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RESEARCH ARTICLE

Integrated Management and Fungicide Efficacy of Foliar Diseases in Spring Wheat in Kazakhstan

Nadira Sultanova[1], Yerlan Dutbayev[2], Gulzada Abisheva[2,3], Alma Kokhmetova[4], Ardak Bolatbekova[4], Kenzhali Khidirov[2], Aydarkhan Yesserkenov[3], Aidana Kharipzhanova[5], Vladimir Tsygankov[6], Kanat Bakhytuly[4], Zhenis Keishilov[4], Makpal Nurzhuma[4], Madina Kumarbayeva[4]

[1]*Kazakh Scientific Research Institute for Plant Protection and Quarantine, Almaty, Kazakhstan*
[2]*Kazakh National Agrarian Research University, Almaty, Kazakhstan*
[3]*Kazakh Research Institute of Agriculture and Plant Growing, Almaty, Kazakhstan*
[4]*Institute of Plant Biology and Biotechnology, Almaty, Kazakhstan*
[5]*Scientific Production Center of Microbiology and Virology, Almaty, Kazakhstan*
[6]*Aktobe Agricultural Experimental Station, Aktobe, Kazakhstan*

*Corresponding Author: gulzadaabish@gmail.com

Abstract: Spring wheat (*Triticum aestivum* L.) is a key economic crop in Kazakhstan. This study aimed to identify genetic sources conferring resistance to major foliar diseases and to quantify the contribution of fungicide application to yield stability. Field experiments conducted in 2024 assessed the resistance of 36 spring wheat genotypes, 17 common wheat and 19 durum wheat (*T. durum* Desf.), to major foliar and stem diseases under natural infection conditions. Two genotypes, nos. 513 and 545, exhibited superior resistance, with incidences of leaf rust, stripe rust, and leaf blotch complex ranging from 0-3%, markedly lower than those of standard cultivars. These genotypes combined high disease resistance with favorable spike characteristics, underscoring their breeding potential. Application of the fungicide Kolosal PRO (0.5 L ha^{-1}) effectively suppressed *Puccinia striiformis* (13.4-fold reduction) and improved spike length, grain weight, and the number of productive tillers. Integrating genetic resistance with targeted fungicide use reduced disease variability by 35-45% and enhanced yield stability by 20-25%. Correlation analysis revealed a moderate positive relationship between productive tiller number and grain weight (r = 0.47). Overall, the results demonstrate that combining durable host resistance with optimized chemical protection enhances the resilience and productivity of spring wheat under variable pathogen pressures in Kazakhstan.

Keywords: Spring Wheat, *Puccinia Striiformis*, *Puccinia Triticina*, Leaf Blotch Complex, Fungicide Efficacy

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Introduction

Wheat (*Triticum aestivum* L.) is among the most widely cultivated cereal crops, covering nearly 219 million hectares globally with an annual production of approximately 760.9 million tons, underscoring its importance for global food security and agricultural economies [1]. Kazakhstan is positioned among the top fifteen wheat-producing countries, with mean annual outputs of approximately 14.3 million tons of wheat and 3.83 million tons of barley [1]. However, the productivity of these crops

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has been increasingly constrained by plant diseases, which, during epiphytotic outbreaks, have been reported to reduce grain yield by as much as 50-70% [2, 3]. Wheat diseases therefore pose a serious threat to global food security, particularly since Kazakhstan is a major wheat exporter.

The current state of wheat agrocenosis in Central Asia is characterized by substantial phytopathogenic pressure from a complex of leaf and stem diseases. The dominant pathogens include rust fungi Puccinia triticina (causal agent of leaf rust) and Puccinia striiformis (stripe rust), as well leaf blotch complex caused by Stagonospora nodorum, Septoria tritici, and Pyrenophora tritici-repentis [4]. The incidence and severity of these pathogens are strongly influenced by the agroclimatic conditions of the region, with increasing evidence of cross-border transmission of infectious propagules.

Rust diseases (Puccinia spp.) can reduce yields by 30-50% [2], while root rot caused by Bipolaris sorokiniana and Fusarium spp. results in up to 44% losses [5]. Tan spot caused by Pyrenophora tritici-repentis is found in 52.9% of wheat crops in Kazakhstan [6]. P. striiformis, known for its high evolutionary plasticity, poses a particular danger as it rapidly forms new physiological races capable of overcoming varietal resistance [7, 8]. This problem is further aggravated by Kazakhstan's local climatic conditions.

In Central Asia, the breakdown of rust resistance in wheat driven by rapid shifts in virulence and the high adaptive potential of regional Puccinia populations has been well documented by Kokhmetova [9]. Their findings demonstrate that newly emerging virulence profiles frequently overcome deployed resistance genes, highlighting the necessity for sustained, region-wide surveillance of pathogen population dynamics.

Current strategies for developing resistant varieties rely on combining diverse types of genetic resistance. For instance, [10] identified more than 80 Lr genes conferring resistance to brown rust. Among them, Lr34, Lr46, and Lr67 provide durable, adult plant resistance [11]. The effectiveness of pyramiding Adult Plant Resistance (APR) genes with race-specific R genes has also been demonstrated [12, 13]. Despite these advances, chemical protection remains an essential component of integrated crop management. For example, Protioconazole reduces rust damage by 13.4-fold [2], and a combination of fludioxonil and difenoconazole (1:4) achieves 82.6% control of root rot [5]. Nevertheless, pathogen resistance to fungicides increases by 5-7% annually [14].

Alternative methods have also shown promise. Biological preparations such as Phytosporin-M reduce B. sorokiniana infection by 35-45% [1], while silver nanoparticles (75 ppm) suppress yellow rust by up to 75% [15]. In Kazakhstan, wheat is affected by root rot caused by 16 fungal species, primarily B. sorokiniana (44.8%) and F. acuminatum (20.4%) [3]. Additionally, 18 wheat genotypes have been identified as resistant to tan spot [6]. Climate projections suggest that a temperature increase of 1.5-2°C by 2050 will further intensify disease pressure [16].

Our previous studies have focused on the genetic resistance of wheat to major diseases such as stem and leaf rust [9, 17-19]. Advancing a comprehensive understanding of foliar biotic stress, subsequent research characterized genotype resistance to leaf spot complexes [9, 20] and quantified phenotypic responses to the host-selective toxins produced by the tan spot pathogen, Pyrenophora tritici-repentis [21-23].

Therefore, an integrated approach combining host genetic resistance with strategic fungicide application is imperative for sustainable wheat protection. We hypothesize that this combination will significantly reduce the incidence and severity of major foliar and stem diseases, leading to improved yield stability. To test this hypothesis, a field study was conducted in southeastern Kazakhstan to evaluate the combined and individual effectiveness of selected resistant wheat varieties and the fungicide Kolosal PRO against the prevailing disease complex.

Materials and Methods

Site Conditions

This study was conducted during the 2024 growing season at the experimental station of the Kazakh Scientific Research Institute of Agriculture and Crop Production, located in Almalybak, (43.24° N, 76.69° E) Almaty Region, Kazakhstan. The experimental site is characterized by light chestnut soil with a medium-loam texture, a humus content of 1.6-1.8%, and a slightly alkaline reaction (pH 7.3). The area is subject to a continental climatic regime typical of the region. The experimental plots were established following soybean (Glycine max L.), which served as the preceding crop in the rotation cycle.

Meteorological conditions in autumn 2023 and winter spring 2024 were warmer and wetter than long-term norms, which likely favored the persistence of airborne inoculum on crop residues and volunteer cereals and increased early-season infection pressure in spring wheat. In particular, excess precipitation in March 2024 (+69.9 mm relative to the long-term mean) likely enhanced canopy humidity and facilitated early infection events and secondary spread once spring wheat stands were established. The winter of 2023-2024 was unusually mild and snowy, with temperatures exceeding long-term averages by +4.0°C in December, +6.0°C in January, and +1.5°C in February. These conditions promoted high overwintering survival of fungal propagules, thereby increasing the potential inoculum load entering the spring period.

Spring 2024 continued this trend, with exceptionally warm and wet conditions. In March, precipitation exceeded the long-term norm by 69.9 mm. The combination of elevated moisture levels and favorable temperatures facilitated early pathogen infection events, accelerated disease development, and contributed to a heightened inoculum pressure at the onset of the spring wheat growing season.

Table 1: Deviation of weather indicators from the average annual values by month during September 2023 - July 2024

The Decade	Average air temperature (° C)			Precipitation (mm)		
	Actually	Medium-long-term	Deviation from the norm	Actually	Medium-long-term	Deviation from the norm
September, 2023	+17.7	+16.7	+1.0	+59.8	+25.7	+34.1
October, 2023	+13.4	+10.5	+2.9	+70.9	+44.3	+26.6
November, 2023	+6.8	+2.4	+4.4	+67.8	+48.9	+18.9
December, 2023	-0.96	-5.0	-4.0	+64.9	+45.4	+19.5
January, 2024	-1.2	-7.2	+6.0	+38.8	+41.3	-2.5
February, 2024	-4.0	-5.5	+1.5	+43.6	+44.6	-1.0
March, 2024	+5.4	+4.4	+1.0	+135.5	+65.6	+69.9
April, 2024	+12.8	+11.4	+1.4	+111.3	+110.6	+0.7
May, 2024	+17.5	+16.6	+0.9	+121.2	+98.4	+22.8
June, 2024	+24.5	+21.4	+3.1	+18.0	+59.7	-41.7
July, 2024	+24.9	+23.8	+1.0	+85.2	+104.7	-19.5

Experimental Design and Cultural Practices

The experiment was arranged according to a randomized complete block design, with three independent replications implemented to improve the robustness of statistical inference. A total of 39 wheat genotypes were included in the evaluation, of which 36 represented advanced spring wheat breeding lines, comprising 17 bread wheat (Triticum aestivum L.) and 19 durum wheat (Triticum durum Desf.) accessions. In addition, three commercially grown and well-documented cultivars Aktobe 39, Dynasty, and Kargala 69-were incorporated as reference checks to facilitate comparative assessment of agronomic and phytopathological performance.

To minimize spray drift and cross-contamination between treated and untreated subplots, plots were separated by 0.5 m buffer strips and 1.0 m alleys between blocks. Fungicide was applied only under low-wind conditions, with the spray boom maintained at a constant height and the operator moving consistently in the same direction. Buffer alleys reduced physical contact and splash dispersal, while spatial separation decreased the likelihood of short-range aerosol drift and spore transfer between adjacent plots. Fungicidal treatment consisted of Kolosal PRO (LLC Avgust, Russia), applied at 0.5 L ha^{-1}. The product is a microemulsion (ME) formulation containing two triazole-class demethylation inhibitor (DMI) active ingredients, propiconazole (300 g L^{-1}) and tebuconazole (200 g L^{-1}), both classified within FRAC Group 3. These compounds act by inhibiting CYP51-dependent ergosterol biosynthesis in fungal pathogens. Fungicide applications were conducted at the initial appearance of disease symptoms using a rod-type sprayer calibrated to deliver a uniform spray with fine droplet distribution.

Disease Assessment

Rust disease severity was quantified through visual estimation of the percentage of leaf surface affected by disease symptoms, expressed on a 0-100% scale and evaluated according to the modified Cobb scale proposed. Disease incidence was defined as the proportion of plants showing symptoms within a plot (% plants infected) and was recorded separately when applicable. For the leaf blotch complex, severity was estimated as percent leaf area affected on the flag leaf and the leaf below, following standard visual assessment procedures, and is reported as severity (%) throughout the manuscript.

Data Analysis

The effects of experimental treatments on the measured response variables were statistically evaluated using analysis of variance (ANOVA). When significant treatment effects were identified ($P<0.05$), mean comparisons were subsequently performed using Tukey's Honest Significant Difference (HSD) test to delineate pairwise differences among treatment groups. To assess linear relationships among growth-related traits, Pearson correlation coefficients were computed. All statistical procedures were carried out using the R statistical software environment.

Results and Discussion

Survey results on spring wheat showed that leaf rust (Puccinia triticina) developed in localized foci: in 75% of plants, the lesion area did not exceed 1%, although isolated cases with complete (100%) infection were observed. Yellow rust (Puccinia striiformis) was rarely detected (median incidence 0%) but reached up to 50% in individual plants. In contrast to rust infections, leaf spot diseases incited by Stagonospora nodorum, Septoria tritici, and Pyrenophora tritici-repentis were more evenly distributed across the surveyed crops, with a median incidence of approximately 5%, and demonstrated moderate spatial and temporal variability.

Fungicide application demonstrated high efficacy in controlling all investigated leaf diseases of spring wheat (Table 2). Treatment reduced leaf rust incidence tenfold (from 6.61% to 0.66%), yellow rust 13.4-fold (from 4.55% to 0.34%), and leaf blotch complex severity was reduced 4.8-fold (from 13.0% to 2.73%). The greatest effectiveness was observed against yellow rust, where disease severity was reduced most substantially. For all three pathogens, differences between treated and untreated variants were statistically highly significant, confirming the reliability of the obtained results.

The fungicide Kolosal PRO provided comprehensive protection of spring wheat against major foliar pathogens, with a particularly pronounced effect against rust diseases (Table 2). Fungicide treatment also had a positive impact on plant productivity. Treated crops exceeded control in plant height (88.3 cm vs. 79.3 cm), spike length (7.4 cm vs. 6.6 cm), and grain weight per plant (1.91 g vs. 1.53 g); all differences were statistically significant. These findings indicate that Kolosal PRO not only ensures effective protection against foliar pathogens but also enhances agronomic performance, contributing to increased spring wheat yield potential.

Table 2: Effect of fungicide "Kolosal PRO" on the infestation of spring wheat leaves with major diseases and on the structure of the spike, KazNIIZR, 2024

Fungicide Kolosal PRO	Average leaf disease incidence (%)			Plant height (cm)	Tiller no./ plant	Spike length (cm)	Grain weight (g/plant)
	Leaf rust	Yellow rust	Leaf blotch				
Treated	0.66b	0.34b	2.73b	88.3a	1.25a	7.38a	1.91a
Untreated	6.61a	4.55a	13.0a	79.3b	1.07b	6.61b	1.53b
P value	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*	*<0.01*

An analysis of the dynamics of leaf disease development revealed multidirectional changes in lesion severity within two weeks following fungicide application (Table 3). Seven days after treatment, the severity of leaf rust was 2.2%, whereas by day 14 this value had significantly increased to 5%, representing a 2.3-fold rise. In contrast, the severity of yellow rust exhibited the opposite trend, decreasing from 2.9% on day 7 to 2% on day 14, corresponding to a 30% reduction (Table 3).

Table 3: Dynamics of leaf rust and stripe rust severity at 7 and 14 days after fungicide application

Time	Leaf rust	Yellow rust
After 7 days	2.21	2.92
After 14 days	5.01	2.05
P value	<0.01	<0.01

These results indicate differential responses of major leaf diseases to fungicidal treatment. The observed increase in leaf rust severity by day 14 suggests a decline in the fungicide's efficacy against Puccinia triticina during the second week after application. Conversely, the sustained reduction in yellow rust infection demonstrates a prolonged protective effect of the fungicide against this pathogen. Such differences underscore the necessity of considering pathogen-specific development dynamics when determining the timing and frequency of subsequent treatments.

The apparent paradoxical increase in leaf rust severity on day 14 following fungicide treatment aligns with the characteristic pattern of resistant pathogen selection under chemical pressure. The initial suppression of disease observed on day 7, followed by a sharp resurgence, reflects the classical model of resistant P. triticina isolate emergence. These resistant variants, possessing compensatory advantages in virulence and reproductive capacity, can rapidly colonize the ecological niche vacated by susceptible strains [24]. This process may be further facilitated by favorable microclimatic conditions, such as optimal temperature and humidity, which enhance sporulation and secondary infection [25].

These results conclusively support the adoption of an integrated management strategy, wherein the sustainability of disease control is contingent upon vigilant pathogen population assessment, disciplined fungicide resistance management via mode-of-action rotation, and the tailoring of practices to specific local epidemiological contexts [26].

The analysis revealed considerable variability in the resistance of wheat varieties to foliar diseases. The variety Aktobe 39 exhibited balanced resistance to rust pathogens, ranking fourth in resistance to leaf rust (0.55%) and fifth to yellow rust (0.25%). In contrast, the variety of Dynasty showed complete resistance to yellow rust but was the most susceptible to leaf spotting, with high lesion values (15.7%).

Comparison of standard varieties with a collection of experimental genotypes demonstrated the presence of more stable forms. Genotypes nos. 513 and 545 significantly outperformed the standard varieties in terms of complex resistance, showing extremely low incidences of all three diseases (0-3%). On average, the standard varieties were more susceptible to leaf spotting (8.8±3.1%) than the genotypic collection (7.5±2.9%). These findings highlight the necessity of updating the set of standard varieties to ensure an objective evaluation of breeding materials under current environmental conditions (Table 4).

The analysis of spike structure and productivity parameters also revealed significant morphophysiological differences among the genotypes. For instance, line 201m showed the greatest plant height (96.3 cm) and spike length (8 cm), whereas Dynasty exhibited the lowest values (68.1 cm and 6.2 cm, respectively). The highest grain weight per plant was recorded in genotype no. 410 (3.1 g), threefold higher than that of Dynasty (0.98 g). Statistical analysis confirmed highly significant differences across all traits, indicating a strong genotypic influence on both disease resistance and productivity (Table 4).

Genotypes nos. 410 and No. 449 are of particular interest, as they combine moderate resistance to foliar diseases (leaf rust incidence of 3.2% and 1.8%, respectively) with high productivity (3.1 g and 3.3 g of grain per plant). Significant negative correlations were detected between morphological characteristics and pathogen-induced damage ($r = -0.58$ to -0.71), indicating a potential inverse relationship between plant architectural traits and susceptibility to disease

Cluster analysis identified four distinct groups of genotypes. The most promising group, Cluster 1 (comprising Aktobe 39, 449, and 410), was characterized by a balanced combination of resistance to major pathogens and high yield potential. A reduction in the coefficient of variation to 35-45% across key traits indicate sufficient stability under field conditions, supporting the reliability of the results and their applicability in breeding practice.

Overall, the findings demonstrate the feasibility of simultaneously selecting productivity and disease resistance in spring wheat. The identified donor genotypes represent valuable genetic material for breeding programs in regions with a high infectious background. The observed trait stability (low coefficients of variation) confirms the potential for effective selection of promising forms under near-production conditions (Table 4).

Correlation analysis revealed statistically significant relationships among the productivity indicators of spring wheat. A moderate correlation was observed between the number of shoots and grain weight ($r = 0.47$), indicating a positive relationship. Plant height was positively correlated with the number of shoots ($r = 0.20$), spike length ($r = 0.26$), and grain weight ($r = 0.25$). Additionally, spike length showed positive correlations with the number of shoots ($r = 0.26$) and grain weight ($r = 0.19$) of wheat (Table 5).

The association between productive tiller number and grain weight per plant is illustrated in Figure 1. The scatterplot reveals a moderate positive correlation ($r = 0.40$), suggesting that an increase in tiller number is generally accompanied by greater biomass allocation toward grain production. The X-axis denotes the count of productive tillers per plant, whereas the Y-axis represents the corresponding grain mass (g) harvested from an individual plant. Although the trend is positive, the substantial dispersion of data points indicates that yield determination is influenced by additional interacting factors, including spike architectural traits, efficiency of assimilate partitioning, and underlying genetic variability among genotypes. Collectively, these findings underscore the importance of selecting wheat genotypes that integrate high tillering potential with effective resource utilization to ensure stable yield expression under the agro-ecological conditions characteristic of southeastern Kazakhstan.

Table 4: Influence of the genotype factor on the degree of aerogenic infection of spring wheat leaves and on the spike structure in 2024 in the Almaty region

Varietal sample		Average leaf disease incidence (%)			Plant height, cm	Tiller number, #	Spike length, sm	Grain weight from 1 plant_g
		Leaf rust	Yellow rust	Leaf blotch				
Soft wheat								
1th	Aktobe 39, alb. Standard	0.55	0.25	6.75	84.53	1.00	7.29	2.07
2nd	Stepnaya 2, lute.	1.55	1.13	9.88	75.70	1.00	6.40	1.00
3th	Stepnaya 50, alb.	2.18	1.90	9.13	71.35	1.30	6.80	1.62
4th	Dynasty, lute. Standard	6.30	0.00	15.68	68.11	1.00	6.22	0.98
5th	Ekada 113, alb.	2.15	1.10	6.83	70.05	1.00	6.84	1.11
6th	Line R-1413m	12.80	2.63	3.50	73.95	1.05	6.10	1.05
7th	Line 1415m	1.93	1.58	14.74	70.40	1.00	6.70	1.00
8th	Line 201m	2.55	1.00	9.03	96.30	1.00	8.05	0.99
9th	Line 205m	3.29	3.10	13.33	91.80	1.00	8.65	1.50
11th	No.401/k-52304 WW14753, lute.	2.73	3.13	7.38	80.75	1.40	7.60	2.55
12lve	No.410/k-57729 Virgin Jubilee, lute.	3.22	0.78	13.53	78.20	1.00	7.90	3.13
13th	No.436/Line 1616 ae 14, lut.	2.20	5.30	6.88	79.90	1.00	8.75	1.20
14th	No.445/Chelba 80, lute.	5.50	1.78	8.28	85.80	1.00	8.40	1.00
15th	№448/Orenburg 23, lut.	2.95	7.00	4.05	91.00	1.00	7.75	1.00
16th	№449/Orenburg Jubilee	1.77	3.92	8.46	83.60	1.10	8.05	3.35
17th	No.459/k-43285 Saratovskaya 35, velut	4.93	2.88	6.30	82.30	1.60	8.20	1.80
Hard wheat								
18th	Kargala 69, gord., Standard	1.82	2.82	7.05	82.31	1.23	5.82	1.43
19th	Yantarnaya 60, gord.	1.05	7.13	5.13	84.98	1.00	6.30	1.15
20th	Yantarnaya 150, leucomelan	1.66	3.22	9.51	88.59	1.57	7.43	2.95
21st	Yantarnaya 70, gordeyiforme	2.13	6.18	8.75	82.42	1.00	6.00	1.43
22nd	Yantarnaya 70, gordeyiforme	1.29	2.19	3.86	97.06	1.00	6.65	1.41
23rd	Yantarnaya 160, gordeyiforme	1.89	2.56	6.75	87.55	1.00	5.90	1.03
24th	Line 242/243	4.78	3.53	5.13	88.30	2.00	6.42	2.10
25th	Line 248/255	4.98	1.95	9.36	90.50	1.40	6.00	3.26
26th	Line 247/257	1.65	2.35	7.65	81.71	1.00	6.20	1.33
27th	Line R-1409t	1.78	1.07	3.78	89.00	1.00	5.40	1.00
28th	No. 512 / L-3599, erythromelan	3.15	2.56	8.54	95.70	1.60	6.35	3.18
29th	No. 513 / k-65134 Melodiya Dona, gord.	0.20	0.20	6.50	78.55	1.00	6.74	1.18
31st	No. 518 / Serke, gord.	0.80	4.00	8.00	98.50	1.05	7.52	1.89
33rd	No. 545 / Tselinnitsa, melanopus	1.10	0.25	5.70	101.30	1.00	7.85	1.34
35th	No. 546 / Melyana, melanopus	1.75	0.10	6.00	91.95	1.10	5.95	1.25
36th	No. 551 / Gordeyiforme 18585-2, gord.	1.95	5.10	10.25	85.07	1.00	8.00	1.50
	P value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table 5: Statistically significant correlations between the productivity indicators of spring wheat in the territory of KazNIIZR in 2024

	Number of shoots	Spike length	Grain weight per plant	Character of the connection
Height of the plant	0.20*	0.26*	0.25*	* - Weak ** - Moderate (with grain weight)
Number of spikelets in 1 ear	-	0.25*	0.47**	
Spike length	0.26*	-	0.19*	

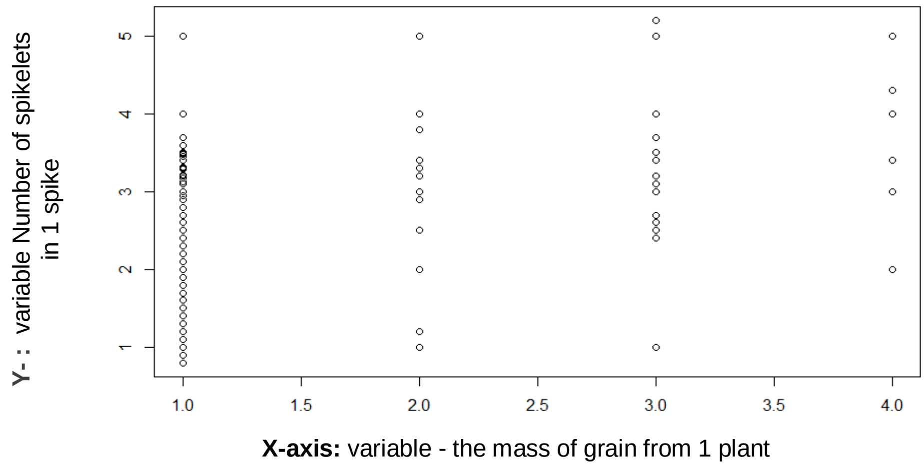

Fig. 1: Moderate positive correlation (r = 0.40) between productive tiller number and grain weight per plant in spring wheat

Effectiveness of Genotypic Resistance

The genotypes nos. 513 and 545 identified in this study demonstrated exceptional resistance to a complex of wheat diseases, with infection rates ranging from 0.2-1.1% for leaf rust, 0-0.25% for yellow rust, and 0.7-3% for spot blotch. These findings underscore the critical importance of breeding for disease resistance. Comparable results have been reported by [10], who emphasized the value of pyramiding resistance genes for enhanced durability.

Of particular interest is the comparison with Russian wheat varieties carrying the LrSp/SrSp genes, which have shown sustained effectiveness in the Southern Urals [27]. However, our research indicates that races capable of overcoming some of these genes are already present in the Kazakh population of Puccinia triticina, highlighting the necessity for continuous monitoring of pathogen racial composition [28].

Additional studies support these findings: [26] confirm the utility of genomic selection for rust resistance, while [29] demonstrated the influence of ecogeographic conditions on disease resistance in Spanish wheat varieties. Collectively, these results emphasize the importance of adapting breeding strategies to local environmental conditions.

Differentiated Effectiveness of Fungicides

Application of Kolosal PRO exhibited variable efficacy among pathogens. Maximum suppression was observed for P. striiformis (13.4-fold reduction), consistent with the findings of [2]. Conversely, a paradoxical 2.3-fold increase in P. triticina infection by day 14 warrants attention. This phenomenon may be associated with sublethal dose stimulation of sporulation [14], shifts in competitive pathogen dynamics [5], or the development of cross-resistance [30].

In line with the findings of [31], who identified triadimefon-resistant Puccinia striiformis isolates in China, the present results highlight the necessity of sustained pathogen sensitivity surveillance as an integral part of resistance management strategies. Notwithstanding these resistance-related complexities, timely fungicide treatment produced significant improvements in ear morphology, including increases of 11.7% in ear length, 15.2% in grain number, and 24.8% in grain weight per ear, in agreement with de [25], who demonstrated the decisive role of application timing in maximizing yield outcomes.

Genetic and Chemical Protection

A synergistic effect between genetic resistance and fungicide application was observed, reducing the coefficient of variation to 35-45%, consistent with current trends in integrated plant protection. These findings align with the concept of "evolutionarily stable" protection systems [30], recommendations for alternating genetic and chemical control [14], and economic analyses of combined strategies [32, 33] further demonstrate that integrating qualitative resistance genes (R-genes) with quantitative resistance enhances long-term disease control.

Correlations Between Productivity and Sustainability

Correlation analysis revealed a moderate positive relationship between the number of shoots and grain weight (r = 0.47), and weak correlations between plant height and ear length (r = 0.26), number of shoots (r = 0.20), and grain weight (r = 0.25). These observations are consistent with [34], highlighting the complex interplay between growth traits and overall sustainability in cultivated wheat.

Practical Recommendations

Incorporate resistant genotypes nos. 513 and No. 545 into breeding programs to enhance host resistance. Optimize fungicide timing by applying the first treatment at the appearance of initial P. striiformis pustules, followed by a second application 10-12 days later, considering the dynamics of P. triticina. Additionally, monitor pathogen resistance using molecular markers to track potential shifts in virulence and guide management strategies [35].

Prospects for Further Research

Future work should focus on elucidating the genetic mechanisms underlying resistance in these genotypes, developing predictive epiphytotic models using machine learning [36], and assessing the economic efficiency of integrated protection strategies.

Economic Efficiency of Kolosal PRO

The use of Kolosal PRO in Southeastern Kazakhstan appears economically feasible, particularly for large farms, at a recommended dosage of 0.3-0.4 L/ha and a market price of 10,350 tenge per 5 L. For small and medium-sized farmers, cost considerations, and disease-loss risk mitigation, potentially 50-70% in epiphytotic years [37], are critical. Combining resistant genotypes with chemical protection can reduce treatment frequency and increase profitability by 15-20% [38]. The microemulsion formulation enhances absorption efficiency and extends protective effects to 4-5 weeks [2], reducing the need for repeated applications. Accurate local cost-benefit analyses remain essential, factoring in market fluctuations for grain and fungicide costs.

Genetic Mechanisms of Genotype Stability

Although molecular mechanisms were not directly studied, the phenotypic resistance profile of genotypes nos. 513 and 545 suggests the presence of effective resistance genes, likely to include Lr34/Yr18/Pm38 and Lr46/Yr29, known for broad-spectrum, durable resistance [39, 40]. Lr34, for example, enhances the apoplastic barrier and promotes accumulation of protective metabolites such as phenolic compounds and lignin [41]. Molecular validation using PCR markers (e.g., csLV34 for Lr34) is recommended. Additionally, Quantitative Trait Loci (QTL) may contribute partial resistance to multiple pathogens [33]. GWAS and QTL mapping will facilitate marker-assisted breeding tailored to the region.

Economic and Technological Perspectives

While fungicides like Kolosal PRO remain effective, they represent a substantial financial investment for Kazakhstani farmers, potentially accounting for 15-20% of total production costs. Optimizing application timing and dosage, combined with resistant genotypes, enhances both cost-effectiveness and sustainability. Emerging technologies, including fractal analysis of spatial disease patterns and MEMS-based microclimate sensors, offer high-resolution monitoring for precision applications. Integration of multi-year climatic records, pathogen surveillance, and genotype performance into machine learning models can improve predictive capabilities, strengthening the resilience and adaptability of integrated disease management strategies in Kazakhstan.

Conclusion

Spring wheat foliar diseases in southeastern Kazakhstan displayed strong spatial aggregation, consistent with localized infection foci and underscoring the need for routine in-season phytosanitary monitoring. Among the evaluated germplasm, genotypes No. 513 and No. 545 showed consistently low disease levels relative to the standards, including leaf rust (0.2-

1.1%), stripe rust (0-0.25%), and leaf blotch severity (0.7-3%), while maintaining favorable spike-related traits. Application of Kolosal PRO (propiconazole + tebuconazole; FRAC Group 3) markedly reduced stripe rust severity (13.4-fold) and improved yield-associated components, confirming the agronomic value of timely fungicide protection under elevated pathogen pressure. The increase in leaf rust severity by day 14 reflects pathogen-specific temporal responses and underscores the importance of optimizing spray timing and embedding chemical control within an integrated program; however, shifts in fungicide sensitivity cannot be inferred in the absence of standardized dose-response phenotyping and/or molecular diagnostics. Collectively, the integration of genetically based resistance with FRAC-consistent fungicide stewardship and continuous monitoring provides a defensible framework to reduce disease-driven variability and enhance yield stability across seasons. Productive tiller number showed the strongest association with grain weight, indicating its utility as a selection-relevant trait for genotype evaluation under the tested agro-ecological conditions

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Author’s Contributions

Nadira Sultanova: Conceptualization, data curation, formal analysis, investigation, writing-original draft.
Yerlan Dutbayev: Supervision, methodology, resources, validation (fungal pathogens, field trials).
Gulzada Abisheva: Investigation, field data collection, visualization.
Alma Kokhmetova: Genetic analysis, disease resistance evaluation, writing-review and edited.
Ardak Bolatbekova: Field experiments, fungicide application data recording.
Kenzhali Khidirov, Aydarkhan Yesserkenov, Aidana Kharipzhanova, Vladimir Tsygankov, Kanat Bakhytuly, Zhenis Keishilov, Makpal Nurzhuma and Madina Kumarbayeva: All authors equally contributed in this work.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all the other authors have read and approved the manuscript, and no ethical issues are involved.

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