

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%) ($p \leq 0.05$) and moderately reduced tan spot severity during early growth stages (15–20%). Treated plants demonstrated a 30–40% improvement in plant vigor, and a 25–50% increase in winter survival. Additionally, grain yield in treated plots increased by 25–50% ($p \leq 0.05$), with test weight and protein content improving by 10% and 15%, respectively. These findings demonstrate the potential of fungicide seed treatments as an integrated pest (or pathogen) management (IPM) 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



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1. 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 (or pathogen) 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 [7–10].

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 [8,11–14]. Infection in wheat can occur through spores and mycelium present in crop residues, such as straw, which act as inoculum sources under favorable conditions. Seed 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 [15–17]. 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]. 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 in New York. Additionally, studies in Australia reported seed treatments containing triadimenol or triticonazole protecting plants from stripe rust for approximately four weeks after sowing [21]. One significant advantage of fungicide seed treatments in wheat is their ability to improve plant vigor and enhance winter survival for winter wheat [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]. However, the efficacy of such seed treatments on wheat foliar leaves in the Northern Great Plains and a larger proportion of other wheat growing regions in the country and worldwide remains unclear.

Fungicide seed treatments offer an IPM approach that protects seedlings during early growth stages by reducing the impact of initial inoculum on seeds and seedlings. These treatments provide systemic protection by translocating active ingredients into plant tissues. On the other hand, fungicide seed treatments may also pose risks of phytotoxicity to seedlings. This study evaluated these risks and benefits to justify their application beyond soil and seedborne pathogen control. Despite successful results in managing seed-borne and soil-borne diseases, their role in suppressing early foliar diseases such as tan spot and stripe rust remains underexplored irrespective of some growers and extension specialists observing and anecdotally reporting improved plant health in fields sowed with fungicide-treated seeds (Byamukama, Personal communication).

This study aimed to evaluate the efficacy of fungicide seed treatments in reducing disease severity, improving plant vigor, and enhancing yield in wheat cultivars under controlled and field conditions. This study was designed to (a) assess the efficacy of fungicide seed treatments in controlling tan spot and stripe rust during early growth stages of wheat, with a focus on reducing disease severity and limiting early pathogen spread, (b) evaluate the impact of reduced disease pressure on plant health, particularly its effects on winter stand establishment, survival, and photosynthetic efficiency, and (c) determine the influence of fungicide seed treatments on yield and yield components, such as test weight and protein content, by mitigating the indirect effects of foliar diseases on grain filling and quality.

2. Materials and Methods

Studies were conducted in a greenhouse (*Pyrenophora tritici-repentis*), growth chamber (*Puccinia striiformis* f. sp. *tritici*), and fields (*Pyrenophora tritici-repentis*) to evaluate the efficacy of fungicide seed treatments in managing tan spot and stripe rust in wheat. This study also assessed the impact of these treatments on plant establishment, winter survival, and yield components. The experiments utilized South Dakota State Experimental Station (SDAES) released cultivars with varying susceptibilities to these diseases. Seeds were treated using a powered agitator (Aginnovation LLC, Walnut Grove, CA, USA) for uniform coating. Untreated seeds served as controls. For all studies, fungicide treatments were mixed in a 2:1 fungicide x water ratio (Supplementary Material S1).

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’ (Reg. No. CV-1056, PI 659554), susceptible to *Ptr*, and ‘Ideal’ (Reg. No. HRW. SD05118-1 no PI#), moderately susceptible to *Ptr*—and two hard red winter wheat cultivars—‘Alice’ (Reg. No. CV-1023, PI 644223) and ‘Expedition’ (Reg. no. CV-947, PI 629060)—all with varying *Pst* susceptibility, were included. Treatments comprised two fungicides (S1), i.e., Warden Cereals WR11[®] (WinField United, Arden Hills, MN, USA) and Stamina F3[®] (BASF, Columbus, OH, USA). 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 Danville, IL, USA) and thinned to four plants after emergence. Both the greenhouse and growth chamber studies were repeated twice in the winter and spring of 2018.

2.2. Pathogen Inoculations

2.2.1. Tan Spot

The virulent *P. tritici-repentis* race 1 isolate (Pti2) was sourced from the culture collection of Dr. Ali at South Dakota State University. The frozen isolate was recovered by growing it on V8-PDA (Midwest Scientific, Valley Park, Mo, USA (200 mL V8 juice, 15 g Potato Dextrose Agar, 2 g CaCO₃, in one liter of distilled water). Following standard procedures by [23,24], five colonies were incubated at 21 °C in the dark until they were at least 5 cm in diameter. The plates were flooded with sterilized distilled water, and mycelia was matted with a flamed test tube, followed by decanting the excess water. The plates were then incubated in alternating cycle of 24 h light at 22 °C and 24 h dark at 16 °C to induce conidiation. The conidia were obtained by adding 30 mL of distilled water to each dish and dislodging it off the media plates using a flamed wire loop. Conidia concentration was adjusted to 3000 spores/mL following procedures by Jordahl and Francel [25]. Tween 20 was added at one drop per 100 mL to enhance adhesion. Plants in each cone were sprayed with the inoculum for about 1 min until all the plants were dripping wet using approximately 50 mL/pot of inoculum. To access the duration of protection offered by seed treatments, plants were inoculated at 7, 14, 21, and 28 days after sowing (DAS) using a Preval sprayer (Fibre Glast Developments Corp, Brookville, OH, USA). Post-inoculation, plants were placed in a misting chamber (98% humidity, 16 °C) for 24 h to promote infection before transferring them to the greenhouse where they were maintained at 23–25 °C and 70% relative humidity.

2.2.2. Stripe Rust

P. striiformis urediniospores were collected from wheat fields in Brookings South Dakota wheat trials and frozen at -80°C until ready for use. They were recovered from the freezer, heat-shocked, and suspended in Soltrol 170 oil (Phillips Petroleum, Bartlesville, OK, USA). Spores were enumerated and brought to 6×10^6 spores/mL. Inoculations were performed 10 days after emergence, and plants were maintained in a growth chamber at 17°C Day/ 20°C night, 98% humidity [26] until they were fully infected and evaluated at the 14th day after inoculation.

Untreated seeds served as controls for both pathogens. Control plants were subjected to the same environmental conditions and inoculation procedures but did not receive any fungicide seed treatment.

2.3. Field Studies

Field trials were conducted on four no till fields in two locations (Northeast Research Farms (NeRF) at South shore (44.71410°N , 96.87863°W), and the Volga Research Farms (44.30323°N , 96.92781°W) managed by South Dakota State University. All these locations had similar soil characteristics including loamy soils with a texture ranging from silt loam to silty clay loam, a pH of 5.6 to 7.3 (moderately acid to neutral), very deep soil depth (more than 152 cm), and well-drained conditions, as per the Web Soil Survey by USDA Natural Resources Conservation Service (NRCS). The average annual temperature and precipitation for these two locations is $\sim 45^{\circ}\text{F}$ and ~ 24 inches, respectively, and climatic details for the year 2017 are included in Supplementary Material S5. The trials were conducted using a split-plot design with cultivars ('Ideal' and 'Redfield') as the main plots and fungicide seed treatments as subplots where each treatment was replicated four times (S4). Two sowings (early and late) were included to assess the timing effects. A total of five fungicide treatments with various chemistries from a range of FRAC categories, as shown in Supplementary Material S2, were used.

Plots measured $1.5\text{ m} \times 4.6\text{ m}$ and were sowed at a seeding rate of 32 seeds/ m^2 using a 7-row John Deere 2155 tractor (All states Ag Parts, Salem, SD, USA) mounted Wintersteiger small grain planter (Wintersteiger inc. Salt Lake City, UT, USA) fitted with cone units. Throughout the study, plots were managed whereby pre-emergence weeds were controlled with glyphosate while post-emergence weeds were managed by PowerFlex HL (Pyroxulam) (FBN, Minot, ND, USA).

2.4. Sowing and Disease Assessments

The sowing dates for NeRF were categorized as early (8 September 2017) and late (10 October 2017), while at the Volga location, sowing occurred on 9 September 2017 and 24 October 2017. Stand establishment was evaluated 8 and 14 days post-emergence for early sowing, and 10 days after emergence in late spring for late sowing. Foliar disease severity was assessed at 10 and 20 days after sowing (DAS) using a standardized scale [27] (Luz & Hosford 1980) to quantify the percentage of chlorotic and necrotic leaf area. Additional assessments of disease severity were conducted on the lower leaves and flag leaves during early summer 2018.

Note: Data from the 2016/2017 growing season were excluded due to adverse environmental conditions, including severe drought and minimal snow cover, which substantially hindered plant emergence. These conditions precluded accurate differentiation among treatment effects, thereby compromising the reliability of the dataset.

2.5. Plant Density, Vigor, and Yield Assessments

Plant density was established at the seedling stage/early vegetative stages where plants were counted using a 1 m² hula hoop (S4e), and plant vigor assessed by the plant height was measured for all the plants along 1 m of row length. Winter survival was evaluated in late spring by measuring plant density and height in the late-sowed plots. Plots were harvested using a small plot combine, and grain yield, test weight, and protein content were recorded.

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 [28] chosen for its robust capabilities in handling mixed models, which were necessary due to the multi-location and multi-treatment experimental design. Models and their respective assumptions are presented in Supplementary Material S3.

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 ($p = 0.234$). 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. Data Analysis for 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, sowing times, and treatments. Where homogeneity was met, data from early and late sowing 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 sowing times were treated as random factors to account for environmental variability between sites.

An ANOVA was performed to assess main effects (treatment, cultivar, location, and sowing time) and interactions. Post hoc comparisons were conducted using Fishers 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. ANOVA model equations and assumptions are explained in Supplementary Material S3.

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 sowing 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.

A mixed-model approach was selected to account for the hierarchical structure of the data (e.g., locations nested within sowing 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) and Growth Chamber (Stripe Rust) Studies

Fungicide treatments significantly reduced disease severity and number of lesions at all assessment time points compared to the untreated control. For example, at 14 days after sowing (DAS), severity decreased from 70.4% in controls to 47.2% and 43.3% for Stamina[®] (pyraclostrobin) and Warden Cereals WR11[®] (Thiamethoxam + Difenconazole + Mefenoxam + Fludioxonil + Sedaxane), respectively ($p \leq 0.05$) (Table 1).

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

Time Days After Inoculation (DAI) and Treatment	Disease Severity (%)	Number of Lesions	Size of Lesions (cm)
7 DAI			
^a Check	55.2 a	32.2 a	0.6 a
Pyraclostrobin	38.4 b	23.1 b	0.5 a
Thiamethoxam + Difenconazole+ Mefenoxam + Fludioxonil + Sedaxane	38.0 b	22.2 b	0.5 a
14 DAI			
Check	70.4 a	33.3 a	0.6 a
Pyraclostrobin	47.2 b	23.3 b	0.5 a
Thiamethoxam + Difenconazole+ Mefenoxam + Fludioxonil + Sedaxane	43.3 b	22.1 b	0.5 a
21 DAI			
Check	72.3 a	41.0 a	0.5 a
Pyraclostrobin	61.2 b	34.1 b	0.5 a
Thiamethoxam + Difenconazole+ Mefenoxam + Fludioxonil + Sedaxane	57.1 b	31.2 b	0.4 a
28 DAI			
Check	69.0 a	39.1 a	0.7 a
Pyraclostrobin	65.1 ab	35.2 b	0.5 b
Thiamethoxam + Difenconazole+ 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 ($p \leq 0.05$). ^a Check is the untreated(control) set of seeds.

Stripe rust severity was reduced by 36% to 42% in treated plants compared to untreated controls (55.3%) in growth chamber experiments ($p \leq 0.05$) (Figure 1). Notably, there were no significant interaction effects between treatment and cultivar observed, indicating that fungicide efficacy was independent of wheat genotype.

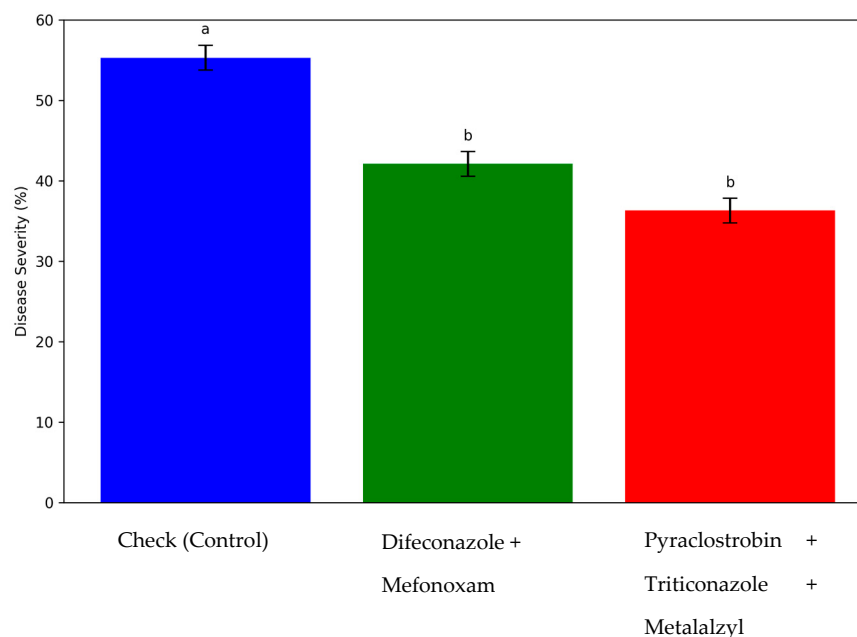


Figure 1. Efficacy of seed treatments to manage stripe rust on wheat seedlings grown in the growth chamber. Treatments followed by the same letter are not significantly different according to Fishers least significant difference test ($p \leq 0.05$).

3.2. Field Assessments of Fungicide Efficacies on Tan Spot

Tan spot severity varied significantly across treatments ($p = 0.001, 0.004$), sowing times ($p = 0.043, 3 \times 10^{-5}$), locations ($p = 2 \times 10^{-5}, 6 \times 10^{-14}$), and cultivars ($p = 0.029, 0.009$) at the 10- and 20-day-after-sowing (DAS) assessment times, respectively (Figure 2, and Table 2). Early sowing generally resulted in lower tan spot severity compared to late sowing, with disease severity ranging from 9.6% to 19.7% at 10 and 20 DAS, respectively. Fungicide-treated plots consistently exhibited lower tan spot severity than untreated plots across both sowing times and locations. For example, at 20 DAS, fungicide treatments reduced tan spot severity to as low as 14.0% (sedaxane) compared to 23.6% in the untreated control (Figure 2).

Table 2. Tan spot severity and yield performance for the early and late plated plots combined for NeRF and Volga research stations.

Sowing Time	Tan Spot Severity		Yield Components from the Early and Late Sowed Plots		
	10 ^a DAS	20 DAS	Yield (kg/ha)	Test weight (kg hL ⁻¹)	Protein (%)
Early Sowing					
^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
Late Sowing					
^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

Table 2. Cont.

Sowing Time	Tan Spot Severity		Yield Components from the Early and Late Sowed Plots		
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 sowing times. Different letters in the same column for each treatment represent significant differences according to Fisher's least significant difference test ($p \leq 0.05$). ^a Days After Sowing. ^b Check is the untreated (control) set of seeds.

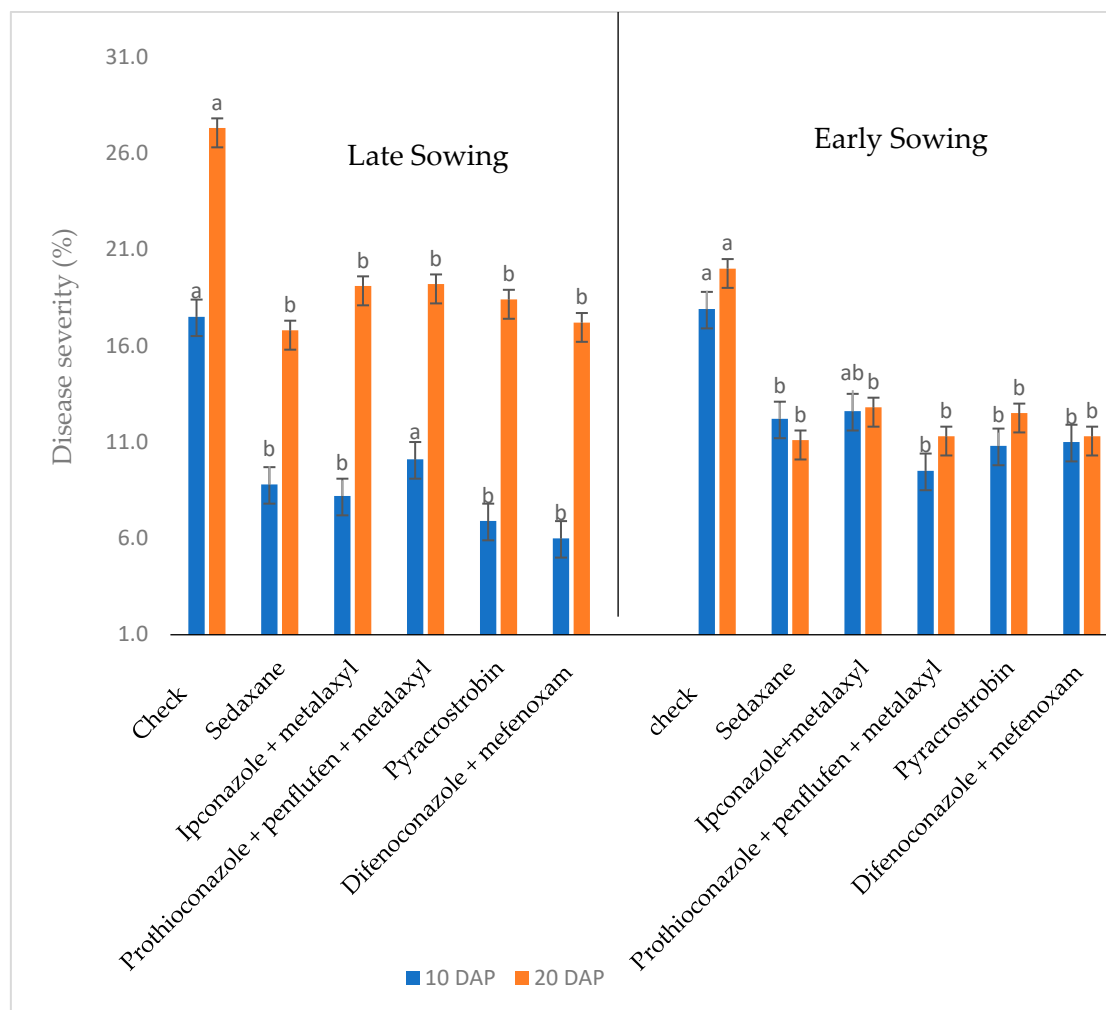


Figure 2. Pooled mean effect of seed treatment on tan spot severity for late and early sowed plots rated at 10 and 20 DAS. Note that data are combined for location and cultivar since they were not significantly different following homogeneity tests. Treatments followed by the same letter are not significantly different according to Fishers least significant difference test ($p \leq 0.05$).

Yield and test weight were significantly influenced by fungicide treatments, particularly in late-sowed plots. For example, pyraclostrobin-treated plots yielded 1033.3 kg/ha compared to 563.3 kg/ha in the untreated control for late-sowed plots (Table 2). 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 sowing times.

3.3. 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/m²) compared to 45.3 plants/m² in the untreated plots (Table 3). 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 3. Tan spot severity and post winter vigor assessments for the late sowed plots from NeRF and Volga locations.

Location and Treatment	Tan Spot Severity		Winter Survival of Late Sowed Plots from NeRF and Volga Locations	
	10 ^a DAE	20 DAE	Plant density /m ²	Height (cm)
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
Volga Location				
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 Fisher's least significant difference test ($p \leq 0.05$). ^a Days after emergency (for ratings in the early spring after seed emergency). ^b Check is the untreated(control) set of seeds.

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 pathogen 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 "Redfield". 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 [29] 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 pathogen 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 [29,30], that seed treatments enhance seedling emergence and early growth. However, poor plant stands at NeRF were attributed to late sowing 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 sowing. However, late-sowed plots exhibited generally lower yields due to poor winter survival and lodging, underscoring the importance of optimal sowing 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 a previous study [21] that reported fungicide seed treatments containing triadimenol or triticonazole providing 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 [14,31].

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 sowing 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.

This study primarily focused on managing early-season diseases, particularly tan spot and stripe rust, which significantly impact wheat during seedling and early vegetative growth stages. While late-season diseases can influence overall yield and plant health, no significant late-season foliar disease pressure was observed during the study period. Disease severity assessments conducted on flag leaves during the summer of 2018 indicated minimal pathogen activity, likely due to environmental conditions unfavorable for late-season pathogen development. However, the limited duration of protection offered by fungicide seed treatments, typically effective for four to six weeks after sowing, underscores the need for an integrated management strategy. This includes the use of foliar fungicides during the grain-filling stage to protect flag leaves, which are critical for photosynthesis and yield formation. Previous studies have demonstrated that combining seed treatments

with foliar fungicides can provide season-long disease management and maximize yield potential. Future research should evaluate the combined effects of seed and foliar fungicide applications under varying late-season disease pressures to validate and expand upon these findings.

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 and other supporting previous studies, fungicide seed treatments are a valuable component of IPM strategies for wheat growers in managing seed-borne/soilborne pathogens. This study suggests they can be a potential part of IPM to manage 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. The authors further recommend multi-year trials for future studies to validate and build upon our findings.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy15020291/s1>, S1: Graphical representation of the 0.35 acres where the RCBD split plots were planted for the trials conducted at the Volga research station. Note that the South shore had similar experimental design. 1–12 are the seed treatments, A1 and A2 are the cultivars, 101–112 are the plots in block 1, 201–212 are the plots in block 2, 301–312 are the plots in block 3, and 401–412 are the plots in block 4. Each block is a replication hence we had 4 replications for each of the sowing times. S2: Doses of seed dressing fungicides used in the greenhouse, growth chamber and field per 100 kg of Grain, Active Ingredients, and the corresponding water volumes for seed coverage, and associated FRAC groups. S3: Statistical models used in the study and including their assumptions and terms. S4: Images with disease symptoms from the greenhouse, growth chamber and field studies on tan spot and stripe rust diseases. S5: Climate data visualization for Volga and South Shore where the field experiments were conducted (Data from South Dakota Mesonet, South Dakota).

Author Contributions: C.B.: Contributed to methodology development, conducted field and greenhouse experiments, performed data analysis, and drafted the manuscript. S.A.: Contributed to the study design, supervised the greenhouse and growth chamber experiments, provided guidance on pathogen identification, and reviewed the manuscript. D.Y.: Assisted with seed treatment, field experiment setup, and data collection. E.B.: 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. All authors have read and agreed to the published version of the manuscript.

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