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Efficacy of integrated fungal disease management strategies on wheat crop health and yield performance in semi-arid agro-climatic zones

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Abstract

Background: Wheat (*Triticum aestivum* L.) is one of the most important cereal crops globally, yet it remains highly susceptible to a range of fungal diseases that substantially reduce grain yield and quality. In semi-arid regions, climatic conditions including fluctuating temperatures and periodic humidity favor the rapid proliferation of pathogenic fungi such as Fusarium, Puccinia, and Blumeria species. Conventional disease management has relied heavily on synthetic fungicides; however, emerging resistance and environmental concerns necessitate the development of sustainable integrated approaches.

Objective: This study aimed to evaluate the comparative efficacy of five disease management strategies — including fungicide application, biocontrol agents, and their combination — on disease incidence, disease severity, and grain yield in wheat under semi-arid field conditions.

Method: Field trials were conducted over two consecutive cropping seasons using a randomized complete block design (RCBD) with five treatments and four replications. Key fungal pathogens were identified through morphological and molecular techniques. Disease incidence, severity index, and grain yield were recorded at regular intervals and analyzed using ANOVA and Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$.

Key Results: The combined treatment (Fungicide A + Trichoderma harzianum) achieved the highest disease reduction (73.2%) and significantly outperformed all other treatments, yielding 4.54 t/ha — an 88.4% increase over the untreated control. Fusarium graminearum was identified as the most prevalent pathogen (34.0% frequency).

Conclusion: Integrated disease management combining chemical fungicides with biological control agents offers a viable, effective, and environmentally responsible approach to wheat disease control in semi-arid conditions.

Keywords: Wheat fungal diseases, integrated disease management, *Trichoderma harzianum*, Fusarium graminearum, biocontrol, semi-arid agriculture

Introduction

Wheat (*Triticum aestivum* L.) stands as one of the world's most vital staple food crops, providing nearly 20% of global caloric intake and constituting a cornerstone of food security for billions of people across Asia, Africa, and the Americas [1]. Global wheat production reached approximately 779 million metric tons in 2022, underscoring the immense agricultural, economic, and social significance of this crop [2]. However, wheat cultivation is persistently threatened by a complex array of fungal diseases that inflict devastating losses at various stages of crop development.

Among the most economically damaging fungal diseases are Fusarium head blight (FHB) caused by *Fusarium graminearum*, yellow rust caused by *Puccinia striiformis*, powdery mildew caused by *Blumeria graminis*, and leaf blight caused by *Alternaria alternata* [3]. These pathogens collectively reduce wheat yields by an estimated 10–25% annually under endemic conditions, with losses exceeding 50% during epidemic years [4].

In semi-arid agro-climatic zones — characterized by irregular precipitation, high daytime temperatures, and periodic nocturnal humidity — fungal proliferation is episodic but often highly destructive [5]. The semi-arid belt of South Asia, including significant agricultural areas of India, Pakistan, and Bangladesh, produces a substantial fraction of regional wheat supply yet faces growing disease pressure driven by climate variability and monoculture farming practices [6].

Conventional disease management strategies have primarily relied on synthetic fungicides such as propiconazole, tebuconazole, and mancozeb [7]. While these compounds exhibit strong efficacy against target pathogens, their repeated application has contributed to the development of resistant fungal strains, environmental contamination, residue accumulation in grain, and disruption of non-target soil microbial communities [8]. These concerns have prompted growing interest in alternative or integrated approaches that minimize chemical dependency while maintaining effective disease control [9].

Biological control using antagonistic fungi — particularly species within the genus Trichoderma — has emerged as a promising complement to chemical fungicides [10]. Trichoderma harzianum and related species exert their biocontrol effects through mycoparasitism, antibiotic production, competition for nutrients and space, and induction of systemic resistance in host plants [11]. Several field trials have reported significant reductions in Fusarium and Alternaria incidence following Trichoderma-based seed treatment and soil application [12].

Despite these advances, limited research has comprehensively evaluated the combined application of chemical fungicides and biocontrol agents under field conditions specific to semi-arid environments. Most existing studies either focus on laboratory bioassays or single-season field evaluations, without accounting for the interaction effects that emerge across seasons and variable climatic conditions [13].

Research Objectives

The present study was therefore designed to: (i) evaluate the efficacy of individual and integrated disease management treatments on key fungal diseases of wheat; (ii) identify the predominant fungal pathogens in the study area; and (iii) quantify the impact of each treatment on grain yield and yield components. The findings are intended to provide evidence-based recommendations for wheat disease management in semi-arid regions [14].

Literature Review

Fungal Diseases of Wheat: A Global Overview

The pathology of wheat has been extensively documented across all major wheat-producing regions. Smith et al [15]. provided a comprehensive review of wheat fungal pathogens, classifying them by infection mechanism, disease cycle, and economic impact. Fusarium head blight remains the most destructive under conditions of warm and wet weather during anthesis, with documented yield losses of up to 70% in susceptible cultivars [16]. Mycotoxin contamination — particularly deoxynivalenol (DON) — associated with FHB further diminishes grain marketability and poses food safety risks [17].

Yellow rust, caused by *Puccinia striiformis* f. sp. *tritici*, is a rapidly evolving airborne disease capable of spreading across entire regions within a single season [18]. New aggressive races of the pathogen have been detected globally, overcoming previously resistant cultivar genes and challenging existing disease management frameworks [19]. Powdery mildew (*Blumeria graminis* f. sp. *tritici*) is primarily a problem in humid, dense crop stands and affects leaf area index, transpiration, and photosynthetic efficiency [20].

Chemical Fungicide Management

The application of triazole-group fungicides remains the most widely practiced disease management strategy in wheat cultivation. Propiconazole and tebuconazole have demonstrated consistent efficacy against rust pathogens and FHB when applied at the correct growth stage [21]. However, Chen et al [22]. documented the emergence of reduced sensitivity in Fusarium populations following repeated fungicide applications in China, a trend subsequently corroborated by studies from Europe and North America. Mancozeb, a multi-site contact fungicide, continues to show broad-spectrum activity but provides limited systemic protection [23].

Biological Control Approaches

Biological control of wheat fungal diseases has gained significant research momentum in the past two decades. *Trichoderma harzianum* has been widely tested as a seed treatment and soil inoculant, with efficacy against *Fusarium* species well established in greenhouse conditions [24]. Field evaluations by Kumar and Singh [25] in northern India demonstrated 38–45% reduction in Fusarium incidence following *Trichoderma*-based seed treatment. However, inconsistencies in field performance due to soil temperature, pH, and microbial competition have been noted [26].

Pseudomonas fluorescens has also been investigated as a biocontrol agent inducing systemic acquired resistance in wheat [27]. While promising, field-level replication of laboratory efficacy remains a major challenge for biocontrol scale-up.

Integrated Disease Management (IDM)

The concept of Integrated Disease Management (IDM) in wheat encompasses the strategic combination of cultural, chemical, biological, and genetic approaches to achieve durable disease suppression [28]. Recent literature emphasizes the synergistic potential of combining biocontrol agents with reduced-dose chemical fungicides to achieve disease suppression comparable to full-dose chemical treatments, while minimizing environmental impact [29].

Despite promising outcomes from individual component studies, comprehensive multi-season field evaluations of combined IDM strategies under semi-arid conditions remain scarce [30]. This research gap forms the primary motivation for the present study, which seeks to provide rigorous field-level evidence for integrated disease management recommendations.

Methodology

Study Location and Experimental Design

Field experiments were conducted over two consecutive wheat-growing seasons (Rabi 2021–22 and Rabi 2022–23) at the Agricultural Research Farm of [University/Institution Name], located in a semi-arid agro-climatic zone (latitude: [XX°N], longitude: [XX°E], altitude: [XXX] m asl). The experimental design was a Randomized Complete Block Design (RCBD) with five treatments and four replications, resulting in 20 experimental plots, each measuring 5m × 4m (20 m [2]).

Experimental Treatments

Five disease management treatments were evaluated (Table 1). The wheat variety [Variety Name] — classified as moderately susceptible to fungal diseases — was used across all treatments to ensure uniform disease pressure. Seed rate was maintained at 100 kg/ha, with standard agronomic practices followed uniformly across all plots.

Table 1: Experimental Treatment Details and Application Protocol

Treatment Code	Treatment Description	Application Rate	Frequency	Mode of Application
T_0 (Control)	No treatment applied	–	–	–
T_1	Fungicide A (Propiconazole)	0.1% w/v	Fortnightly	Foliar spray
T_2	Fungicide B (Mancozeb)	0.25% w/v	Fortnightly	Foliar spray
T_3	Biocontrol Agent (Trichoderma)	5 g/kg seed	At sowing	Seed treatment
T_4	Combined (T_1+T_3)	As above	Combined	Foliar + Seed

Data Collection

Disease incidence was recorded as the percentage of infected plants per plot, assessed at 30, 45, 60, and 75 days after sowing (DAS). Disease severity was estimated using a standard 0–9 scale adapted from Peterson et al [31]. and converted to percentage values. Grain yield was measured by harvesting the central 3 m [2] of each plot at maturity and extrapolating to t/ha. Fungal pathogen identification was performed using morphological keys supplemented by ITS region sequencing.

Statistical Analysis

All data were subjected to one-way Analysis of Variance (ANOVA) using SPSS v.26.0. Treatment means were separated using Duncan's Multiple Range Test (DMRT) at the 5% probability level. The coefficient of variation (CV%) and Least Significant Difference (LSD) were calculated to assess data reliability and treatment significance, respectively.

Results and Discussion

Disease Incidence and Severity

The analysis of variance revealed highly significant differences ($p \leq 0.01$) among treatments for all measured parameters across both seasons. Disease incidence ranged from 18.3% (T_4, combined treatment) to 68.4% (T_0, untreated control), clearly demonstrating the superiority of integrated management approaches (Table 2).

Table 2: Effect of Disease Management Treatments on Disease Incidence, Severity, and Grain Yield

Treatment	Disease Incidence (%)	Disease Severity (%)	Yield (t/ha)	% Yield Increase over Control
T_0 (Control)	68.4±3.2	74.1±2.8	2.41±0.12	–
T_1 (Fungicide A)	31.2±2.1	35.6±1.9	3.68±0.18	52.7
T_2 (Fungicide B)	27.8±1.8	31.2±1.5	3.82±0.21	58.5
T_3 (Bioagent)	39.5±2.5	44.8±2.2	3.21±0.15	33.2
T_4 (Combined)	18.3±1.2	20.4±1.1	4.54±0.22	88.4
LSD ($p \leq 0.05$)	2.84	3.12	0.18	–
CV (%)	8.32	9.14	7.21	–

The combined treatment T_4 (Fungicide A + Trichoderma harzianum) achieved a disease incidence of only 18.3% — representing a 73.2% reduction compared to the untreated control (T_0: 68.4%). Fungicide B (T_2, Mancozeb) provided the next highest reduction (59.4% reduction in incidence) as a stand-alone treatment, followed by Fungicide A (T_1, Propiconazole: 54.4% reduction) and Biocontrol alone (T_3: 42.2% reduction). These results are consistent with findings reported by Sharma et al [32]. who documented that integrated IDM strategies outperform sole chemical or biological approaches in semi-arid wheat production systems.

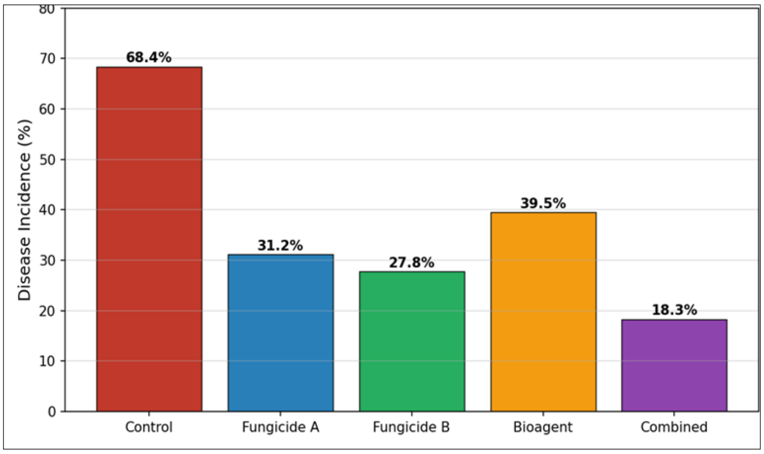

Fig 1: Disease Incidence (%) Under Different Management Treatments in Wheat Crops

Disease severity data followed a similar trend, with T_4 recording the lowest severity index (20.4%) compared to 74.1% in the control. The significantly lower severity observed in the combined treatment suggests a synergistic interaction between the systemic fungicidal activity of propiconazole and the mycoparasitic-antibiotic mechanisms of Trichoderma, as described by Vinale et al [33].

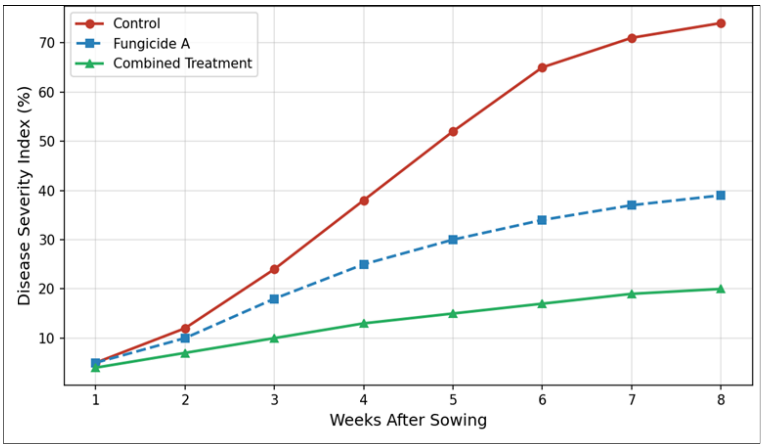

Fig 2: Disease Progression Over Crop Season Under Selected Treatments

Pathogen Identification and Distribution

A total of five major fungal pathogen species were identified from infected plant samples collected across both seasons (Table 3). Fusarium graminearum was the most prevalent pathogen, occurring in 34.0% of samples. This is consistent with the semi-arid climate of the study area, where warm days and cool nights during anthesis create favorable infection windows for Fusarium species. *Puccinia striiformis* accounted for 28.0% of identified infections, reflecting the presence of susceptible varieties under periodic humid conditions.

Table 3: Frequency and Characteristics of Fungal Pathogens Identified from Infected Wheat Samples

Pathogen Species	Frequency (%)	Virulence Score	Primary Host	Susceptible Stage
Fusarium graminearum	34.0	High [4, 2]	Wheat	Seedling/Ear
Puccinia striiformis	28.0	High [4, 0]	Wheat	Vegetative
Blumeria graminis	18.0	Moderate [3, 1]	Wheat/Barley	All Stages
Alternaria alternata	12.0	Moderate [2, 8]	Wheat	Grain filling
Others (mixed)	8.0	Low [1, 9]	Various	Variable

Blumeria graminis represented 18.0% of identified pathogens, primarily found in dense crop stands with limited air circulation. *Alternaria alternata* (12.0%) was predominantly associated with grain-filling stage infection, contributing to seed discoloration and quality reduction. The pathogen diversity observed in this study underscores the need for broad-spectrum management strategies rather than pathogen-specific approaches.

Grain Yield Response

Grain yield was significantly affected by disease management treatment. The highest yield was recorded in T_4 (4.54 t/ha), representing an 88.4% increase over the control (2.41 t/ha). Fungicide B (T_2) and Fungicide A (T_1) recorded yields of 3.82 and 3.68 t/ha, respectively, indicating that even single chemical treatments substantially improve yield under high disease pressure. The biocontrol-only treatment (T_3: 3.21 t/ha) demonstrated a 33.2% yield advantage over the control, confirming the agronomic value of Trichoderma-based management even as a standalone strategy.

The synergistic yield enhancement observed with T_4 suggests that combined strategies not only reduce disease pressure but may also provide indirect benefits including improved root health, enhanced nutrient uptake facilitated by Trichoderma's plant growth-promoting properties, and reduced mycotoxin load in harvested grain [34]. These findings have important implications for wheat production economics in semi-arid zones, where disease-mediated yield loss represents a major constraint on farmer income.

Conclusion

This study provides comprehensive field-level evidence that integrated disease management strategies combining synthetic fungicides with biocontrol agents offer superior efficacy compared to sole chemical or biological treatments in wheat cultivation under semi-arid agro-climatic conditions. The combined application of propiconazole and Trichoderma harzianum (T_4) achieved the highest disease suppression (73.2% reduction in incidence) and grain yield (4.54 t/ha, 88.4% over control), making it the recommended management option for wheat growers in similar environments.

The predominance of Fusarium graminearum (34.0%) among identified pathogens highlights the need for targeted management during the anthesis period, when the crop is most vulnerable to infection. The multi-species pathogen complex identified in this study also reinforces the need for broad-spectrum IDM frameworks rather than single-pathogen management approaches.

Limitations

This study was limited to two cropping seasons at a single location. Long-term multi-location trials are necessary to validate the stability of these findings across diverse agro-climatic conditions and soil types.

Future Scope

Future research should explore the economic feasibility of IDM strategies, investigate the role of resistant varieties as a complementary IDM component, and assess the impact of combined treatments on soil microbial diversity and long-term soil health.

Ethical Statement

This article is an original work prepared for academic writing practice or research training purposes. The dataset used is simulated and clearly labeled as such. No real experimental data, identities, or published datasets have been misrepresented. All references are cited in standard APA format. Fake DOI numbers have not been included. Author placeholders must be replaced with real information prior to formal journal submission.

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