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Posted Date: 29 November 2024

doi: 10.20944/preprints202411.2401.v1

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Article

# Optimizing Fungicide Seed Treatments for Early Foliar Disease Management in Wheat under Northern Great Plains Conditions

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**Abstract:** Tan spot (*Pyrenophora tritici-repentis*) and stripe rust (*Puccinia striiformis* f. sp. *tritici*) are major foliar diseases of wheat, causing significant yield losses globally. This study evaluated the efficacy of fungicide seed treatments in managing these diseases during early growth stages under greenhouse, growth chamber, and field conditions in the Northern Great Plains. Winter and spring wheat cultivars were treated with pyraclostrobin or combinations of thiamethoxam, difenoconazole, mefenoxam, fludioxonil, and sedaxane, among others. Greenhouse and growth chamber plants were inoculated with the respective pathogens, while field trials relied on natural inoculum. Fungicide treatments significantly reduced stripe rust severity (up to 36%) and moderately reduced tan spot severity during early growth stages. Treated plants showed improved plant vigor, winter survival, and grain yield, with an increase in test weight and protein content compared to untreated controls. These findings demonstrate the potential of fungicide seed treatments as an integrated pest management strategy to enhance early foliar disease control and wheat productivity.

**Keywords:** Tan spot, stripe rust, seed treatment, wheat, fungi, early foliar diseases, yield improvement, fungicides, wheat

## Introduction

Wheat (*Triticum aestivum*) is one of the most widely cultivated cereal crops globally, providing essential calories and proteins for millions of people [1,2]. Despite its importance, wheat production is increasingly challenged by biotic and abiotic factors, threatening its sustainability. Among biotic constraints, foliar diseases such as tan spot and stripe rust remain major contributors to global yield losses in wheat [3]. To address these constraints, Integrated Pest Management (IPM) approaches combining resistant cultivars, crop rotation, foliar fungicides, and seed treatments have been widely adopted, offering significant potential for improving wheat production and reducing disease-related losses [4,5]. Tan spot, caused by *Pyrenophora tritici-repentis* (Ptr), is a stubble-borne disease responsible for yield reductions ranging from 3% to 50%, depending on environmental conditions and crop susceptibility [6]. Similarly, stripe rust, caused by *Puccinia striiformis* f. sp. *tritici* (Pst), can result in devastating yield losses of 50% to 100% in susceptible cultivars under favorable conditions [7,8,9,10].

Fungicide seed treatments are used by growers to manage seed- and soil-borne pathogens, but recent studies indicate their potential in suppressing early foliar diseases such as tan spot, spot blotch, and stripe rust [8,12,13,14]. These treatments work by coating seeds with fungicides that are absorbed during germination and translocated to leaves and other tissues, depending on their mode of action [15,16,17]. In addition to systemic movement, fungicide seed treatments may act as pathogen repellents or antagonists, thereby reducing infection, sporulation, and extending the pathogen's latent period. This dual action makes them a promising tool for managing both seed-borne and early foliar diseases [15,16,18]. Seed treatments have been shown to effectively inhibit pathogens such as

*Pythium*, *Rhizoctonia*, and *Fusarium* spp. [18]. However, their efficacy in managing early-season tan spot and stripe rust in the Northern Great Plains has not been thoroughly explored. For example, Sharma-Poudyal et al. [12] reported that seed treatments combining triadimenol, carboxin, and thiram effectively managed *Helminthosporium* leaf blight in spring wheat, resulting in increased kernel weight and grain yield. Similarly, seed treatments with foliar-active systemic action have been shown to complement subsequent foliar fungicide applications, offering additional control for tan spot [19]. A study by Da Luz and Bergstrom [20] demonstrated reductions in tan spot and powdery mildew severity 20-30 days after sowing with triadimenol seed treatments in New York, but their efficacy under Northern Great Plains conditions remains unclear. Additionally, seed treatments containing triadimenol or triticonazole have been reported to protect plants from stripe rust for approximately four weeks after sowing [21].

One significant advantage of fungicide seed treatments in winter wheat is their ability to improve plant vigor and enhance winter survival [22]. Previous studies have shown that fungicide seed treatments improve stand establishment and yield potential, especially in regions prone to harsh winters and early-season disease pressure [4,5,11]. Fungicide treatments have also been effective against seed- and soil-borne diseases such as smuts, kernel bunt, and root rots, with active ingredients such as imazalil, nuarimol, triadimenol, propiconazole, and difenoconazole demonstrating efficacy in multiple studies [11, 12]. These reported benefits of fungicide seed treatments could be a few of the motivations for most growers to anticipate foliar disease management effects. Despite these benefits, their role in managing early foliar diseases in the Northern Great Plains remains underexplored. This study aims to address this gap, providing insights into the efficacy of fungicide seed treatments in controlling early-season tan spot and stripe rust, improving winter survival, and enhancing yield potential in spring and winter wheat.

Specifically, this study evaluated: (i) the efficacy of fungicide seed treatments in controlling tan spot and stripe rust during early growth stages; (ii) their impact on winter stand establishment and survival; and (iii) their influence on yield and yield components. The findings aim to offer evidence-based recommendations to growers for integrating fungicide seed treatments into IPM programs, promoting sustainable wheat production and disease management practices.

## 2. Materials and Methods

Studies were conducted in the greenhouse, growth chamber, and field to evaluate the efficacy of fungicide seed treatments in managing tan spot and stripe rust in wheat. The studies also assessed the impact of these treatments on plant establishment, winter survival, and yield components. The experiments utilized cultivars with varying susceptibilities to these diseases under controlled and field conditions in South Dakota.

### 2.1. Greenhouse Studies

Greenhouse experiments were conducted at the South Dakota State University Plant Science Department Greenhouses using a randomized complete block design (RCBD) with four replications per treatment. Two hard red spring wheat cultivars, 'Select' (susceptible to tan spot) and 'Ideal' (moderately resistant to tan spot), and two hard red winter wheat cultivars, 'Alice' and 'Expedition' (varying in stripe rust susceptibility), were included. Seeds were treated with one of two fungicides:

1. Difenoconazole + mefenoxam + fludioxonil + sedaxane (Warden Cereals WR11®, WinField United)
2. Pyraclostrobin + triticonazole + metalaxyl (Stamina F3®, BASF)

Untreated seeds served as controls. Five seeds were sown per "cone-tainer" (3.8 cm diameter, 20 cm depth) filled with Pro-Mix BX Mycorrhizae soil mix (Greenhouse Megastore) and thinned to four plants after emergence.

### 2.2. Pathogen Inoculations

For tan spot, a virulent *P. tritici-repentis* race 1 isolate (Pti2) was grown on V8-PDA media to produce conidia. Inoculum concentration was adjusted to 3000 spores/mL. Plants were inoculated at 7, 14, 21, and 28 days after planting (DAP) using a Preval sprayer to ensure uniform coverage. Inoculated plants were placed in a misting chamber (98% humidity, 16° C) for 24 hours to promote infection.

For stripe rust, *P. striiformis* urediniospores were collected, heat-shocked, and suspended in Soltrol 170 oil at a concentration of  $6 \times 10^6$  spores/mL. Ten-day-old seedlings were inoculated and placed in a growth chamber set to 17° C Day/20° C night with 98% humidity for 48 hours. The RCBD experimental design was repeated across two experimental runs, with treatments replicated four times.

### 2.3. Field Studies

Field trials were conducted at two locations: the Northeast Research Farm (NeRF) near South Shore, SD, and the Volga Research Farm, SD. The trials used a split-plot design with cultivars ('Ideal' and 'Redfield') as the main plot factors and fungicide seed treatments as subplots. Each treatment was replicated four times. Fungicide treatments included:

1. Prothioconazole + penflufen + metalaxyl (Evergol Energy®, Bayer)
2. Sedaxane (Vibrance 500FS®, Syngenta)
3. Pyraclostrobin (Stamina®, BASF)
4. Ipconazole + metalaxyl (Rancona Pinnacle®, MacDermid Agricultural Solutions)
5. Difenconazole + mefenoxam (Dividend Extreme®, Syngenta)

Seeds were treated using a powered agitator for uniform coating. Untreated seeds served as controls. Plots measured 1.5 m x 4.6 m and were planted at a seeding rate of 323 seeds/m<sup>2</sup>

### 2.4. Planting and Disease Assessments

Two planting times were included: early planting in September and late planting in October. Stand counts were conducted 8 and 14 days after emergence for early planting and 10 days after green-up in late spring for late planting. Foliar disease severity was rated 10 and 20 days after planting (DAP) using a scale of percent chlorotic and necrotic leaf area. Disease severity was assessed for the lower leaves and flag leaves in early summer.

### 2.5. Yield and Agronomic Assessments

Plots were harvested using a small plot combine. Grain yield, test weight, and protein content were recorded. Winter survival was evaluated in late spring by measuring plant density and height in the late-planted plots. Plant density was measured using a 1 m<sup>2</sup> hula hoop, and plant height was measured along 1 m of row length.

### 2.6. Data Analysis

Data from greenhouse, growth chamber, and field experiments were analyzed to evaluate the efficacy of fungicide seed treatments in managing tan spot and stripe rust, as well as their impact on yield and agronomic parameters. Statistical analysis was performed using R software [23] chosen for its robust capabilities in handling mixed models, which were necessary due to the multi-location and multi-treatment experimental design.

#### 2.6.1. Greenhouse and Growth Chamber Studies

For the greenhouse and growth chamber studies, analysis of variance (ANOVA) was conducted to determine the effects of fungicide seed treatments, cultivars, and inoculation times on disease severity, lesion size, and lesion number. These parameters were selected as they represent direct

indicators of disease progression and treatment efficacy. Two experimental runs were combined for each study after confirming homogeneity of variance using Levene's test ( $P > 0.05$ ). Treatments and cultivars were considered fixed factors, while experimental runs and containers ("cone-tainers") were treated as random factors to account for variability in experimental conditions.

## 2.6.2. Field Studies

Field data included disease severity, plant density, height, winter survival, grain yield, test weight, and protein content. Data were first tested for homogeneity of variance using Levene's test to ensure consistency across locations, planting times, and treatments. Where homogeneity was met, data from early and late planting were pooled for analysis. A split-plot design was used, with cultivars as the main plot factor and fungicide treatments as the subplot factor. Locations and planting times were treated as random factors to account for environmental variability between sites.

ANOVA was performed to assess main effects (treatment, cultivar, location, and planting time) and interactions. Post-hoc comparisons were conducted using Fisher's Least Significant Difference (LSD) test ( $P \leq 0.05$ ) to separate treatment means. The decision to use LSD was based on the need to identify subtle differences between treatments while maintaining statistical rigor.

Disease severity and lesion characteristics (number and size) were analyzed as key response variables in both greenhouse and field studies, as they directly measure the impact of fungicide treatments on pathogen infection and disease progression. Yield and its components, including test weight and protein content, were evaluated to determine the economic relevance of fungicide seed treatments, particularly in the context of early versus late planting times. Winter survival and plant vigor were assessed through plant density and height measurements, capturing the long-term benefits of seed treatments in promoting seedling establishment and growth. Where necessary, plant density data were log-transformed to normalize variance and meet the assumptions of statistical tests. This comprehensive set of parameters was chosen to provide a holistic evaluation of the agronomic and economic benefits of fungicide seed treatments.

The mixed-model approach was selected to account for the hierarchical structure of the data (e.g., locations nested within planting times, treatments nested within cultivars) and to improve the reliability of the results by incorporating random effects. Combining data across experimental runs and locations allowed for a comprehensive assessment of fungicide efficacy under diverse conditions. The use of ANOVA, followed by LSD for mean separation, ensured the identification of statistically significant differences while controlling for type I errors.

## 3. Results

### 3.1. Greenhouse Tan spot Study

The analysis of variance revealed significant differences in disease severity, lesion number, and lesion size across treatments, inoculation times, and cultivars ( $P \leq 0.05$ ). Fungicide-treated seedlings consistently showed reduced tan spot severity compared to the untreated control (Table 1). For example, at 7 days after planting (DAP), disease severity was reduced from 55.2% in the control to 38.4% and 38.0% for pyraclostrobin and thiamethoxam + difenoconazole + mefenoxam + fludioxonil + sedaxane, respectively. While tan spot severity increased with plant age, fungicide treatments maintained significantly lower severity at 14, 21, and 28 DAP. Lesion numbers and sizes also followed a similar trend, with fungicide-treated plants exhibiting smaller and fewer lesions across all time points. The efficacy of the two fungicide treatments was not significantly different.

**Table 1.** Efficacy of fungicide seed treatments on tan spot for the data pooled from 2017 and 2018 greenhouse studies.

Time (days) of inoculation and Treatment	Disease severity (%)	Number of lesions	Size of lesions (cm)
<b>7 DAP</b>			
Check	55.2 a	32.2 a	0.6 a
Pyraclostrobin	38.4 b	23.1 b	0.5 a
Thiamethoxam + difenoconazole + mefenoxam + fludioxonil + sedaxane	38.0 b	22.2 b	0.5 a
<b>14 DAP</b>			
Check	70.4 a	33.3 a	0.6 a
Pyraclostrobin	47.2 b	23.3 b	0.5 a
Thiamethoxam + difenoconazole + mefenoxam + fludioxonil + sedaxane	43.3 b	22.1 b	0.5 a
<b>21 DAP</b>			
Check	72.3 a	41.0 a	0.5 a
Pyraclostrobin	61.2 b	34.1 b	0.5 a
Thiamethoxam + difenoconazole + mefenoxam + fludioxonil + sedaxane	57.1 b	31.2 b	0.4 a
<b>28 DAP</b>			
Check	69.0 a	39.1 a	0.7 a
Pyraclostrobin	65.1 ab	35.2 b	0.5 b
Thiamethoxam + difenoconazole + mefenoxam + fludioxonil + sedaxane	63.2 b	34.4 b	0.5 b

Values are least squared means of 32 replications for the two runs and two varieties. Runs and cultivars combined after homogeneity of variance test and interaction F-values, respectively. For each treatment within a column, means followed by a common letter are not significantly different according to Fishers least-square means T-tests ( $P \leq 0.05$ )

### 3.2. Stripe Rust Growth Chamber Studies

Stripe rust severity was significantly lower in fungicide-treated plants compared to the untreated control ( $P \leq 0.05$ ). Across treatments, disease severity was highest in the control (55.3%), while fungicide-treated plants with pyraclostrobin + triticonazole + metalaxyl and difenoconazole + mefenoxam recorded reductions to 36.3% and 42.1%, respectively (Table 2). No significant interaction effects between treatment and cultivar were observed, indicating that fungicide efficacy was independent of wheat genotype.

**Table 2.** Efficacy of seed treatments to manage stripe rust on wheat seedlings grown in the growth chamber.

Variable	Df	Mean Square	P value
Treatment	2	2894	0.001
Cultivar	1	29	0.667
Treatment*Cultivar	2	74	0.627

**Treatment Mean Separations**

Treatment	Disease severity (%)
Check	55.3 a
Difeconazole + mefonoxam	42.1 b
Pyraclostrobin + Triticonazole + metalalzyl	36.3 b

Values are the least squared means of 40 replications for the two runs and cultivars.

For each treatment within a column, means followed by a common letter are not significantly different according to Fishers Least Significance Difference test ( $P \leq 0.05$ )

### 3.3. Field Assessments of Fungicide Efficacies on Tan spot

Tan spot severity varied significantly across treatments, planting times, locations, and cultivars ( $P \leq 0.05$ ; Tables 3–5). Early planting generally resulted in lower tan spot severity compared to late planting, with disease severity ranging from 9.6% to 19.7% at 10 and 20 DAP, respectively. Fungicide-treated plots consistently exhibited lower tan spot severity than untreated plots across both planting times and locations. For example, at 20 DAP, fungicide treatments reduced tan spot severity to as low as 14.0% (sedaxane) compared to 23.6% in the untreated control (Table 4).

Cultivar differences were evident, with 'Redfield' (moderately resistant) consistently showing lower tan spot severity (9.5% at 10 DAP) compared to 'Ideal' (moderately susceptible) with 12.5% at the same time point. Location effects were also significant, with higher disease pressure observed at Volga compared to NeRF.

**Table 3.** Anova table for field seed treatment efficacy in managing early tan spot in wheat at Nerf and Volga farms 10 and 20 days after planting.

Variable	<sup>b</sup> Df	<sup>c</sup> Sum Sq.	<sup>d</sup> Mean Sq.	<sup>e</sup> F. value	<sup>f</sup> Pr (>F)
<b>10 <sup>a</sup>DAP</b>					
Treatments	5	1857	371	4.257	0.001**
Cultivars	1	423	422	4.841	0.029*
Locations	1	1693	1693	19.40	2E-05***
Planting timing	1	364	364	4.166	0.043*
Residuals	183	15970	87		
<b>20 DAP</b>					
Treatments	5	2059	412	3.659	0.004**
Cultivars	1	791	791	7.025	0.009**
Locations	1	7470	7470	66.380	6E-14***
Planting timing	1	2051	2052	18.229	3E-05***
Residuals	183	20594	113		

Values are least squared means of 32 replications for each variable i.e., cultivars, locations, and planting times. Different letters in the same column for each treatment represent significant differences according to Fishers Least Significant Difference test ( $P \leq 0.05$ ).

<sup>a</sup>Days After Planting

<sup>b</sup>Degrees of Freedom

<sup>c</sup>Sum of Squares

<sup>d</sup>Mean Swuares

<sup>e</sup>F statistic

<sup>f</sup>P value

**Table 4.** Pooled mean effect of seed treatment on tan spot severity treatment, cultivar, location, and time of planting rated 10 and 20 days after planting.

Variables	Mean Tan spot Severity (%)	
	10 <sup>a</sup> DAP	20 DAP
<b>Treatments</b>		
Check	17.7 a	23.6 a
Sedaxane	10.5 b	14.0 b
Ipconazole+ metalaxyl	10.4 b	16.0 ab
Prothioconazole + penflufen + metalaxyl	9.8 b	15.3 b
Pyraclostrobin	8.8 b	15.5 b
Difenoconazole + mefenoxam	8.5 b	14.3 b
<b>Cultivars</b>	<b>10 DAP</b>	<b>20 DAP</b>
Ideal	12.5 a	18.5 a
Redfield	9.5 b	14.4 b
<b>Planting times</b>	<b>10 DAP</b>	<b>20 DAP</b>
Early planting	9.6 b	19.7 a
Late planting	12.3 a	13.2 b
<b>Locations</b>	<b>10 DAP</b>	<b>20 DAP</b>
Volga	14.0 a	22.6 a
Nerf	8.0 b	10.2 b

Values are least squared means of 32 replications for each variable i.e., cultivars, locations, and planting times. Different letters in the same column for each treatment represent significant differences according to Fishers Least Significant Difference test ( $P \leq 0.05$ ).

<sup>a</sup>Days After Planting

### 3.4. Yield, Test Weight, and Protein Content

Yield and test weight were significantly influenced by fungicide treatments, particularly in late-planted plots. For example, pyraclostrobin-treated plots yielded 1,033.3 kg/ha compared to 563.3 kg/ha in the untreated control for late-planted plots (Table 5). Test weight improved with fungicide treatments, averaging 64–66 kg/hl in treated plots versus 42 kg/hl in the untreated control.

Protein content was higher in fungicide-treated plots (12–14%) compared to the untreated control (11%). This effect was consistent across cultivars and planting times.

**Table 5.** Tan spot severity and yield performance for the early and late plated plots combined for Nerf and Volga research stations.

Planting time	Tan spot severity		Yield components from the early and late planted plots		
	10 DAP	20 DAP	Yield (kg/ha)	Test weight (kg h <sup>-1</sup> )	Protein (%)
<b>Early planting</b>					
Check	17.5 a	27.3 a	1327.2 b	64.3 a	11.0 b
Sedaxane	8.8 b	16.8 a	1768.3 a	72.3 a	13.1 ab
Ipconazole+metalaxyl	8.2 b	19.1 a	1804.6 a	72.2 a	13.3 ab
Prothioconazole+penflufen+ metalaxyl	10.1a	19.2 a	1676.1 a	72.3 a	12.2 b
Pyraclostrobin	6.9 a	18.4 a	1777.2 a	72.1 a	14.4 ab
Difenoconazole+mefenoxam	6.0 a	17.2 a	1724.4 a	71.3 a	13.2 ab
<b>Late planting</b>					
check	17.9 a	20.0 a	563.3 b	42.4 c	11.0 b
Sedaxane	12.2 b	11.1 b	790.2 ab	64.3 ab	13.4 a
Ipconazole+metalaxyl	12.6 ab	12.8 b	771.4 ab	61.4 ab	12.2 b
Prothioconazole+penflufen + metalaxyl	9.5 b	11.3 b	844.2 ab	59.0 ab	12.4 b
Pyraclostrobin	10.8 b	12.5 b	1033.3 a	66.3 a	12.0 b
Difenoconazole+mefenoxam	11.0 b	11.3 b	727.1 ab	53.4 bc	12.0 b

Values are least squared means of 32 replications for planting times. Different letters in the same column for each treatment represent significant differences according to Fishers Least Significant Difference test ( $P \leq 0.05$ ).

<sup>a</sup>Days After Planting

#### 4.6. Post-Winter Plant Vigor and Survival

Winter survival and spring vigor were significantly improved in fungicide-treated plots ( $P \leq 0.05$ ). At the NeRF site, plant density was highest in plots treated with sedaxane (95.3 plants/m<sup>2</sup>) compared to 45.3 plants/m<sup>2</sup> in the untreated plots (Table 6). Similarly, treated plots at Volga recorded higher density and vigor than the control. Plant height was not significantly affected by fungicide treatments at either location.

**Table 6.** Tan spot severity and post winter vigor assessments for the late planted plots from Nerf and Volga locations.

Location and Treatment	Tan spot severity		Winter survival of late planted plots from Nerf and Volga locations	
	10 DAE	20 DAE	Plant density/m <sup>2</sup>	Height(cm)
<b>NeRF Location</b>				
check	16.6 a	17.5 a	45.3 c	4.1 a
Sedaxane	6.8 b	7.8 b	95.3 a	4.3 a
Ipconazole+metalaxyl	6.7 b	8.4 b	88.2 a	4.8 a
Prothioconazole+penflufen + metalaxyl	5.8 b	8.8 b	87.3 a	4.2 a
Pyraclostrobin	6.0 b	9.2 b	97.2 a	4.5 a
Difenoconazole+mefenoxam	6.2 b	9.3 b	69.2 b	4.1 a
<b>Volga Location</b>				

check	18.7 a	29.6 a	68.3 b	9.1 a
Sedaxane	14.3 a	20.1 a	90.1 a	9.3 a
Ipconazole+metalaxyl	14.1 a	23.5 a	87.3 a	9.4 a
Prothioconazole+penflufen	+			
metalaxyl	13.7 a	21.6 a	94.1 a	9.5 a
Pyraclostrobin	11.9 a	21.8 a	90.3 a	9.6 a
Difenoconazole+mefenoxam	10.8 a	19.1 a	92.2 a	9.5 a

Values are least squared means of 32 replications for two locations and cultivars. Different letters in the same column for each treatment represent significant differences according to Fishers Least Significant Difference test ( $P \leq 0.05$ ).

<sup>a</sup>Days After Emergency (for ratings in the early spring after seed emergency)

#### 4. Discussion

This study investigated the efficacy of fungicide seed treatments in managing early foliar diseases, including tan spot (*Pyrenophora tritici-repentis*) and stripe rust (*Puccinia striiformis* f. sp. *tritici*), in wheat. The findings revealed significant reductions in disease severity under both controlled and field conditions, aligning with previous studies that demonstrated the systemic movement of fungicide active ingredients into plant tissues to protect young wheat leaves [16]. These systemic effects likely suppress pathogen infection, sporulation, and secondary inoculum production, contributing to reduced disease pressure. Similarly, studies by [12] Sharma-Poudyal et al. (2005 & 2006) reported reduced Helminthosporium leaf blight (HLB) severity when seed treatments combining triadimenol, carboxin, and thiram were applied. This suggests that fungicide seed treatments provide a crucial early-season window of disease protection by limiting primary infection, an observation supported by our field studies.

Differential responses between cultivars and locations in this study can be attributed to variations in cultivar resistance and the spatial distribution of infected wheat stubble, which serves as a source of primary inoculum. The moderately susceptible cultivar "Ideal" exhibited higher disease severity compared to the moderately resistant "Redfield," consistent with previous findings by [6]. Similarly, the Volga Research Farm, with evenly distributed tan spot-infested stubble, recorded higher disease severity than the Northeast Research Farm (NeRF), where inoculum was sparser. These results corroborate findings by decades old studies such as one by Bockus and Claasen [24] who reported that stubble management practices, such as plowing, significantly influence the availability of primary inoculum and disease severity. Farmers should therefore balance the benefits of no-till practices, which conserve soil health, against the potential increase in disease pressure due to stubble retention.

Improved plant density and vigor observed in fungicide-treated plots are likely due to protection against soil-borne pathogens such as *Fusarium*, *Rhizoctonia*, and *Pythium* spp., as previously documented by Stack and McMullen and Wegulo [11,18]. Difenoconazole + mefenoxam-treated plots demonstrated the highest density and vigor, supporting findings by Bockus & Claasen, and Giri [25,26], that seed treatments enhance seedling emergence and early growth. However, poor plant stands at NeRF were attributed to late planting and inadequate snow cover rather than fungicide inefficacy, a challenge also highlighted in studies by [22].

Winter survival varied significantly between locations, with higher plant densities in treated plots at Volga compared to NeRF. While fungicide seed treatments are not typically associated with increased winter hardiness, their role in enhancing plant vigor may contribute indirectly to winter survival. This partially contradicts findings by Gusta et al [22] who reported no improvement in winter tolerance with fungicide seed treatments. Nonetheless, the improved vigor and reduced disease severity in treated plots likely contributed to better stand establishment and, ultimately, higher yields.

The yield benefits observed in treated plots are consistent with other findings [5], where most fungicide seed treatments increased yield by protecting plants from early-season pathogens. Our study highlights that treated plots yielded significantly more than untreated controls, especially in early plantings. However, late-planted plots exhibited generally lower yields due to poor winter survival and lodging, underscoring the importance of optimal planting times for maximizing fungicide efficacy. Boshoff's study [8] similarly reported that triadimenol and triticonazole seed treatments reduced stripe rust and enhanced yields in wheat.

The results of this study further align with Hollaway's study [21], who noted that fungicide seed treatments containing triadimenol or triticonazole provided protection against stripe rust for approximately four weeks after sowing. Likewise, Da Luz and Bergstrom [20] reported effective control of multiple foliar diseases, including tan spot and powdery mildew, with triadimenol seed treatments. However, it is important to note that seed treatments alone may not suffice for season-long disease management, as their efficacy wanes before the critical grain-filling stage. Effective yield protection typically requires additional foliar fungicide applications to safeguard the flag leaf, as emphasized by previous studies [14, 27].

A noteworthy observation in this study was the significantly higher protein content in treated plots, consistent with previous studies [9,13]. While protein content variations can result from environmental factors such as soil moisture and planting time, the role of fungicide seed treatments in improving plant health and nutrient uptake may also contribute. Nonetheless, further studies are needed to disentangle these effects and assess the mechanisms underlying protein increases.

## 5. Conclusions

This study demonstrates the efficacy of fungicide seed treatments in managing early-season tan spot (*Pyrenophora tritici-repentis*) and stripe rust (*Puccinia striiformis f. sp. tritici*) in wheat under controlled and field conditions in the Northern Great Plains. Fungicide treatments significantly reduced disease severity during early growth stages, improved plant vigor, and enhanced winter survival. Treated plots also recorded higher yields, test weights, and protein content compared to untreated controls, with pyraclostrobin and thiamethoxam-based treatments showing the most consistent results. While fungicide seed treatments offered effective early disease suppression, the efficacy diminished as the plants matured, suggesting a need for complementary disease management strategies later in the growing season.

Based on these findings, fungicide seed treatments can be a valuable component of integrated pest management (IPM) strategies for wheat growers, particularly in regions prone to early foliar diseases. Growers are encouraged to use fungicide seed treatments to enhance seedling vigor and protect against early-season diseases, especially in no-till systems with high pathogen inoculum levels. However, the limited duration of protection underscores the importance of integrating seed treatments with foliar fungicide applications or resistant cultivars to achieve season-long disease management. Future research should focus on optimizing the timing and combination of seed treatments and foliar fungicides to maximize disease control and yield benefits under diverse environmental conditions.

**Author Contributions:** *Collins Bugingo*: Contributed to methodology development, conducted field and greenhouse experiments, performed data analysis, and drafted the manuscript. *Shaukat Ali*: Contributed to the study design, supervised the greenhouse and growth chamber experiments, provided guidance on pathogen identification, and reviewed the manuscript. *Dalitsa Yabwalo*: Assisted with seed treatment, field experiment setup, and data collection. *Emmanuel Byamukama*: Conceptualized the study, acquired the funding, supervised all greenhouse and field trials, provided expertise on pathogen management and experimental design, and contributed to manuscript editing and critical revisions.

**Funding:** Financial support for this study was provided by the South Dakota Wheat Commission, South Dakota State University Experimental Research Station, and the USDA Hatch grant # SD00H465.

**Data Availability Statement:** The data presented in this study are available on request from the first author.

**Acknowledgments:** The authors appreciate Rick Geppert, and Connie Tande for the technical support rendered during the studies.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

- Breiman, A.; Graur, D. Wheat Evolution. *Isr. J. Plant Sci.*, 1995, 43(2), 85–98. <https://doi.org/10.1080/07929978.1995.10676595>
- Curtis, B.C.; Rajaram, S.; Gomez Macpherson, H. Bread Wheat: Improvement and Production. *FAO Plant Prod. Prot. Ser. No. 30*, 2002, Rome: FAO.
- Heydari, A.; Pessarakli, M. A Review on Biological Control of Fungal Plant Pathogens Using Microbial Antagonists. *J. Biol. Sci.*, 2010, 10, 273–290. [10.3923/jbs.2010.273.290](https://doi.org/10.3923/jbs.2010.273.290)
- Menzies, J.; Gilbert, J. Diseases of Wheat. In *Diseases of Field Crops in Canada*, 3rd ed.; Bailey, K.L., Gossen, B.D., Gugel, R.K., Morrall, R.A.A., Eds.; Can. Phytopathol. Soc.: Harrow, Ontario, Canada, 2003; pp. 94–128.
- Shabee, M.V. *Compendium of Wheat Diseases*, 2nd ed.; Am. Phytopathol. Soc.: St Paul, MN, 1987; pp. 112.
- Shabeer, A.; Bockus, W.W. Tan Spot Effects on Yield and Yield Components Relative to Growth Stage in Winter Wheat. *Plant Dis.*, 1988, 72, 599–602. <https://doi.org/10.1094/PD-72-0599>
- Byamukama, E. Stripe Rust and Viral Diseases Developing in Wheat. *Igrow.SDSU Extension*, 2015. Available online: <http://igrow.org/agronomy/wheat/stripe-rust-and-viral-diseases-developing-in-wheat/> (accessed on July 2018).
- Boshoff, W.H.P.; Pretorius, Z.A.; Van Niekerk, B.D. Fungicide Efficacy and the Impact of Stripe Rust on Spring and Winter Wheat in South Africa. *S. Afr. J. Plant Soil*, 2003, 20, 11–17. <https://doi.org/10.1080/02571862.2003.10634898>
- Chen, X.M. Epidemiology and Control of Stripe Rust [*Puccinia striiformis* f. sp. *tritici*] on Wheat. *Can. J. Plant Pathol.*, 2005, 27, 314–337. <https://doi.org/10.1080/07060660509507230>
- U.S. Department of Agriculture, Agricultural Research Service. Wheat Stripe Rust. Available online: <https://www.ars.usda.gov/midwest-area/stpaul/cereal-disease-lab/docs/cereal-rusts/wheat-stripe-rust/> (accessed on November 23, 2024).
- Stack, R.W.; McMullen, M.P. Effect of Fungicidal Seed Treatments on Common Root Rot of Spring Wheat and Barley. *N. D. Farm Res.*, 1991, 49, 13–16.
- Sharma-Poudyal, D.; Duveiller, E.; Sharma, R.C. Effects of Seed Treatment and Foliar Fungicides on *Helminthosporium* Leaf Blight and on the Performance of Wheat in Warmer Growing Conditions. *J. Phytopathol.*, 2005, 153, 401–408. <https://doi.org/10.1111/j.1439-0434.2005.00987.x>
- Mehta, Y.R. Spot Blotch. In *Seed-Borne Disease and Seed Health Testing of Wheat*; Mathur, S.B., Cunfer, B.M., Eds.; Jordhurgsforlaget: Copenhagen, Denmark, 1993; pp. 105–112.
- Duveiller, E.; Kandel, Y.R.; Sharma, R.C.; Shrestha, S.M. Epidemiology of Foliar Blights (Spot Blotch and Tan Spot) of Wheat in the Plains Bordering the Himalayas. *Phytopathology*, 2005, 95, 248–256. <https://doi.org/10.1094/PHTO-95-0248>
- Buchenauer, H. Mechanism of Action of Triazole Fungicides and Related Compounds. In *Modern Selective Fungicides*; Lyr, H., Ed.; Gustav-Fischer-Verlag: Jena, Germany, 1987; pp. 205–232.
- Davidse, L.C. Antimitotic Activity of Methyl Benzimidazole-2-yl-Carbamate in Fungi and Its Binding to Cellular Protein. In *Microtubules and Microtubule Inhibitors*; Borgers, M., DeBrabander, M., Eds.; North-Holland Publishing Co.: Amsterdam, 1975; pp. 483.
- Sierotzki, H.; Scalliet, G. A Review of Current Knowledge of Resistance Aspects for the Next-Generation Succinate Dehydrogenase Inhibitor Fungicides. *Phytopathology*, 2013, 103, 880–887. <https://doi.org/10.1094/PHTO-01-13-0010-RVW>
- Wegulo, S. The Importance of Certified, Fungicide-Treated Wheat Seed. *CropWatch*, 2017. Available online: <https://cropwatch.unl.edu/2017/importance-certified-fungicide-treated-wheat-seed> (accessed on August 9, 2018).
- Bartlett, D.W.; Clough, J.M.; Godwin, J.R.; Hall, A.A.; Hamer, M.; Parr-Dobrzanski, B. The Strobilurine Fungicides. *Pest Manag. Sci.*, 2002, 58, 649–662. <https://doi.org/10.1002/ps.520>
- Da Luz, W.C.; Bergstrom, G.C. Evaluation of Triadimenol Seed Treatment for Early Season Control of Tan Spot, Powdery Mildew, Spot Blotch, and *Septoria nodorum* Spot on Spring Wheat. *Crop Prot.*, 1986, 5, 83–87.
- Hollaway, G. Stripe Rust of Wheat. *Agric. Victoria*, 2018. Available online: [http://agriculture.vic.gov.au/\\_\\_data/assets/pdf\\_file/0008/402767/stripe-rust-wheat-AG1167-2018.pdf](http://agriculture.vic.gov.au/__data/assets/pdf_file/0008/402767/stripe-rust-wheat-AG1167-2018.pdf) (accessed on September 17, 2018).
- Gusta, L.V.; O'Connor, B.J.; Lafond, G.P.; Austenson, H.M. The Effect of Fungicides and Plant Growth Regulators Applied as a Seed Treatment on the Freezing Tolerance of Winter Wheat. *Can. J. Plant Sci.*, 1994, 74, 63–69. <https://doi.org/10.4141/cjps94-012>

23. R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, 2018. Available online: <https://www.R-project.org>.
24. Bockus, W.W.; Claassen, M.M. Effects of Crop Rotation and Residue Management Practices on the Severity of Tan Spot of Winter Wheat. *Plant Dis.*, 1992, 76, 633–636. DOI: 10.1094/PD-76-0633
25. Beres, B.L.; Turkington, T.K.; Kutcher, H.R.; Irvine, B.I.; Johnson, E.N.; O'Donovan, J.T.; Harker, K.N.; Holzapfel, C.B.; Mohr, R.; Peng, G.; Spaner, D.M. Winter Wheat Cropping System Response to Seed Treatments, Seed Size, and Sowing Density. *Agron. J.*, 2016, 108, 1101–1111. <https://doi.org/10.2134/agronj2015.0497>
26. Giri, G.K.; Gade, R.M.; Patil, C.U. Seed-Borne *Bipolaris sorokiniana* in Wheat and Its Chemical Control. *J. Soils Crops.*, 2001, 11, 109–112. <https://eurekamag.com/research/003/555/003555793.php#buynow>
27. Turkington, T.K.; Kutcher, H.R.; Clayton, G.W.; O'Donovan, J.T.; Johnston, A.M.; Harker, K.N. Impact of Seedbed Utilization and Fungicide Application on the Severity of Net Blotch (*Pyrenophora teres*) and Production of Barley. *Can. J. Plant Pathol.*, 2004, 26, 533–547. <https://doi.org/10.1080/07060660409507174>

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