(3), 275-281.

[37] Zhang, Y.-J., Zhang, X., Chen, C.-J., Zhou, M.-G., & Wang, H.-C. (2010). Effects of fungicides JS399-19, azoxystrobin, tebuconazloe, and carbendazim on the physiological and biochemical indices and grain yield of winter wheat. *Pesticide Biochemistry and Physiology*, *98*(2), 151-157.

[38] Zheng, W., Huang, L., Huang, J., Wang, X., Chen, X., Zhao, J., Guo, J., Zhuang, H., Qiu, C., & Liu, J. (2013). High genome heterozygosity and endemic genetic recombination in the wheat stripe rust fungus. *Nature Communications*, *4*(1), 2673.