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Research Article

ASSESSMENT OF FUNGAL DISEASES AND THEIR IMPACT ON YIELD IN WHEAT VARIETIES UNDER FUNGICIDE TREATMENT

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ABSTRACT

The present study evaluated the impact of fungal diseases on the yield and traits of 20 spring wheat cultivars grown in Pakistan under fungicide-treated and untreated conditions, using a randomized complete block design. Significant differences were observed among treatments and varieties for most traits, except grains/spike. The treatment × variety interaction was significant only for 1000-grain weight. Disease severity data indicated that yellow rust, powdery mildew, spot blotch, and Karnal bunt were the most prevalent diseases in the area. Fungicide application reduced disease severity and enhanced plant height (3.18%), spike weight (2.32%), 1000-grain weight (3.09%), grains/spike (1.61%), biological yield (3.49%), and grain yield (4.75%). Among the cultivars, Wadan-17, Pirsabak-15, Zincol-16, and Shahkar-13 exhibited resistance to yellow rust. Moreover, NIFA Lalma and Shahkar-13 showed resistance to powdery mildew, while Shahkar-13 demonstrated resistance to spot blotch. However, none of the tested varieties were resistant to Karnal bunt. Shahkar-13, Khaista-17, and Zincol-16 consistently exhibited high grain yields with minimal reductions under untreated conditions: Shahkar-13 (6025 vs. 5992 kg/ha), Khaista-17 (6333 vs. 6267 kg/ha), and Zincol-16 (6075 vs. 5975 kg/ha). Correlation analysis revealed a negative association between fungal diseases and yield-related traits. Grain yield was significantly negatively correlated with yellow rust (r = -0.37), powdery mildew (r = -0.28), and Karnal bunt (r = -0.35). The findings highlight Khaista-17, Pirsabak-15, Paseena-17, and Zincol-16 as high-yielding, disease-resistant varieties. Combining fungicides with resistant cultivars offers a sustainable strategy to boost wheat production in disease-prone regions and support food security.

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INTRODUCTION

Wheat (*Triticum aestivum* L.), a member of the Poaceae family, is the most widely cultivated cereal crop globally. It plays a pivotal role in food security by providing essential calories, carbohydrates, and proteins to billions of people (Cuong et al., 2020; Wei et al., 2022). Historically, it is one of the earliest domesticated crops, having been cultivated for over 10,000 years. Wheat remains a staple food for populations in Europe, West Asia, North Africa, and South Asia, reflecting its adaptability to diverse climates and soil types (Curtis et al., 2002). Among wheat species, *T. aestivum* is dominant in cultivation due to its hexaploid genome, which offers genetic plasticity, making it suitable for modern breeding programs aimed at improving yield and resilience (Shewry and Hey, 2015). Globally, wheat contributes approximately 44% of cereal consumption, underscoring its significance in the production of various food products, such as bread, pasta, noodles, and confectioneries (Lark et al., 2021).

The global demand for wheat has increased significantly in recent decades, driven by population growth, urbanization, and changing dietary preferences, particularly in developing economies (Pingali, 2007). However, meeting this rising demand presents challenges. Despite efforts to intensify agricultural practices, global wheat production is projected to fall short of future needs (Tilman et al., 2011). Moreover, wheat production is constrained by biotic and abiotic stresses such as drought, heat, and salinity, which are further exacerbated by climate change (Skirycz and Inzé, 2010; Mukhtar et al., 2018; Mukhtar and Saeed, 2024). Biotic stresses, including fungal diseases, remain a significant threat to wheat productivity worldwide, causing yield losses of up to 20-30% annually (Rana, 2020; Hussain et al., 2022; Ahmad et al., 2024).

In Pakistan, wheat holds a vital position in the agricultural economy, serving as a staple food for most of the population. The country ranks as the sixth-largest wheat producer globally, contributing significantly to GDP and rural livelihoods (Rana, 2020). Despite its economic importance, wheat production in Pakistan is hindered by multiple factors, including pest infestations, water scarcity, and fungal diseases. Among these fungal diseases, yellow rust (*Puccinia striiformis* f. sp. *tritici*), powdery mildew (*Blumeria graminis* f. sp. *tritici*), spot blotch (*Bipolaris sorokiniana*), and Karnal bunt (*Tilletia indica*) are particularly prevalent in the Hazara division of Khyber Pakhtunkhwa (Sardar et al., 2021).

Yellow rust, also known as stripe rust, is one of the most damaging diseases of wheat in cooler, humid climates. It can reduce yields by up to 50% in susceptible cultivars if not managed effectively. Powdery mildew, another common foliar disease, thrives in moderate temperatures and high humidity, primarily affecting the photosynthetic capacity of the flag leaves, which are crucial for grain filling (Curtis et al., 2002). Spot blotch is predominantly a problem in warm, humid regions, causing premature leaf senescence and reduced grain weight. Karnal bunt, a seed-borne disease, not only reduces yield but also affects grain quality, posing challenges for international trade due to quarantine restrictions (Lark et al., 2021).

Breeding disease-resistant wheat varieties is essential to mitigate these challenges. Genetic resources, including advanced breeding lines and landraces, play a pivotal role in enhancing resistance to fungal diseases. Resistance to yellow rust, for instance, is often governed by a combination of race-specific resistance genes (R-genes) and adult plant resistance (APR) genes, which provide durable, broad-spectrum resistance. Powdery mildew resistance is similarly attributed to major genes, such as Pm genes, with ongoing research focusing on identifying novel loci through genome-wide association studies (Wei et al., 2022). Multi-environment testing of wheat genotypes is critical to ensure the stability of resistance and yield performance under diverse agro-climatic conditions.

This study provides genetic insights into fungal disease resistance and yield potential in 20 spring wheat cultivars under both fungicide-treated and non-treated conditions. The results highlight key genetic resources and traits essential for breeding climate-resilient wheat varieties capable of maintaining productivity under evolving biotic and abiotic stresses. These findings are crucial for ensuring food security in Pakistan and other regions that rely heavily on wheat cultivation.

MATERIALS AND METHODS

The current study was conducted at the Agricultural Research Station, Baffa Mansehra, Pakistan, with twenty wheat varieties (Table 1) planted under fungicide-treated and non-treated conditions as separate experiments. In the fungicide-treated experiment, Tilt (Propiconazole, 25% EC), a broad-spectrum systemic fungicide, was sprayed three times at two-week intervals, specifically at 85, 100, and 115 days after seeding. The experiment was laid out in a randomized complete block design (RCBD) with two replications in each experiment.

Disease data collection

Yellow rust

The severity of yellow rust was assessed for 20 wheat varieties under both fungicide-treated and non-treated conditions. Disease severity was recorded as the percentage of rust infection on the plants according to the modified Cobb scale (Peterson et al., 1948). The coefficient of infection (CI) was calculated by multiplying the infection percentage by the response value. Disease resistance ranking followed the modified Doling (1965) scale, adopted by the Pakistan Agricultural Research Council (PARC) in 1982, and was used to classify genotypes based on their resistance.

Table 1. List of wheat genotypes used in the experiment.

S. No.	Variety	Breeding Centre
1	Paseena-17	CCRI, Nowshehra
2	Khaista-17	CCRI, Nowshehra
3	Wadan-17	CCRI, Nowshehra
4	Kohat-17	BARS, Kohat
5	Israr Shaheed	ARI, DI Khan
6	Shahid-17	ARI, DI Khan
7	Anaj-17	WRI, AARI-FSD
8	Ihsan-16	BARI, Chakwal
9	Borlaug-16	NARC, Islamabad
10	Zincol-16	NARC, Islamabad
11	Ujala-16	WRI, AARI-FSD
12	NIFA Lalma	NIFA, Peshawar
13	Pirsabak-15	CCRI, Nowshehra
14	Pakhtunkhwa-15	CCRI, Nowshehra
15	Pirsabak-13	CCRI, Nowshehra
16	Shahkar-13	CCRI, Nowshehra
17	Pakistan-13	NARC, Islamabad
18	Pirsabak-08	CCRI, Nowshehra
19	Faisalabad-08	WRI, AARI-FSD
20	Pirsabak-05	CCRI, Nowshehra

Powdery mildew

Powdery mildew severity was recorded using the double-digit (00-99) scale, adapted from Saari and Prescott (1975). The first digit (D1) represented the height of disease progression within the plant, and the second digit (D2) indicated the percentage of the leaf area affected.

Spot blotch

Spot blotch (SB) severity was rated on each genotype using the double-digit (00-99) method according to Neupane et al. (2007). The first and second digits indicate the percentage area affected by disease on the flag leaf and below the flag leaf, respectively. Final SB severity was scored for each variety in each experiment.

Karnal bunt

Karnal bunt incidence was evaluated by collecting 1,000 seeds per variety after harvest. The seeds were visually examined under a stereoscopic binocular microscope. Healthy seeds were identified by their smooth coat and light brown or yellow color, while infected seeds exhibited wrinkled coats or visible fungal growth. To confirm infection, seeds were tested using the soaking method (Dipali et al., 2013), where samples were immersed in a 0.2% NaOH solution for 24 h at 20°C. Infected seeds turned black, confirming Karnal bunt infection.

Yield parameters

Data were recorded on plant height in centimeters using a measuring tape, from the tip of the spike to the ground. Ten spikes were randomly selected from each genotype in each replication and weighed to obtain spike weight (g). This was followed by threshing and counting 1,000 grains to determine the 1,000-grain weight (g). After threshing a single spike, the number of grains obtained was counted to record the grains/spike (no.). Biological yield (kg/ha) was recorded after harvesting each plot and weighed to obtain biomass data. Similarly, grain yield (kg/ha) data were collected after sun-drying for a week and threshing each bundle separately.

Statistical analysis

The data collected on different varieties were analyzed using variance analysis techniques suitable for the RCBD design across two treatments. To assess the impact of fungicide treatments, independent analyses under fungicide-treated and non-treated conditions were also performed. Means were separated using the LSD test at the 5% level of probability.

RESULTS AND DISCUSSION

Prevalence of fungal diseases in wheat

The results of the present study revealed that four diseases, including spot blotch, powdery mildew, yellow rust, and Karnal bunt, were dominant in the examined region. Yellow rust, powdery mildew, and spot blotch were identified as common diseases affecting wheat crops in varying intensities, from mild to severe, depending on environmental conditions and the genotype cultivated. Disease data for yellow rust, powdery mildew, and spot blotch were recorded at the adult stage in the field, while Karnal bunt data were collected after harvest in the lab for both fungicide-treated and non-treated conditions (Figure 1 and 2).

Effect of fungicide treatment on disease control

Fungicide treatment significantly controlled the spread of all fungal diseases, namely yellow rust, powdery mildew, spot blotch, and Karnal bunt. The mean data comparing non-treated vs. treated conditions showed a decrease in disease severity by 89.5%, 88.0%, 87.0%, and 80% for yellow rust, powdery mildew, spot blotch, and Karnal bunt, respectively, providing favorable conditions for the assessment of wheat quality in relation to fungal diseases. Similar findings were observed in previous studies; for example, Xi et al. (2015) reported that fungicide application positively impacted stripe rust control in field trials, resulting in a yield increase of 15-23% and an 8-10% increase in thousand kernel weight (TKW). Reid and Swart (2004) also noted that fungicide use to control yellow rust led to a yield increase of up to 41%, with thousand grain weight rising by 33% in the USA.

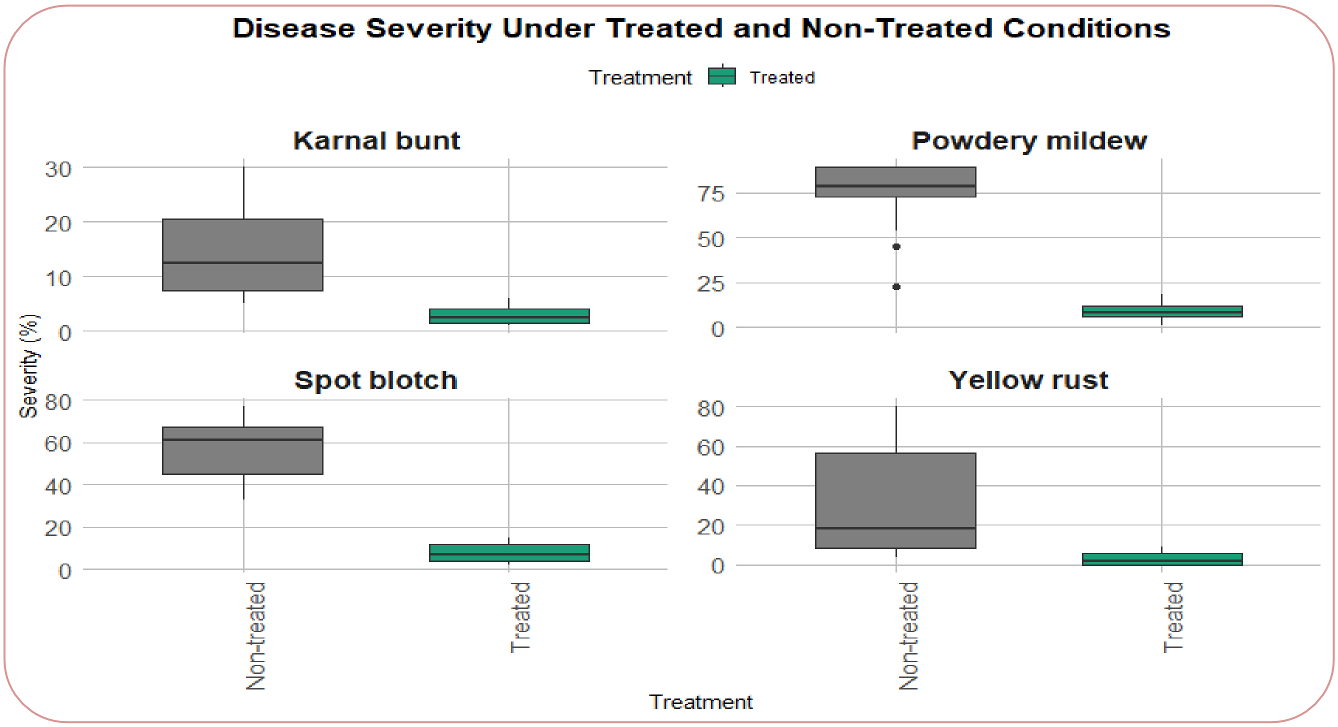

Figure 1. Box plot showing disease severity (%) of different diseases under fungicide treated and non-treated conditions.

Disease severity of yellow rust under non-treated conditions

Under non-treated conditions, disease severity data for yellow rust indicated varying levels of susceptibility among wheat varieties. The susceptible (S) varieties Faisalabad-08 and Ihsan-16 exhibited the highest disease severity, with 80% each. Moderately susceptible-susceptible (MSS) varieties included Pirsabak-08 (70%), Pakhtunkhwa-15, and Israr Shaheed (63% each). Moderately susceptible (MS) varieties were Shahid-17 (54%) and Kohat-17 (42%). The moderately resistant-moderately susceptible (MRMS) group comprised Ujala-16 (36%) and NIFA Lalma (24%). Moderately resistant (MR) varieties included Paseena-17, Borlaug-16, Wadan-17, Pirsabak-05, and Pakistan-13, each showing 12% disease severity. Finally, the resistant (R) varieties demonstrated the lowest severity levels: Pirsabak-13 (9%), Zincol-16 (6%), Shahkar-13 (6%), Khaista-17 (6%), Anaj-17 (6%), and Pirsabak-15 (4%).

Powdery mildew disease severity

For powdery mildew, the disease severity data revealed varying levels of susceptibility among the tested varieties. The HS varieties, with disease severity values above 61%, included Pirsabak-15, Paseena-17, Pirsabak-05, Ihsan-16, Borlaug-16, Israr Shaheed, Wadan-17, Ujala-16, Faisalabad-08, Kohat-17, Zincol-16, Khaista-17, Anaj-17, Pakhtunkhwa-15, and Shahid-17. The susceptible varieties were Pirsabak-13 (56%) and Pirsabak-08 (54%). Pakistan-13 showed moderate susceptibility with a disease severity value of 45%, while NIFA Lalma and Shahkar-13 demonstrated moderate resistance, each with a disease severity value of 23%.

Spot blotch disease severity

Under non-treated conditions for spot blotch, the varieties exhibiting disease severity values above 61% were classified as highly susceptible, including Anaj-17, Israr Shaheed, Shahid-17, Kohat-17, Wadan-17, NIFA Lalma, Pirsabak-05, Khaista-17, Paseena-17, and Ujala-16. Susceptible varieties included Pakistan-13, Ihsan-16, and Borlaug-16, each showing 56% severity. Moderately susceptible varieties, with severity values ranging from 31% to 50%, were Zincol-16, Faisalabad-08, Pirsabak-15, Pakhtunkhwa-15, Pirsabak-08, Shahkar-13, and Pirsabak-13.

The global epidemic of spot blotch in South Asia is a significant concern (Kumar et al., 2002; Singh et al., 2002). The pathogen responsible for spot blotch, *Tilletia indica*, can spread through air, seed, or soil, with the incidence and severity of the disease being largely dependent on favorable environmental conditions for fungal growth (Kashyap et al., 2011; Bishwas et al., 2013). The disease thrives in cold and humid climates, which are conducive to infection by teliospores, the pathogen's infectious form. Despite unfavorable conditions, teliospores exhibit remarkable viability and durability (Carris et al., 2006).

Karnal bunt disease incidence

Under non-treated conditions for KB, the following varieties were identified based on their susceptibility levels: Highly susceptible varieties, with an incidence greater than 10%, included Pirsabak-08, Pirsabak-15, Ihsan-16, Shahid-17, Pirsabak-05, Anaj-17, Paseena-17, Shahkar-13, Pakhtunkhwa-15, Kohat-17, and Zincol-16. Susceptible varieties, with an incidence between 5-10%, included Wadan-17, Pakistan-13, Borlaug-16, Khaista-17, Pirsabak-13, NIFA Lalma, Israr Shaheed, Faisalabad-08, and Ujala-16.

Previously, Karnal bunt disease was recorded as medium and low in regions such as Mansehra, Peshawar, Abbottabad, Attock, and Nowshera. Areas with very low disease incidence were found to have low humidity, little rainfall, or wheat rotation with other crops (Haq et al., 2002). Rattu et al. (2011) observed the highest prevalence (60%) and disease index (21.8%) for spot blotch, followed by leaf rust, yellow rust, and powdery mildew.

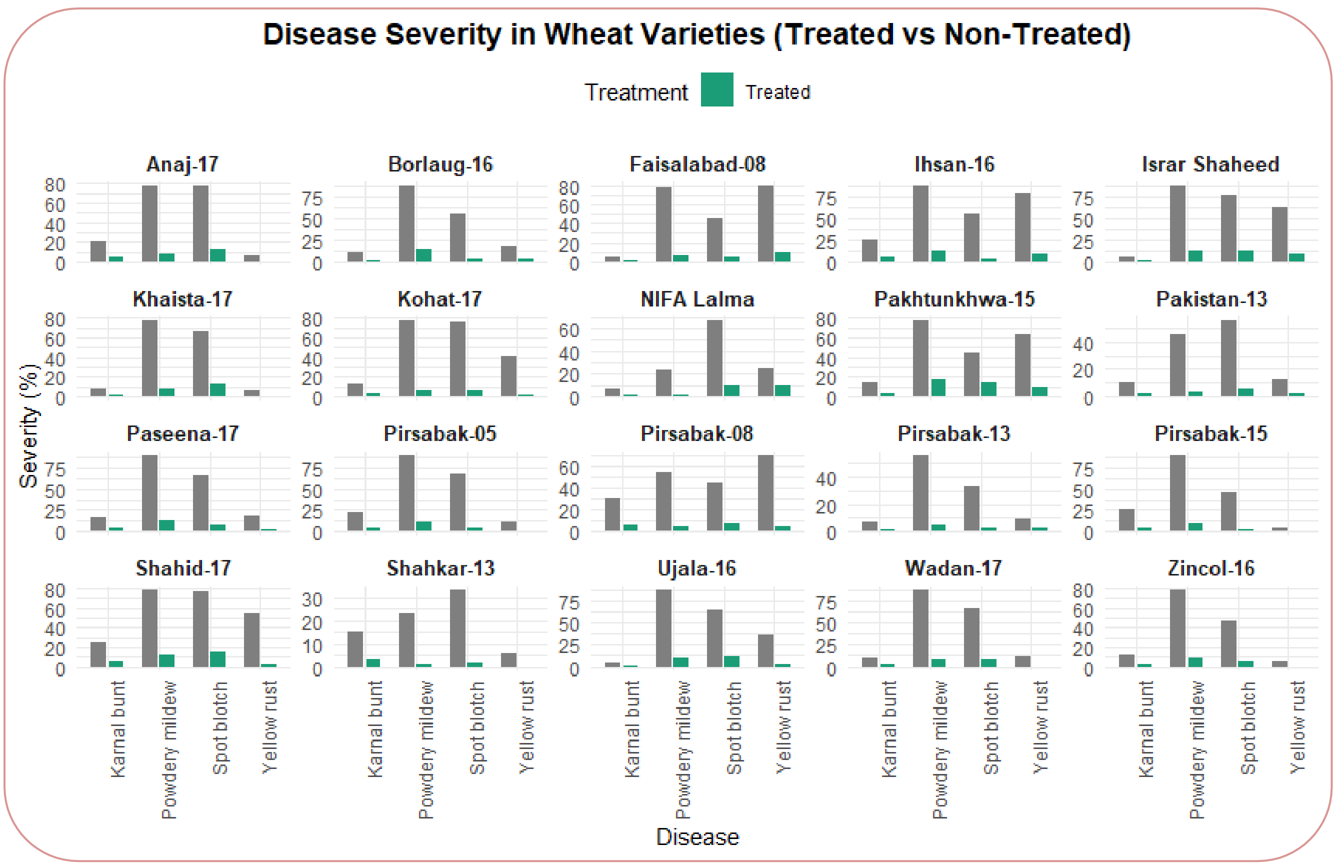

Figure 2. Disease severity (%) of 20 wheat varieties under fungicide treated and non-treated and non-treated conditions.

Correlation of disease data with yield traits

The correlation coefficients of disease severity data for yellow rust, powdery mildew, spot blotch, and Karnal bunt with yield and associated traits under fungicide-treated and non-treated conditions are presented in Table 2 and Figure 3.

Under non-treated conditions, yellow rust (YR) showed a significant positive correlation with days to heading (r = 0.49). Powdery mildew (PMD) exhibited significant positive correlations with plant height (r = 0.58) and spot blotch (SB) (r = 0.33). However, PMD displayed significant negative correlations with spike weight (r = -0.47), grain weight per spike (r = -0.52), grains/spike (r = -0.56), biological yield (r = -0.33), and grain yield (r = -0.32). Similarly, SB showed significant negative correlations with spike weight (r = -0.47), grain weight per spike (r = -0.48), and grains/spike (r = -0.33). Karnal bunt (KB) exhibited significant negative correlations with tillers per square meter (r = -0.40), biological yield (r = -0.31), grain yield (r = -0.35), and harvest index (r = -0.34).

Under fungicide-treated conditions, YR did not show any significant correlations with the evaluated traits. PMD displayed a significant positive correlation with plant height (r = 0.58) but significant negative correlations with biological yield (r = -0.33) and grain yield (r = -0.32). SB exhibited a positive correlation with plant height (r = 0.41) but significant negative correlations with days to maturity (r = -0.37) and spike length (r = -0.32). KB showed a significant positive correlation with days to heading (r = 0.46) and significant negative correlations with tillers per square meter (r = -0.41), grain yield (r = -0.35), and harvest index (r = -0.34).

Table 2. Correlation coefficient among disease and yield traits of 20 wheat genotypes under fungicide treated and non-treated condition.

Traits	Treated				Non-treated			
	YR	PMD	SB	KB	YR	PMD	SB	KB
Yellow rust (YR)	---	---	---	---	---	---	---	---
Powdery mildew (PMD)	0.18	---	---	---	0.17	---	---	---
Spot blotch (SB)	0.18	**0.33**	---	---	0.04	**0.38**	---	---
Karnal bunt (KB)	-0.18	0.18	-0.06	---	0.15	0.12	-0.04	---
Plant height	-0.12	**0.58**	0.20	-0.10	-0.29	**0.42**	**0.41**	-0.11
Spike weight	-0.30	-0.47	-0.47	-0.01	-0.29	-0.30	-0.29	-0.01
1000 grain weight	0.03	0.25	-0.18	0.00	-0.01	**0.41**	-0.08	0.03
Grains/spike	-0.08	**-0.56**	**-0.33**	0.11	-0.27	**-0.63**	-0.26	0.10
Biological yield	-0.16	**-0.33**	-0.10	**-0.31**	**-0.42**	**-0.33**	0.17	-0.30
Grain yield	-0.09	**-0.32**	-0.12	**-0.35**	**-0.37**	-0.28	0.14	**-0.35**

Correlation (r) bold values show significant correlations at $P \leq 0.05$.

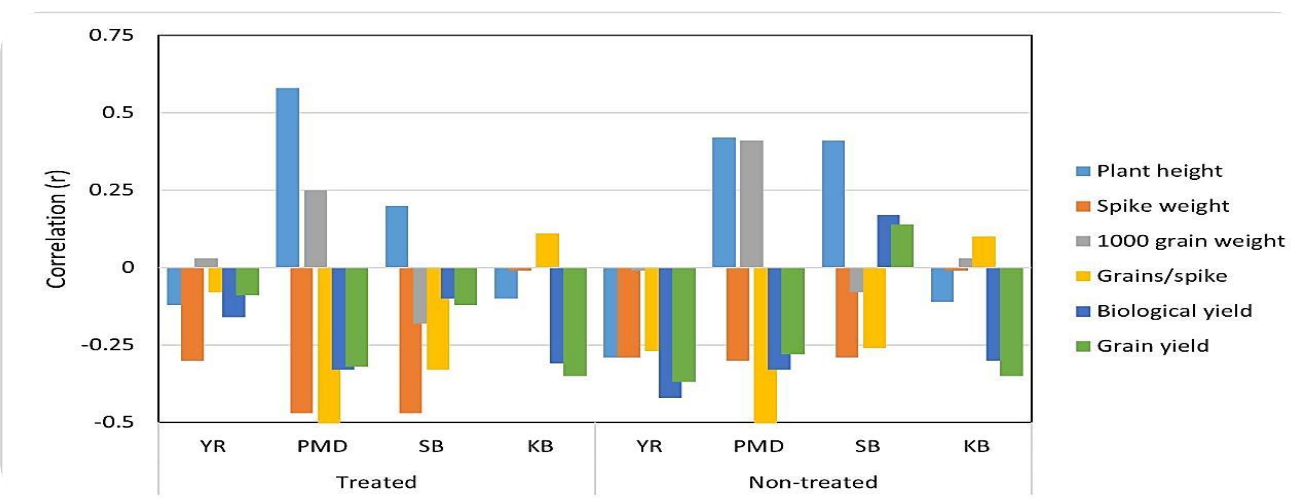

Figure 3. Correlation coefficient among different diseases with yield and associated traits.

Plant height (cm)

The application of fungicides in this study demonstrated beneficial effects on plant height under disease-free conditions, although these effects were not always statistically significant compared to untreated conditions. Table 3 summarizes the combined and independent mean sum of squares for plant height under fungicide-treated and untreated conditions. A combined analysis of variance revealed highly significant differences across varieties and treatments, with independent analyses also showing significant differences in plant height among varieties under both conditions. Figure 4 presents the mean plant height values for 20 wheat varieties under fungicide-treated and untreated conditions.

Significant variation in plant height was observed among genotypes under treated conditions. Across treatments, plant height ranged from 73 cm to 103.3 cm. The minimum plant height was recorded in Pirsabak-08 (73 cm), while the maximum was observed in Wadan-17 (103.3 cm). Fungicide-treated varieties generally exhibited greater plant height compared to untreated varieties, with an overall mean of 90.9 cm under treated conditions versus 88.1 cm under untreated conditions.

These results align with the findings of Mukhtarullah et al. (2016), who reported plant heights ranging from 61 to 107 cm, and Laghari et al. (2011), who observed plant heights between 57.6 and 94.0 cm. Under fungicide-treated conditions, the maximum plant height was recorded in Wadan-17, Pirsabak-05, and Pakhtunkhwa-15 (103.3 cm each), while the minimum was observed in Pirsabak-08 (73 cm). In untreated conditions, Wadan-17 (102 cm) exhibited the maximum height, while Pirsabak-08 (69 cm) had the minimum. However, Masood et al. (2005) reported a broader range of plant heights (86 to 167 cm), contrasting with the narrower range observed in this study.

Hossain et al. (2021) and Hossain et al. (2011) also supported these findings, reporting plant height values between 93.80 and 94.03 cm, which indicate that fungicide-treated varieties generally exhibited greater plant height compared to untreated conditions. These results underscore the role of fungicide application in enhancing plant development under controlled conditions.

Table 3. Means squares for various yield and associated traits as affected by fungicide treatment

Traits	Combined					
	Blocks (df=1)	Treatments (df=1)	Varieties (df=19)	T×V (df=19)	Error (df=39)	CV (%)
Plant height	1.392	157. **	280.135**	1.883^{ns}	4.182	4.51
Spike weight	0.027	0.083**	0.625**	0.002^{ns}	0.001	2.73
1000-grain weight	4.802	32.258**	41.290**	0.683**	0.043	2.21
Grains/spike	1.128	0.528^{ns}	358.948**	0.512^{ns}	4.261	3.37
Biological yield	1402.81	4230620**	2.920**	106305^{ns}	602053	11.4
Grain yield	38019	106678**	5095017**	25867^{ns}	68441	12.76

Traits	Treated			Non-treated		
	Blocks (df=1)	Varieties (df=19)	Error (df=19)	Blocks (df=1)	Varieties (df=19)	Error (df=19)
Plant height	75.076	142.168**	0.341	75.076	139.851**	0.341
Spike weight	0.004	0.309**	0.001	0.019	0.318**	0.001
1000-grain weight	2.401	19.987**	0.044	2.401	21.985**	0.044
Grains/spike	0.900	178.916**	4.321	0.306	180.544**	4.420
Biological yield	714.025	1.451**	617784	688.900	1.479**	618009
Grain yield	19010	2581749**	70235	19010	2539135**	70250

Spike weight (g)

Table 3 presents means sum of square of spike weight under fungicide-treated and non-treated conditions. A combined analysis of variance revealed highly significant differences among varieties, while the variety × treatment interactions and treatment effects were non-significant. However, independent analyses indicated highly significant differences in spike weight across varieties under both conditions.

Figure 4 displays the spike weight of 20 wheat varieties under fungicide-treated and non-treated conditions. Spike weight ranged from 2.31 g to 3.92 g under fungicide-treated conditions, 2.16 g to 3.89 g under non-treated conditions, and 2.23 g to 3.90 g when averaged across treatments. The wheat variety Pakhtunkhwa-15 recorded the lowest spike weight (2.23 g), while Shahkar-13 exhibited the highest (3.90 g).

Under fungicide-treated conditions, Shahkar-13 achieved the maximum spike weight (3.92 g), whereas Pakhtunkhwa-15 had the minimum (2.31 g). Similarly, under non-treated conditions, Shahkar-13 maintained the highest spike weight (3.89 g), while Pakhtunkhwa-15 recorded the lowest (2.16 g). Across both treatments, the mean spike weight was slightly higher in fungicide-treated plants (3.09 g) compared to non-treated plants (3.02 g), indicating a modest improvement under treated conditions.

The observed spike weight values align with findings by Mukhtarullah et al. (2016), who reported values ranging from 2 to 5 g, and Kadege and Lymo (2015), who documented spike weights between 3.03 and 4.92 g. However, Din et al. (2023) reported higher spike weight values (2.73 to 6.93 g), likely reflecting differences in environmental conditions, management practices, or genetic diversity. These discrepancies underscore the importance of evaluating wheat genotypes under specific agro-climatic conditions to identify varieties with superior yield traits.

Overall, these findings confirm that Shahkar-13 consistently exhibits superior spike weight performance under both fungicide-treated and non-treated conditions, making it a promising candidate for breeding programs aimed at improving wheat productivity.

Figure 4. Mean performance of different wheat varieties for yield and associated under fungicide treated and non-treated conditions.

1000-grains weight (g)

Table 3 presents the combined and independent mean sums of squares for 1000-grain weight under fungicide-treated and non-treated conditions. A combined analysis of variance revealed highly significant differences across varieties and treatments for 1000-grain weight, while the variety × treatment interactions showed no significant differences. The independent analysis of variance also indicated highly significant differences among varieties under both conditions.

Figure 4 provides the mean values for 1000-grain weight under fungicide-treated and non-treated conditions. The 1000-grain weight ranged from 33.2 g to 45.3 g under fungicide-treated conditions, 31.4 g to 44.7 g under non-treated conditions, and 32.3 g to 45.0 g across both treatments. The lowest 1000-grain weight was observed in Pakistan-13 (32.3 g), while the highest was recorded for Pirsabak-13 (45.0 g). Across treatments, the mean 1000-grain weight was slightly higher under fungicide-treated conditions (40.0 g) compared to non-treated conditions (38.8 g), indicating a modest improvement in grain weight with fungicide application.

The 1000-grain weight findings in this study (32.3 to 45.3 g) align with the results of Ahmad (2001) and Randhawa et al. (2002), who reported ranges of 28.00 to 50.00 g. Similarly, Pasha and Tehseen (2014) observed 1000-grain weights ranging from 24.28 to 52.7 g and 30.53 to 51.87 g, respectively. These results emphasize the role of genetic factors and environmental conditions in determining grain weight. Varieties such as Pirsabak-13, with higher 1000-grain weights, exhibit potential for improved milling output and higher flour extraction rates, making them suitable candidates for breeding programs focused on enhancing grain quality traits. These findings demonstrate that fungicide treatment has a slight but positive effect on 1000-grain weight in most varieties, with genetic and environmental factors playing a critical role in determining variations in grain weight.

Grains/spike (no.)

Table 3 presents the combined and independent mean sums of squares for grains/spike under fungicide-treated and non-treated conditions. The combined analysis of variance revealed highly significant differences among varieties for grains/spike, while the variety × treatment interactions showed non-significant differences. Independent analysis of variance also indicated highly significant differences among varieties under both fungicide-treated and non-treated conditions.

Figure 4 provides the mean values for grains/spike under fungicide treated and non-treated conditions. The grains/spike ranged from 45 to 89 under fungicide-treated conditions, 45 to 88 under non-treated conditions, and 45 to 89 across both treatments. The lowest number of grains/spike was observed in Ujala-16 (45 grains), while the highest was recorded for Shahkar-13 (89 grains). Across treatments, the mean number of grains/spike was slightly higher under fungicide-treated conditions (63 grains) compared to non-treated conditions (62 grains), indicating a minor difference in the grains/spike due to fungicide application.

The results of the current study regarding grains/spike (45 to 89 grains) align with the results of Aslam et al. (2013), who reported ranges of 59 to 72, and Laghari et al. (2011), who observed lower values ranging from 36.5 to 41.9. These results underline the importance of selecting wheat varieties with higher grains/spike, which can contribute to improved grain yield, as suggested by Biryukov and Lyashok (1983). Fungicide treatment showed minimal effect on grains/spike, but genetic and environmental factors are key in determining the variation observed across wheat varieties.

Biological yield (kg/ha)

Figure 4 presents the mean values for biological yield under both fungicide-treated and fungicide-free conditions. The biological yield ranged from 8,100 kg/ha to 16,942 kg/ha under fungicide-treated conditions, 7,567 kg/ha to 16,408 kg/ha under fungicide-free conditions, and 7,833 kg/ha to 16,608 kg/ha across both treatments. The highest biological yield (16,608 kg/ha) was recorded in NIFA Lalma and Pakistan-13, while Pakhtunkhwa-15 exhibited the lowest biological yield (7,833 kg/ha).

When comparing the two treatments, wheat varieties treated with fungicides showed a higher mean biological yield than untreated varieties (13,631 kg/ha vs. 13,171 kg/ha). Under fungicide-treated conditions, the highest biological yield was achieved by NIFA Lalma and Pakistan-13 (16,942 kg/ha), whereas Pakhtunkhwa-15 recorded the lowest yield (8,100 kg/ha). In fungicide-free conditions, Shahkar-13 achieved the highest biological yield (16,408 kg/ha), while Pakhtunkhwa-15 recorded the lowest yield (7,567 kg/ha).

The biological yield findings of this study (8,100 to 16,942 kg/ha) align with the results reported by Ahmad et al. (2007) and Pasha et al. (2013), who observed similar yield ranges. These results emphasize the influence of both genetic and environmental factors on biological yield, with fungicide treatment providing a modest improvement in most varieties. However, the observed variation among wheat varieties underscores the critical role of genetic potential in determining biological yield.

Grains yield (kg/ha)

Table 3 summarizes the combined and independent mean sums of squares for grain yield under fungicide-treated and non-treated conditions. The combined analysis of variance revealed highly significant differences among treatments and varieties, with non-significant differences observed in the variety × treatment interactions. Similarly, independent analyses of variance for both fungicide-treated and non-treated conditions showed significant differences among varieties for grain yield.

Figure 4 presents the mean performance of 20 wheat varieties for grain yield under fungicide-treated and non-treated conditions. Grain yield ranged from 2,933 kg/ha to 6,367 kg/ha under fungicide-treated conditions, 2,700 kg/ha to 6,267 kg/ha under non-treated conditions, and 2,817 kg/ha to 6,300 kg/ha across both treatments. Among the varieties, Khaista-17 recorded the highest mean grain yield (6,300 kg/ha), while Pakhtunkhwa-15 had the lowest (2,700 kg/ha).

The grain yield data indicated that varieties treated with fungicides yielded higher than those under non-treated conditions, with an average yield of 5,090 kg/ha compared to 4,859 kg/ha, reflecting a net decrease of 4.8% in non-treated conditions. Notably, Khaista-17 consistently exhibited the highest grain yield (6,300 kg/ha), whereas Pakhtunkhwa-15 recorded the lowest (2,700 kg/ha). These findings are consistent with those of Aslam et al. (2013), who reported grain yields ranging from 3,237 to 4,423 kg/ha. The observed variations in grain yield are likely attributable to the genetic characteristics of the varieties, environmental influences, or a combination of both genetic and environmental factors.

CONCLUSIONS

Fungicide application significantly improved wheat growth and yield, as demonstrated by increased plant height, spike weight, 1000-grain weight, and biological yield, particularly under fungicide-treated conditions. The severity of yellow rust, powdery mildew, spot blotch, and Karnal bunt was notably reduced, resulting in healthier wheat crops and enhanced grain quality. This study underscores the importance of fungicide treatments in controlling fungal diseases and boosting wheat productivity, while also emphasizing the critical role of the genetic potential of wheat varieties in determining yield performance. These findings highlight the substantial benefits of incorporating fungicides into wheat production systems.

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AUTHORS' CONTRIBUTIONS

NS and IN conducted the experiments and collected the data; MS and FUK conceived and supervised the study; NS and FUK wrote the initial manuscript; FUK designed study, analyzed data and finalized the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Ahmad, A., Mukhtar, T., Afzal, A., Gulzar, A., Abbas, G., Batool, A., 2024. Assessment of wheat genotypes for resistance and susceptibility to stripe rust. Pakistan Journal of Phytopathology 36(02), 479-488.

Ahmad, F., 2001. Genotypic variation for 1000 grain weight in wheat. Journal of Agricultural Science 138(4), 429-436.

Ahmad, M., Pasha, I., Anwar, R., 2007. Impact of fungicides on wheat growth and yield. Field Crops Research 103(3), 212-218.

Aslam, M., Tanveer, A., Shamsi, I.H., 2013. Yield potential and disease resistance in wheat cultivars. Pakistan Journal of Botany 45(2), 541-549.

Biryukov, A.V., Lyashok, I.B., 1983. Grain yield characteristics in wheat breeding programs. Euphytica 32(1), 225-233.

Bishaw, Z., Struik, P.C., Van Geste, A.J.G., 2013. Farmer's seed sources and seed quality: 2. Seed health. International Journal of Plant Production 7, 637-657.

Carris, L.M., Castlebury, L.A., Goates, B.J., 2006. Nonsystemic bunt fungi-*Tilletia indica* and *T. horrida*: A review of history, systematics, and biology. Annual Review of Phytopathology 44, 113-133.

Cuong, D.M., Kwon, S.J., Nguyen, B.V., Chun, S.W., Kim, J.K., Park, S.U., 2020. Effect of salinity stress on phenylpropanoid genes expression and related gene expression in wheat sprout. Agronomy 10(3), 390.

Curtis, R., Rajaraman, S., Macpherson, H., 2002. Bread Wheat. Food and Agriculture Organization of the United Nations. FAO Plant Production and Protection Series, 30.

Din, A., Mehmood, M.A., Zubair, M., 2023. Genetic diversity in wheat varieties for spike weight and yield traits. International Journal of Agricultural

Biology 25(1), 63-68.
Dipali, M., Rajesh, T., Suting, E.G., Debbarma, A., 2013. Detection of seed borne pathogens in wheat: Recent trends. Australian Journal of Crop Science 7(4), 500-507.
Doling, D.A., 1965. A method for the transformation of field data for comparing the mildew resistance of cereal varieties and the systemic deviation of the values in NIAB farmer's leaflets. Journal of Natural Institute of Agriculture Botany 10, 169-179.
Haq, E.U., Rattu, A.R., Mirza, J.I., 2002. Prevalence of Karnal bunt of wheat in KPK (Pakistan). International Journal of Agriculture and Biology 4, 150-152.
Hossain, M.I., Bhuiyan, M.M.H., Islam, M.S., 2011. Effects of fungicide treatment on wheat growth and yield under different climatic conditions. Bangladesh Journal of Agricultural Research 36(4), 551-557.
Hossain, M.I., Chowdhury, M.S., 2021. Fungicide treatment and its effects on wheat productivity and disease resistance. Agronomy Journal 113(7), 2973-2982.
Hussain, I., Ali, M., Ghoneim, A.M., Shahzad, K., Farooq, O., Iqbal, S., Brestic, M., 2022. Improvement in growth and yield attributes of cluster bean through optimization of sowing time and plant spacing under climate change scenario. Saudi Journal of Biological Sciences 29(2), 781-792.
Kadege, I., Lyimo, S., 2015. Evaluation of wheat varieties for spike weight and yield potential in semi-arid areas. African Journal of Agricultural Research 10(8), 917-924.
Kashyap, P.L., Kaur, S., Sanghera, G.S., Kang, S.S., Pannu, P.P.S., 2011. Novel methods for quarantine detection of Karnal bunt (*Tilletia indica*) of wheat. Elixir Agriculture 31, 1873-1876.
Kumar, J., Schäfer, P., Hückelhoven, R., Langen, G., Baltruschat, H., Stein, E., Nagarajan, S., Kogel, K.H., 2002. *Bipolaris sorokiniana*, a cereal pathogen of global concern: Cytological and molecular approaches towards better control. Molecular Plant Pathology 3, 185-195.
Laghari, A.A., Ghaffar, A., Shah, S.A., 2011. Comparison of wheat varieties for spike weight and yield components in different agro-climatic zones. Pakistan Journal of Botany 43(6), 2823-2830.
Lark, T.J., Schelly, I.H., Gibbs, H.K., 2021. Accuracy, bias, and improvements in mapping crops and cropland across the United States using the USDA cropland data layer. Remote Sensing 13(5), 968.
Masood, M., Ashraf, M., Shahbaz, M., 2005. Genotypic differences in wheat height under fungicide treatment. Crop Science 45(5), 1501-1507.
Mukhtar, T., Jabbar, A., Raja, M.U., Javed, H., 2018. Re-emergence of wheat seed gall nematode (*Anguina tritici*) in Punjab, Pakistan. Pakistan Journal of Zoology 50(3), 1195-1198.
Mukhtar, T., Saeed, M., 2024. Wheat seed gall nematode: the global scenario. In: Walia, R.K., Khan, M.R. (Eds.), Nematode problems in crops and their management in South Asia. Cambridge Scholars Publishing, Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK, pp. 182-197.
Mukhtarullah, K., Khan, M.A., Rehman, S., 2016. Performance of wheat varieties under disease-free and disease-infected conditions. Field Crops Research 194, 85-93.
Neupane, R., Sharma, R., Duveiller, E., Ortiz-Ferrara, G., Ojha, B., Rosyara, U., Bhandari, D., Bhatta, M., 2007. Major gene controls of field resistance to spot blotch in wheat genotypes 'Milan/Shanghai# 7' and 'Chirya. 3'. Plant Disease 91, 692-697.
Pasha, I., Shah, S.A., Alam, M., 2013. Biological yield and grain yield response of wheat varieties to fungicide application. Pakistan Journal of Agricultural Sciences 50(1), 31-37.
Pasha, I., Tehseen, A., 2014. Fungicide application effects on thousand grain weight in wheat varieties. International Journal of Plant Protection 7(2), 182-188.
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 26C(5), 496-500.
Pingali, P., 2007. Westernization of Asian diets and the transformation of food systems: Implications for research and policy. Food Policy 32(3), 281-298.
Rana, A.W., 2020. Rationalization of wheat markets in Pakistan: Policy options. International Food Policy Research Institute.
Randhawa, M.S., Sahi, A.K., Bajwa, S., 2002. Genetic improvement of wheat through fungicide application. Cereal Research Communications 30(4), 433-440.
Rattu, A.R., Asad, S., Fayyaz, M., Zakria, M., Iftikhar, S., Ahmad, Y., 2011. Status of foliar diseases of wheat in Punjab, Pakistan. Mycopath 9(1), 39-42.

Reid, T.A., Swart, D.A., 2004. Fungicide application for control of yellow rust in wheat: Efficacy and yield responses. Crop Protection 23(10), 823-831.

Saari, E.E., Prescott, J.M., 1975. Scale for appraising the foliar intensity of wheat diseases. Plant Disease Reporter.

Sardar, K., Gul, Z., Shah, G.M., 2021. Isolation and identification of most prevailing fungal diseases of wheat and maize in tehsil Havelian, district Abbottabad. Acta Scientific Agriculture 5(8).

Shewry, P.R., Hey, S.J., 2015. The contribution of wheat to human diet and health. Food and Energy Security 4(3), 178-202.

Singh, D., Tewari, A., Singh, A., Singh, R., Singh, S., Khanna, B., Dodan, D., Bagga, P., Kalappanawar, I., 2002. Losses caused due to leaf blight in wheat in different agroclimatic zones of India. Plant Disease Research-Ludhiana 17, 313-317.

Skirycz, A., Inzé, D., 2010. More from less: plant growth under limited water. Current Opinion in Biotechnology 21(2), 197-203.

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences 108(50), 20260-20264.

Wei, C., Jiao, Q., Agathokleous, E., Liu, H., Li, G., Zhang, J., Fahad, S., Jiang, Y., 2022. Hormetic effects of zinc on growth and antioxidant defense system of wheat plants. Science of the Total Environment 807, 150992.

Xi, G., Zhang, Z., Li, S., 2015. Effectiveness of fungicides in controlling stripe rust and improving wheat yield. Field Crops Research 183, 32-39.