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Yield Loss Assessment from Leaf Rust in Bread Wheat (*Triticum aestivum* L.) Across Different Seasons and Locations

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ABSTRACT

In the context of climate change and evolving pathogen populations, wheat leaf rust (Puccinia triticina) remains one of the most damaging cereal diseases worldwide, threatening food security through significant yield and quality losses. This study evaluated nine bread wheat genotypes over two consecutive seasons (202/2024 and 2024/2025) at two locations to examine the relationship between disease severity and yield loss. Disease development was measured using final rust severity (FRS%), area under disease progress curve (AUDPC), and relative AUDPC (rAUDPC). Differences in 1000-kernel weight, kernels per spike, and grain yield per plot were evaluated between protected and infectedplants.Thehighest disease levels were detected by Sids1, Gemmeiza7, and Gemmeiza11(FRS up to 41.67%, AUDPC > 500, rAUDPC > 6, and yield reductions in some traits exceeded 35%. In contrast, Shandweel2 (FRS 10–18.33%, rAUDPC < 25%), Nubaria2 (FRS 12.5–21.67%, rAUDPC 18–30%), and Misr3 (FRS 18.33–28.33%, rAUDPC 25–35%) consistently exhibited low disease parameters and minimal yield losses, indicating strong partial resistance. Significant correlations between AUDPC, rAUDPC, and yield losses confirm their value as reliable indicators for resistance screening. The integration of multi-parameter disease assessment with yield loss analysis offers a robust and updated basis for identifying high-yielding, rust-resistant genotypes and guiding global breeding and integrated disease management strategies .

Keywords: Wheat, Leaf rust, yield losses and Tolerance indices.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is a major source of calories and protein for much of the world's population, ranking among the three of the 10 most important cereal crops, along with maize and rice (Nigus *et al.,* 2022 and Mabrouk *et al.,* 2025). In Egypt, wheat plays a crucial role in national food security, providing a significant share of calories and protein for the population. However, domestic production does not meet annual demand, and the country depends heavily on wheat imports (Selim *et al.,* 2021; and Gemeda and Gure, 2025). Egypt's average wheat production over the past five years was about 8.8 million tons. Production rose slightly 9.5 million tons in 2023, , but fell to around 9.2 million tons in 2025. Given that national consumption is nearly 20 milion tons annually, Egypt faces a persistent production gap, leaving the country vulnerable to global grain market fluctuations (FAO, 2024 and Mabrouk *et al.,* 2025).

Among the most serious biotic constraints to wheat yield, and quality are rust diseases, leaf rust (*Puccinia triticina*), stem rust (*P. graminis* f. sp. *tritici*), and stripe rust (*P. striiformis* f. sp. *tritici)*. Leaf rust is the most widespread and can reduce kernel weight and photosynthetic efficiency, ultimately causing yield losses of up to 40%. Rust diseases occur annually with varying severity (Ali *et al.,* 2022 and Saranya *et al.,* 2025). Leaf rust pathogen has incredible genetic variability, which enables the pathogen to evade resistance genes, particularly when performance of previously resistant genetic resources faces break down. In Egypt, and in most wheat production areas worldwide, leaf rust accounted for a top biotic or growing threat to wheat productivity; confronting producers annually and regularly as the most founding and damaging of the three rust diseases (Atia *et al.,* 2021 and Mabrouk *et al.,* 2025).

An integrated approach is necessary for the management of leaf rust disease, combining the use of resistant or tolerant cultivars, judicious use of fungicide applications, and cultural practices that reduce the rate of the advance and impact of the disease, particularly from using, or finding germplasm with useful breeding features of long-lasting resistance remain the most practical and sustainable solution. Conducting field tests for genotypes under both diseased and protected conditions is important for identifying lines of wheat that can maintain agronomic performance under stress (Omara *et al.,* 2021 and Saranya *et al.,* 2025).

Several stress tolerance indices, including tolerance index (TOL), mean productivity (MP), harmonic mean (HM), geometric mean productivity (GMP), and stress tolerance index (STI), are used to compare genotypes under stressed and non-stressed conditions (Gaikwad *et al.,* 2025). These indices typically calculated at harvest and may be affected by environmental variability. When combined with epidemiological parameters such as final rust severity (FRS) and area under the disease progress curve (AUDPC), they provide a comprehensive assessment of genotype performance (Singh *et al.,* 2024 and Atwa *et al.,* 2025).

Previous studies on bread and durum wheat have reported strong correlations among these indices, indicating that they can classify genotypes for stress tolerance in similar

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ways. Recognizing these correlations can help simplify breeding programs by decreasing overlap in evaluation criteria (Singh *et al.,* 2024; Atwa *et al.,* 2025; Gemeda and Gure, 2025).

The present study was conducted at Sids Agricultural Research Station and Itay Elbaroud Agricultural Research Station, both recognized as endemic hot spots for leaf rust in Egypt. These locations provide high-disease-pressure environments that are ideal for assessing wheat genotype resistance under realistic field conditions (Fath El-Bab *et al.,* 2023 and Mabrouk *et al.,* 2025).

The objective of this research was to evaluate the resistance and yield performance of selected bread wheat genotypes under natural leaf rust infection in two distinct agroecological zones in Egypt. The study also aimed to quantify yield losses in relation to disease severity using both epidemiological and yield-based parameters. Four stress tolerance indices (MP, GMP, HM, STI) were applied to identify superior genotypes.

Additionally, correlations between disease severity and yield components were examined to facilitate the selection high-yielding wheat genotypes resilient to leaf rust, thereby contributing to improved wheat self-sufficiency in Egypt and reducing reliance on imports.

MATERIAL AND METHODS

Experimental Design and Plant Material

Field trials were conducted during 2023/2024 and 2024/2025 growing seasons at two locations: Itay Elbaroud Agricultural Research Station (30.9531° N, 30.3075° E), Beheira Governorate and Sids Agricultural Research Station (28.9000° N, 31.3167° E), Beni Suef Governorate, Egypt. The locations are considered endemic "hot spots" for wheat leaf rust because natural conditions that produce extreme and consistent disease pressure. Nine wheat genotypes were evaluated (Table 1), including eight Egyptian bread wheat (*Triticum aestivum* L.) cultivars (Sids 1, Sids 12, Gemmeiza 7, Gemmeiza 11, Misr 3, Shandweel 2, Nubaria 2, Giza 171) and one landrace (*Triticum spelta* L; *Triticum spelta saharinsis*) used as a highly susceptible check. Each genotype was grown under two conditions: fungicide-protected (healthy) and artificially inoculated (unprotected).

Three replications of a randomized complete block design (RCBD) were used in the experiment. Each genotype was seeded in a 3.6 m² plot with six rows; each row was 3 m long and 20 cm apart. Seedlings from both seasons were seeded in November and during the growing season, all recommended agronomic practices were followed.

Table 1. Name, pedigree, and year of release of the nine tested wheat genotypes.

#	Genotypes Names	Scientific Names	Pedigrees	Year of release
1	Sids 1	*Triticum aestivum* L.	HdHD2172/Pavon"S"//1158.57/Maya74"S" SD46-4SD-2SD-1SD-0SD	1996
2	Sids 12	*Triticum aestivum* L.	BUC//7C/ALD/5/MAYA74/ON//1160.147/3/BB/GLL/4/CHAT"S "/6/MAYA/VUL//CMH74A.630/4*SX SD7096-4SD-1SD-1SD-0SD	2007
3	Gemmeiza 7	*Triticum aestivum* L.	CMH 74A.360 / SX // SERI 8213 / AGENT CGM4611-2GM-3GM-1GM-0GM	1999
4	Gemmeiza 11	*Triticum aestivum* L.	BOW"S"/KVZ"S"//7C/SER182/3/GIZA168/SAKHA61GM5820-3GM-1GM-2GM-0GM	2011
5	Misr 3	*Triticum aestivum* L.	ATTILA*2/PBW65*2//KACHUCMSS06Y00582T-099TOPM-099Y-099ZTM-099Y-099M-10WGY-0B-0EGY	2021
6	Line Shadweel 2	*Triticum aestivum* L.	QUAIU/5/FRET2*2/4/SNT/TRAP#1/3/HAUZ*2/TRAP//	2011
7	Line Nubaria 2	*Triticum aestivum* L.	FRET2*2/4/SNI/TRAP#1/3/KAUZ*2/TRAP//KAUZ*2/5/BOW/URES//2*WEAVER/3/CROC 1/AESQUARROSA (213)//POG	2005
8	Giza 171	*Triticum aestivum* L.	SAKHA 93 / GEMMEIZA 9 S.6-1GZ-4GZ-1GZ-2GZ-0S	2013
9	*Triticum spelta saharinsis* (T.S.S)	*Triticum spelta* L.	Local land race- Highly susceptible check variety	--------

Disease and Yield Assessments

Susceptible spreader rows of *Triticum spelta var. saharensis* and the landrace "Morocco" were used to border each plot to ensure uniform leaf rust inoculum pressure. The genotypes that were analyzed did not include the "Morocco" spreader. Infected plots were artificially inoculated at booting with a mixture of leaf rust races, while protected plots received Tilt® 25% EC (75 cm³/300 L water/feddan) at the early dough stage.

Adult-plant reactions were assessed weekly from disease onset until the early dough stage. Rust seveity was recorded using the modified Cobb's scale (Peterson *et al.*, 1948) and infection types were classified according to Singh *et al.* (2011). The final rust severity (FRS) was measured following Das *et al.* (1993), when the susceptible check was heavily rusted and the disease had reached its maximum level. The area under the disease progress curve (AUDPC) was calculated using the formula of Pandey *et al.* (1989): AUDPC = D [½ ($Y_1 + Y_k$) + $\Sigma Y_2 \ldots Y_{k-1}$], where D refers to the interval in days between two consecutive disease assessments, Y1 is the data record of the first disease, and Y_k is the data record for the last disease.

The relative area under the disease progress curve (rAUDPC) was estimated according to Shaner and Finney (1977) by expressing the AUDPC as a percentage of the maximum possible AUDPC over the assessment period.

Grain yield per plot(kg), 1000-kernel weight (g), number of kernels per spike, and number of spikes/m² were recorded. Yield loss was calculated according to Calpouzos *et al.* (1976):

$$\textbf{Loss (\%)} = (1- y_d / y_h)*100,$$

Where

***Y_d* is the grain yield of diseased plants and *Y_h* is the grain yield of healthy plants. All assessed traits, including disease severity and yield components, were recorded on ten randomly sampled plants per plot.**

Statistical analysis

Data was analyzed using ANOVA (Steel *et al.* 1997) in GenStat software (VSN International Ltd., Hemel Hempstead, UK) following a randomized complete block design anteriorly with three replications. Homogeneity of error variances across locations was tested using Levene test, 1960). Mean comparisons were performed using LSD at 5% significance. Phenotypic correlations among traits were estimated across seasons (Dixet & Dubey 1984) to assist in identifying genotypes combining desirable characteristics. Linear regression was used to relate grain yield to disease and yield traits.

Tolerance index: Average grain yield output at Sids and Itay Elbaroud under stress conditions (Ys) throughout both seasons was used to calculate four stress tolerance indices: mean productivity (MP), harmonic mean (HM), geometric mean productivity (GMP), and stress tolerance index (STI), as shown in Table 2. These selected indices assessed tolerance by comparing genotypes based on yield performance in both protected and stressed environments (Rosielle & Hamblin, 1981; Fernandez, 1992; and Jafari *et al.,* 2009).

Table 2. Names, formulas, and references of selected stress tolerance indices

No.	Index name	Formula	Reference
	% Reduction	$(Y_n-Y_s)*100/Y_n$	where Y_n is the grain yield under non-stress conditions and Y_s is the grain yield under stress condition
Higher values of these indices indicate greater stress tolerance			
1	Mean Productivity (MP)	$(Y_n+Y_s)/2$	(Rosielle and Hamblin, 1981)
2	Harmonic Mean (HM)	$2(Y_n*Y_s)/(Y_n+Y_s)$	(Jafari *et al.*, 2009)
3	Geometric Mean Productivity (GMP)	$(Y_n*Y_s)^{0.5}$	(Fernandez, 1992)
4	Stress Tolerance Index (STI)	$(Y_n*Y_s)/(\bar{Y}_n)^2$	(Fernandez, 1992)

RESULTS AND DISCUSSION

Results

1- Epidemiological Parameters in Wheat cultivars Compared with Susceptible Check (T.S.S)

Disease parameters of leaf rust: Final Rust to Severity, Area Under the Disease Progress Curve, and Relative Area Under the Disease Progress Curve were measured across both seasons and locations. To perform this evaluation, multiple wheat genotypes were assessed during the 2023 to 2024 and 2024 to 2025 growing seasons, across two locations; Itay Elbaroud and Sids (Tables 3 and 4).

The analyses of variance indicated that the location had a significant impact on all disease parameters for both years, which demonstrates the significance of the environment in causing disease, and the analysis also indicated that there were significant differences among wheat genotypes for all measured parameters, which led to confirmation of the genetic variation of resistance to leaf rust.

Table 3. Analysis of variance for leaf rust parameters at Itay Elbaroud and Sids Research Stations during the 2023/24 and 2024/25 growing seasons

S.O.V	df	Leaf rust diseases parameters					
		FRS (%)[1]		AUDPC[2]		RAUDPC[3]	
		2023/24	2024/25	2023/24	2024/25	2023/24	2024/25
(L)[A]	1	1204.17*	1350.00*	110523.*	132066.*	1293.89*	787.50*
(R)[B]	4	92.59	92.59	12289	17157.	84.48	102.31
(G)[C]	8	3685.88**	3790.74**	723305.**	752814.**	5128.57**	4488.98**
(L×G)[D]	8	2.08[Ns]	8.2*	3182.[NS]	7057.[NS]	38.91[NS]	42.08[NS]
Error	32	22.80	25.93	4977.	7485.	34.48	44.63

1: Final Rust Severity (FRS), 2: Area under disease progress curve (AUDPC), 3: Area under disease progress curve (rAUDPC) A: Location, B: Residual, C: Genotype, D: Location*Genotype.*Significant at p less than or equal to 0.05; **Highly significant at p less than or equal to 0.01.

Table 4. Wheat genotypes response to leaf rust infection based on FRS, AUDPC, and rAUDPC under field conditions at Itay Elbaroud and Sids during 2023/24 and 2024/25 seasons.

Wheat genotypes	Leaf rust disease parameters during the 2023 to 2024 season								
	FRS[1](%)			AUDPC[2]			rAUDPC[3]		
	Itay Elbaroud	Sids	Mean	Itay Elbaroud	Sids	Mean	Itay Elbaroud	Sids	Mean
Sids 1	63.33	73.33	68.33	729.2	933.3	831.25	59.52	80.81	70.165
Sids 12	23.33	33.33	28.33	234.5	327.8	281.15	19.14	28.38	23.76
Gemmeiza 7	53.33	63.33	58.33	659.2	740.8	700.0	53.81	64.14	58.98
Gemmeiza 11	33.33	43.33	38.33	341.8	429.3	385.55	27.90	37.17	32.54
Misr 3	13.33	23.33	18.33	110.8	185.5	148.15	9.05	16.06	12.55
Line Shandweel 2	6.67	13.33	10.00	82.8	122.5	102.65	6.76	10.61	8.68
Line Nubaria 2	8.33	16.67	12.50	92.2	150.5	121.35	7.52	13.03	10.28
Giza 171	26.67	36.67	31.67	281.2	362.8	322.0	22.95	31.41	27.18
T.S.S	73.33	83.33	78.33	1026.7	1120.0	1073.35	83.81	96.97	90.39
Mean	33.52	42.96	38.24	395.4	485.9	440.65	32.28	42.07	37.17
LSD 0.05	Location= 7.27 Genotype = 5.616 Genotype*Location = Ns			Location= 83.76 Genotype = 82.96 Genotype*Location= Ns			Location=6.95 Genotype = 6.91 Genotype*Location= Ns		
	Leaf rust disease parameters during the 2024 to 2025 season								
Sids 1	73.33	83.33	78.33	878.50	1015.00	946.75	67.84	78.38	73.11
Sids 12	33.33	43.33	38.33	341.83	452.67	397.25	26.40	34.95	30.68
Gemmeiza 7	63.33	73.33	68.33	845.83	845.83	845.83	65.32	65.32	65.32
Gemmeiza 11	43.33	53.33	48.33	478.33	606.67	542.50	36.94	46.85	41.89
Misr 3	23.33	33.33	28.33	218.17	341.83	280.00	16.85	26.40	21.62
Line Shandweel 2	13.33	23.33	18.33	122.50	246.17	184.33	9.46	19.01	14.23
Line Nubaria 2	16.67	26.67	21.67	150.50	281.17	215.83	11.62	21.71	16.67
Giza 171	36.67	46.67	41.67	339.50	511.00	425.25	26.22	39.46	32.84
T.S.S	83.33	93.33	88.33	1201.67	1166.67	1184.17	92.79	90.09	91.44
Mean	42.96	52.96	47.96	508.54	607.44	557.99	39.27	46.91	43.09
LSD 0.05	Location= 7.271 Genotype = 5.988 Genotype*Location = Ns			Location= 98.976 Genotype = 98.976 Genotype*Location= Ns			Location= 7.643 Genotype = 7.857 Genotype*Location = Ns		

(1) Final Rust Severity (FRS), (2) Area under disease progress curve (AUDPC) and (3) Relative Area under disease progress curve (rAUDPC).

The interaction of location and genotype usually did not significant for most traits indicating most genotypes to demonstrate stable resistance under different environments. The only other notable exception was Final Rust Severity in the first season with significant interaction. This suggests that local environmental factors can influence disease severity for some genotypes in specific contexts. Overall, the findings suggest the action of genetic and environmental factors to explain severity of leaf rust infection but support the idea that wheat genotypes had equivalent levels of resistance regardless of location.

As per data shown in Table 4, the Final Rust Severity (FRS), Area Under the Disease Progress Curve (AUDPC), and Relative AUDPC (rAUDPC) values were consistently greater at Sids than Itay Elbaroud during both growing seasons. The FRS was recorded as the percentage of disease severity when the highly susceptible check genotype (T.S.S) exhibited severe rust infection, reaching the maximum disease levels in both seasons.

Among the eight wheat genotypes examined, variation was observed in FRS, AUDPC, and rAUDPC values when compared with the susceptible check T.S.S. The FRS and rAUDPC values typically demonstrated a parallel pattern of variation with the AUDPC values, with deviations between the three genotypes, Sids 12, Giza 171, and Gemmeiza 11 within the first growing season. Moreover, all three epidemiological parameters were higher in the second season compared to the first.

In the first season, FRS values ranged from 6.67% to 73.33% at Itay Elbaroud and from 13.33% to 83.33% at Sids. The genotypes of Shandweel 2, Nubaria 2, and Misr 3 recorded the lowest percentage disease severities (6.67% and 8.33% and 13.33%) at Itay Elbaroud, while at Sids they recorded slightly increased severities (13.33% and 16.67% and 23.33%). The percent severities from the susceptible check T.S.S at Itay Elbaroud and Sids were very high for FRS (73.33% and 83.33%, respectively). In addition, the highest FRS values among the infected genotypes were recorded for the susceptible check T.S.S and genotypes Sids 1 and Gemmeiza 11.

A similar trend was evident in season 2. The FRS values ranged from 13.33% to 83.33% at Itay Elbaroud and 23.33% to 93.33% at Sids. Disease severity was generally greater in season 2, however again, the relative performance of the genotypes was similar.

To characterize slow rusting resistance, wheat genotypes were reported in three groups based on their AUDPC values. Group 1 was comprised of genotypes resistant or partially resistant with an AUDPC value 650.

For the first season, group 1, showed the lowest AUDPC values (82.8 to 110.8 at Itay Elbaroud and 122.5 to 185.5 at Sids) Among the intermediate AUDPC values (Sids 12, Gemmeiza 11, and Giza 171) were variable between the two locations. The highest AUDPC values (Gemmeiza 7, Sids 1 and susceptible check T.S.S.) were >1026.7 at Itay Elbaroud and >1073.35 at Sids. For the second season, similar groups were found, although the intermediate group presented greater variability between locations. The rAUDPC both seasons showed the same trend as AUDPC, except for genotypes Sids 12 and Giza 171 in season 2.

2- Quantitative Analysis of Wheat Yield Components under Leaf Rust across Two Locations and Seasons

The current investigation evaluated location, genotype, and their interaction to predict three yield components: 1000-kernel weight, number of kernels per spike (K/S) and grain yield per plot (kg) at Itay Elbaroud and Sids locations for the 2023/2024 and 2024/2025 growing seasons, in an infected, protected, and loss percent condition (Tables 5, 6 and 7).

The results established the genotypes of wheat showed significant differences among in their yield components influenced by leaf rust infection. A few and some of the most resistant genotypes, like Shandweel 2, Nubaria 2, and Sids 1, all had considerably higher 1000-kernel weight, kernel number per spike and grain yield with significantly lower loss percent as compared to more susceptible genotypes such as T.S.S. There also appeared a clearly demonstrated ongoing influence of location with generally higher losses at Sids. Given these findings, it would be prudent to select genotypes known to be resistant and follow their selection with protective applications to lessen the impacts of leaf rust on wheat yield.

In table 5, the location showed highly significant effects on loss percentages for 1000-kernel weight and number of kernels per spike in both seasons. Similarly, genotype had a highly significant effect on these parameters. The interaction between location and genotype was significant for infected 1000-kernel weight in the first season and highly significant for infected and loss percentage of 1000-kernel weight. For the number of kernels per spike, interaction effects were highly significant at most levels except for infected in the same trait.

Location also had a highly significant effect on grain yield per plot (infected, protected, and losses) in both seasons, while genotype showed highly significant differences in grain yield per plot. The interaction between location and genotype was highly significant for grain yield loss percentage.

According to table 6, In the season one, wheat genotypes Shandweel 2, Nubaria 2, Sids 1, and Misr 3 recorded the highest 1000-kernel weights under infection at Itay Elbaroud and Sids (48.6 & 49.42, 43.65 & 44.16, 42.73 & 43.18, and 42.42 & 43.02 g, respectively), though their values differed under protected conditions. Genotypes Gemmiza 11, Giza 171, and Sids 12 showed increased 1000-kernel weight when treated with fungicides at both locations. The Shandweel 2 maintained the highest production among all cultivars under both infected and protected conditions, whereas Gemmiza 7 yielded the lowest but still outperformed T.S.S.

Loss percentages for 1000-kernel weight were greater at the Sids location than Itay Elbaroud. The most losses were in the susceptible genotype T.S.S (53.22% and 55.08%), followed with Gemmiza 7 (22.13% and 23.49%) and Gemmiza 11 (16.59% and 17.35%). Conversely, genotypes Sids 1 (5.47% and 6.92%), Nubaria 2 (6.48% and 7.23%), and Shandweel 2 (6.68% and 7.35%) showed the lowest losses (Table 6).

The estimated number of kernels per spike at Itay Elbaroud and Sids ranged from 22.29% to 66.55% and 23.32% to 67.20%, respectively. The Nubaria 2, Shandweel 2, and Misr 3 had the highest values compared to other tested cultivars, while Gemmiza 7, Gemmiza 11, and Giza 171 showed the lowest values.

Table 5. Analysis of variance (ANOVA) of mean squares for yield component parameters, including 1000-kernel weight (g), number of kernels per spike (K/S), and grain yield per plot (kg) under infected, protected, and loss (%) conditions, evaluated under field conditions at Itay Elbaroud and Sids research stations during the 2023/2024 and 2024/2025 growing seasons.

S.O.V	df	Mean squares of yield component parameters																	
		1000 kernel weight (gm)						Number of kernels per spike (K/S)						Grain yield / plot (kg)					
		2023/2024			2024/2025			2023/2024			2024/2025			2023/2024			2024/2025		
		I	P	Loss.%	I	P	Loss.%	I	P	Loss.%	I	P	Loss.%	I	P	Loss.%	I	P	Loss.%
$(L)^{A}$	1	2.61^{NS}	18.97^{NS}	18.19**	13.76^{NS}	11.19^{NS}	11.19*	132.51^{NS}	46.72^{NS}	78.14**	11.152^{NS}	0.73267^{NS}	34.94**	126.382**	558.503**	671.947**	54.734**	318.014**	31.76**
$(R)^{B}$	4	6.50	8.37	0.16	79.59	10.02	0.3241	74.00	86.74	0.1684	71.43	10.16759	0.0458	0.2280	0.5084	0.4306	0.0779	0.0193	0.25
$(G)^{C}$	8	447.68**	61.56**	1395.36**	464.03**	60.21**	13.97**	1125.996**	312.94**	133.01**	1148.53**	3166.0140**	13.66**	2074.201**	1126.251**	3040.4093**	2228.887**	1134.048**	304.357**
$(L{\times}G)^{D}$	8	0.079*	0.08^{NS}	0.297^{NS}	0.175**	0.034^{NS}	0.71**	0.079^{NS}	0.295**	0.2269**	0.861**	1.10945**	0.3015**	0.1600^{NS}	0.7895^{NS}	1.2645**	0.1263^{NS}	1.0322^{NS}	1.20**
Error	32	0.031	0.041	0.214	0.0338	0.0220	0.0792	0.041	0.0202	0.05652	0.036	0.06974	0.06454	0.3808	0.5859	0.1482	0.4567	0.8682	0.13

(A) Location, (B) Residual, (C) Genotype, D: Location, C: Genotype, I: Infected and P: protected

Table 6. Mean performance of nine wheat genotypes for yield component parameters—1000-kernel weight (g) and number of kernels per spike (K/S)—under infected, protected, and loss (%) conditions, evaluated under field conditions at two locations (Itay Elbaroud and Sids) during the 2023/2024 and 2024/2025 growing seasons.

Wheat genotype	1000 kernel weight (gm)																	
	(2023/2024)									(2024/2025)								
	Infected			Protected			Losses%			Infected			Protected			Losses%		
	Itay Elbaroud	Sids	Mean	Itay Elbaroud	Sids	Mean	Itay Elbaroud	Sids	Mean	Itay Elbaroud	Sids	Mean	Itay Elbaroud	Sids	Mean	Itay Elbaroud	Sids	Mean
Sids 1	42.73	43.18	42.95	45.20	46.38	45.79	5.47	6.92	6.19	43.15	44.04	43.60	46.69	47.44	47.07	7.57	7.18	7.37
Sids 12	41.52	42.02	41.77	46.55	47.95	47.25	10.82	12.37	11.59	42.03	42.41	42.22	47.92	48.98	48.45	12.29	13.42	12.85
Gemmeiza 7	34.84	35.11	34.98	44.74	45.89	45.32	22.13	23.49	22.81	35.02	35.09	35.06	45.93	46.95	46.44	23.76	25.27	24.51
Gemmeiza 11	40.68	41.26	40.97	48.78	49.92	49.35	16.59	17.35	16.97	41.03	41.03	41.03	49.96	50.79	50.37	17.87	19.22	18.55
Misr 3	42.42	43.02	42.72	45.62	46.95	46.28	7.01	8.37	7.69	43.02	43.03	43.02	46.95	47.88	47.41	8.37	10.13	9.25
LineShandweel2	48.68	49.42	49.05	52.16	53.34	52.75	6.68	7.35	7.02	49.56	50.03	49.79	53.52	54.53	54.03	7.40	8.26	7.83
Line Nubaria 2	43.65	44.16	43.90	46.68	47.60	47.14	6.48	7.23	6.86	44.21	45.02	44.62	47.90	48.93	48.42	7.71	7.99	7.85
Giza 171	41.81	42.16	41.99	47.82	48.60	48.21	12.56	13.26	12.91	42.04	42.20	42.12	48.95	49.88	49.42	14.12	15.41	14.77
T.S.S	18.78	18.73	18.75	40.12	41.69	40.91	53.22	55.08	54.15	18.87	18.96	18.92	41.97	42.59	42.28	55.06	55.48	55.27
Mean	39.46	39.90	39.68	46.41	47.59	47.00	15.66	16.82	16.24	39.88	40.20	40.04	47.75	48.66	48.21	17.13	18.04	17.58
LSD0.05	Location=NS Genotype=0.208 Location*Genotype=1.908			Location=NS Genotype=0.239 Location*Genotype=NS			Location=0.301 Genotype=0.544 Location*Genotype=NS			Location=2.132 Genotype=0.216 Location*Genotype=NS			Location=NS Genotype=0.175 Location*Genotype=NS			Location=0.430 Genotype=0.331 Location*Genotype=0.550		
	Number of kernels per spike (K/S)																	
Sids 1	62.04	63.14	62.59	66.94	68.90	67.92	7.32	8.35	7.84	62.43	62.83	62.63	67.95	69.91	68.93	8.12	10.12	9.12
Sids 12	63.03	64.02	63.53	69.96	71.94	70.95	9.90	11.01	10.46	63.46	63.46	63.46	71.53	72.78	72.15	11.28	12.81	12.05
Gemmeiza 7	55.67	56.89	56.28	70.96	73.14	72.05	21.56	22.21	21.89	56.05	55.06	55.55	72.85	72.85	72.85	23.06	24.43	23.74
Gemmeiza 11	58.50	59.80	59.15	69.05	71.55	70.30	15.28	16.43	15.85	59.34	58.15	58.74	71.04	71.04	71.04	16.47	18.15	17.31
Misr 3	64.20	65.23	64.72	70.21	71.92	71.07	8.56	9.27	8.91	64.90	63.25	64.08	71.11	71.11	71.11	8.73	11.05	9.89
Lien Shandweel 2	66.55	67.05	66.80	71.92	72.91	72.41	7.47	8.04	7.75	67.47	65.98	66.73	72.95	72.95	72.95	7.51	9.55	8.53
Lien Nubaria 2	66.27	67.20	66.73	71.55	72.95	72.25	7.38	7.89	7.63	67.05	66.13	66.59	72.97	72.97	72.97	8.11	9.37	8.74
Giza 171	60.99	61.89	61.44	70.71	72.71	71.71	13.75	14.88	14.31	61.86	60.00	60.93	71.98	71.00	71.49	14.06	15.50	14.78
T.S.S	22.38	23.32	22.85	48.80	50.82	49.81	54.13	54.11	54.12	22.49	22.00	22.25	50.31	50.17	50.24	55.28	56.16	55.72
Mean	57.74	58.73	58.23	67.79	69.65	68.72	16.15	16.91	16.53	58.34	57.43	57.88	69.19	69.42	69.30	16.96	18.57	17.76
LSD0.05	Location=NS Genotype=0.237 Location*Genotype=NS			Location=NS Genotype=0.167 Location*Genotype=2.214			Location=0.310 Genotype=0.280 Location*Genotype=0.439			Location=NS Genotype=0.224 Location*Genotype=2.000			Location=Ns Genotype=0.311 Location*Genotype=2.379			Location=0.162 Genotype=0.299 Location*Genotype=0.414		

Table 7. Mean Performance of Nine Wheat Genotypes for Yield Component Parameters — Grain Yield per Plot (kg) Under Infected, Protected, and Loss (%) Conditions at Two Locations (Itay El-Baroud and Sids) During the 2023/2024 and 2024/2025 Growing Seasons

Wheat genotype	Grain yield / plot (kg)																	
	(2023/2024)									(2024/2025)								
	Infected			Protected			Losses%			Infected			Protected			Losses%		
	K / S	Sids	Mean	Itay Elbaroud	Sids	Mean	Itay Elbaroud	Sids	Mean	Itay Elbaroud	Sids	Mean	Itay Elbaroud	Sids	Mean	Itay Elbaroud	Sids	Mean
Sids 1	14.16	15.16	14.66	15.10	16.42	15.76	6.25	7.65	6.95	16.90	17.46	17.18	18.50	19.24	18.87	8.67	9.24	8.96
Sids 12	13.46	14.23	13.84	17.16	18.54	17.85	21.59	23.25	22.42	13.96	14.49	14.23	18.60	19.74	19.17	24.95	26.59	25.77
Gemmeiza 7	11.71	12.72	12.22	17.55	20.03	18.79	33.29	36.48	34.88	13.45	13.72	13.58	20.79	22.37	21.58	35.32	38.68	37.00
Gemmeiza 11	13.00	14.36	13.68	17.99	20.59	19.29	27.70	30.26	28.98	13.45	14.55	14.00	19.68	21.87	20.78	31.70	33.45	32.58
Misr 3	21.16	22.05	21.61	23.55	25.52	24.53	10.15	13.59	11.87	22.20	22.65	22.42	25.95	26.84	26.39	14.45	15.62	15.04
Lien Shandweel 2	21.37	22.89	22.13	23.44	25.33	24.38	8.82	9.64	9.23	22.23	23.08	22.66	24.84	26.05	25.44	10.52	11.37	10.95
Lien Nubaria 2	17.20	18.09	17.65	18.32	19.77	19.05	6.11	8.48	7.29	17.97	18.97	18.47	19.88	21.15	20.51	9.61	10.27	9.94
Giza 171	17.25	18.12	17.69	23.33	25.02	24.18	26.05	27.59	26.82	18.16	18.75	18.45	25.32	26.68	26.00	28.27	29.71	28.99
T.S.S	2.27	2.67	2.47	9.88	13.42	11.65	77.02	80.13	78.58	2.22	2.57	2.39	10.94	14.38	12.66	79.75	82.13	80.94
Total	14.62	15.59	15.10	18.48	20.51	19.50	24.11	26.34	25.23	15.61	16.25	15.93	20.50	22.04	21.27	27.03	28.56	27.80
LSD0.05	Location=0.361 Genotype=0.726 Location*Genotype=NS			Location=0.539 Genotype=0.900 Location*Genotype=NS			Location=0.496 Genotype=0.453 Location*Genotype=0.708			Location=0.076 Genotype=0.390 Location*Genotype=NS			Location=0.105 Genotype=1.096 Location*Genotype=Ns			Location=0.379 Genotype=0.428 Location*Genotype=0.634		

Table 7 showed grain yield per plot (kg) differences between protected and infected plants for each genotype. These differences corresponded to disease severity levels in the tested cultivars. In the first season, grain yield loss ranged from 6.25% to 77.02%. The check variety T.S.S and susceptible cultivars Gemmiza 7, Gemmiza 11, Giza 171, and Sids 12 showed higher losses (33.29%, 27.7%, 26.05%, and 21.59% at Itay Elbaroud; 36.48%, 30.26%, 27.59%, and 23.25% at Sids, respectively). In contrast, partially resistant genotypes Nubaria, Sids 1, Shandweel, and Misr 3 showed the lowest losses (6.11%, 6.25%, 8.82%, and 10.15% at Itay Elbaroud; 7.65%, 8.48%, 9.64%, and 13.59% at Sids).

These findings were consistent for the second season where again susceptible genotypes had the greatest losses in grain yield as follows, Itay Elbaroud (35.32% to 24.959) and Sids (38.68% to 26.59). Resistant genotypes again showed the least grain yield losses, Itay Elbaroud (8.67% to 14.45%) and Sids (9.24% to 15.62%).

3- Correlation Analysis Between Disease Parameters and Yield Losses in Wheat Genotypes

This section presented the simple correlation coefficients estimated over two growing seasons and two locations, Itay Elbaroud and Sids, to investigate the relationships between disease severity parameters and yield losses in wheat. The results were summarized in Tables (8a-d).

Table 8a. Correlation coefficients between wheat disease parameters and percentage losses of yield components during the first season (2023/2024) at Itay Elbaroud location.

Studied Traits	FRS %	AUDPC	rAUDPC	Losses Grain (%)	Losses 1000 (%)
AUDPC	.978**				
rAUDPC	.978**	1.000**			
Losses Grain (%)	.655**	.718**	.718**		
Losses 1000 (%)	.677**	.750**	.750**	.986**	
Losses K/S (%)	.685**	.761**	.761**	.978**	.997**

**. Correlation is significant at the 0.01 level (2-tailed).

Table 8b. Correlation coefficients between wheat disease parameters and percentage losses of yield components during the first season (2023/2024) at Sids location.

Studied Traits	FRS %	AUDPC	rAUDPC	Losses Grain (%)	Losses 1000 (%)
AUDPC	.982**				
rAUDPC	.982**	1.000**			
Losses Grain (%)	.654**	.668**	.668**		
Losses 1000 (%)	.679**	.709**	.709**	.987**	
Losses K/S (%)	.685**	.716**	.716**	.982**	.997**

**. Correlation is significant at the 0.01 level (2-tailed).

Table 8c. Correlation coefficients between wheat disease parameters and percentage losses of yield components during the second season (2024/2025) at Itay Elbaroud location.

Studied Traits	FRS %	AUDPC	rAUDPC	Losses Grain (%)	Losses 1000 (%)
AUDPC	.969**				
rAUDPC	.969**	1.000**			
Losses Grain (%)	.648**	.706**	.706**		
Losses 1000 (%)	.686**	.757**	.757**	.985**	
Losses K/S (%)	.688**	.759**	.759**	.979**	.999**

**. Correlation is significant at the 0.01 level (2-tailed).

Table 8d. Correlation coefficients between wheat disease parameters and percentage losses of yield components during the second season (2024/2025) at Sids location.

Studied Traits	FRS %	AUDPC	rAUDPC	Losses Grain (%)	Losses 1000 (%)
AUDPC	.983**	1			
rAUDPC	.983**	1.000**	1		
Losses Grain (%)	.650**	.651**	.651**	1	
Losses 1000 (%)	.671**	.679**	.679**	.989**	1
Losses K/S (%)	.690**	.701**	.701**	.976**	.996**

**. Correlation is significant at the 0.01 level (2-tailed).

The data revealed highly significant and positive correlations among all studied traits. The Final disease severity, AUDPC (Area Under Disease Progress Curve), and relative AUDPC (rAUDPC) showed strong positive correlations with grain yield loss, loss in 1000-kernel weight percentage, and loss in kernel number per spike percentage. The Final disease severity demonstrated a very strong direct correlation with both AUDPC and rAUDPC with correlation coefficients nearing 0.97 and a moderate positive correlation with grain yield loss and losses due to kernels. Both AUDPC and rAUDPC were perfectly correlated with one another with a correlation coefficient of 1 and often times moderate to strong correlations with grain yield loss and losses related to kernel components. Grain yield loss was strongly correlated with % losses in both 1000-kernel weight and kernels per spike and a strong relationship was also shown between % losses in 1000-kernel weight and kernels per spike. These findings indicate that higher disease severity as measured by Final Rust Severity (FRS), AUDPC, and rAUDPC is closely associated with greater reductions in yield and its components.

Tables 8a to 8d showed the correlation coefficients between disease parameters and yield losses for two seasons and two locations. For all cases, and all correlations were statistically significant ($p < 0.01$), indicating that relationships indicated above are robust. The correlation analysis showed strong and positive relationships of more severe disease parameters of wheat with estimated yield losses (both grain weight and number of kernals). The 100% correlation value for AUDPC and rAUDPC validates their credibility as measures of disease progress. Overall, these results indicate a fundamental need for acceptable disease management methods that minimize yield losses.

4. Tolerance Indices of Wheat Cultivars under Protected and Unprotected Conditions at Sids and Itay El Baroud Locations

The grain yield of the studied wheat cultivars in protected (ideal environment) and unprotected (stress environment) conditions at Sids & Itay El Baroud locations, with their tolerance indices and ranks, was summarized in Figure 1. There was pronounced variation in grain yield among cultivars in two environments, indicating genetic variability & diversity in stress tolerance.

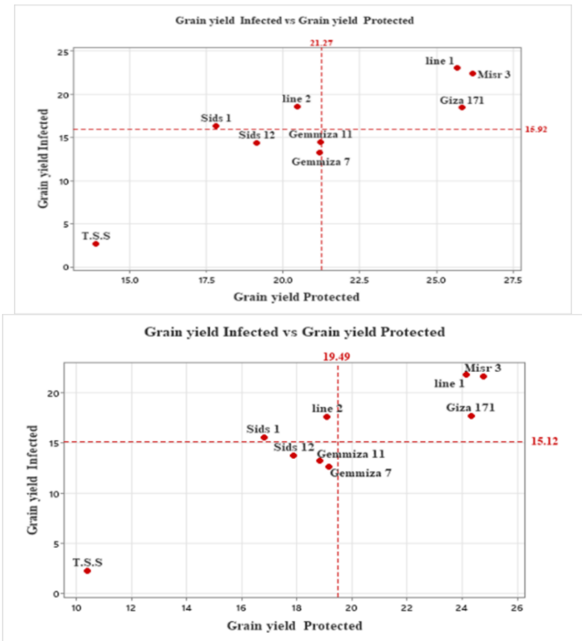

*Figure divided into upper (A) refers to sids location and below (B) refers to Itay Elbaroud

Figure 1. Interaction effect of wheat genotypes under protected vs. unprotected conditions on grain yield at Sids and Itay Elbaroud locations across two growing seasons.

Additionally, the four tolerance indices in the study were based on the average grain yield of the two environments. Therefore, cultivars with higher values in each of the four indices were classified as stress tolerant, and cultivars with lower yield values were classified as sensitive. The results show slight differences among the four indices for the ranking of the cultivars. Therefore, the use of a single tolerance index may be sufficient for future assessments.

Location Sids

The average grain yield of all the cultivars under unprotected conditions was 15.72 ardab/fed and 21.27 ardab/fed under protected conditions, which was about a 22.41% productivity gain in the protected environment. According to Table 10, the cultivars Line 1 (Shandweel 2), Misr 3, and Giza 171 were categorized as stress tolerant from the highest values detected from the four tolerance indices. The cultivars Gemmeiza 7 and Gemmeiza 11 had medium tolerance, while the cultivars Sids 12, Sids 1, and Line 2 (Nubaria 2) had average listed. The cultivar T.S.S. had the lowest performance in the protected environment.

Under unprotected conditions, all the same tolerant cultivars were present: Line 2 (Nubaria 2), Sids 1, Misr 3, Line 1 (Shandweel 2), and Giza 171, while Gemmeiza 7, Gemmeiza 11, and Sids 12 were less tolerant. Misr 3, Line 1 (Shandweel 2), and Giza 171 were recommended for growing under both unprotected and protected conditions for the Itay El Baroud location. In contrast, Gemmeiza 7, Gemmeiza 11, Sids 12, Sids 1, and T.S.S. were determined as susceptible, with lower tolerance index values indicating that these cultivars will not provide profit under stress.

Location Itay Elbaroud

For this location, the average grain yield under unprotected conditions was 15.12 ardab/fed and increased to 19.49 ardab/fed for the protected conditions, which also reflected an improvement of 22.41%. As noted on Sids' site, Line 1 (Shandweel 2), Misr 3, and Giza 171 also would have the highest tolerance based on the tolerance indices, while lower tolerance scores were exhibited by Gemmeiza 7, Gemmeiza 11, Sids 12, Sids 1, and Line 2 (Nubaria 2). The tolerant cultivars also exhibited the least reductions in grain yield in the two locations, while the susceptible cultivars had higher reductions in yields to reduce profitability.

The tables table (9 and 10) indicated the four tolerance indices, which mean productivity (MP), harmonic mean (HM), geometric mean productivity (GMP), and stress tolerance index (STI), along with percentage yield reduction (Red%) and the rank of the cultivars of the two locations. Overall, the results confirmed better performance of Shandweel 2, Misr 3, and Giza 171 cultivars as stress-tolerance cultivars and a lower performance of Gemmeiza 7, Gemmeiza 11, Sids 12, and T.S.S. cultivars.

Table 9. Estimates of four tolerance indices and their respective ranks for nine bread wheat cultivars based on grain yield at Sids location under protected and unprotected conditions across two growing seasons.

No.	Wheat cultivars	Grain yield		Tolerance indices				
		Protected	Unprotected	MP	HM	GMP	STI	Red %
1	Gemmeiza 11	21.23	14.46	17.85	17.20	17.52	0.68	31.91
2	Gemmeiza 7	21.20	13.22	17.21	16.29	16.74	0.62	37.64
3	Giza 171	25.85	18.43	22.14	21.52	21.83	1.05	28.69
4	Line 1 (Shandweel 2)	25.69	22.99	24.34	24.26	24.30	1.30	10.52
5	Line 2 (Nubaria 2)	20.46	18.53	19.50	19.45	19.47	0.84	9.41
6	Misr 3	26.18	22.35	24.27	24.11	24.19	1.29	14.63
7	Sids 1	17.83	16.31	17.07	17.04	17.05	0.64	8.51
8	Sids 12	19.14	14.36	16.75	16.41	16.58	0.61	24.97
9	T.S.S	13.90	2.62	8.26	4.41	6.03	0.08	81.16
			Corresponding ranks					
1	Gemmeiza 11	4	6	5	5	5	5	7
2	Gemmeiza 7	5	8	6	8	7	7	8
3	Giza 171	2	4	3	3	3	3	6
4	Line 1 (Shandweel 2)	3	1	1	1	1	1	3
5	Line 2 (Nubaria 2)	6	3	4	4	4	4	2
6	Misr 3	1	2	2	2	2	2	4
7	Sids 1	8	5	7	6	6	6	1
8	Sids 12	7	7	8	7	8	8	5
9	T.S.S	9	9	9	9	9	9	9

Table 10. Estimates of four tolerance indices and their respective ranks for nine bread wheat cultivars based on grain yield at Itay Elbaroud location under protected and unprotected conditions across two growing seasons.

No.	Wheat cultivars	Grain yield		Tolerance indices				
		Protected	Unprotected	MP	HM	GMP	STI	Red %
1	Gemmeiza 11	18.83	13.22	16.03	15.54	15.78	0.66	29.80
2	Gemmeiza 7	19.17	12.58	15.87	15.19	15.53	0.63	34.38
3	Giza 171	24.32	17.71	21.01	20.49	20.75	1.13	27.21
4	Line 1 (Shandweel 2)	24.14	21.80	22.97	22.91	22.94	1.39	9.70
5	Line 2 (Nubaria 2)	19.10	17.59	18.34	18.31	18.33	0.88	7.93
6	Misr 3	24.75	21.68	23.21	23.11	23.16	1.41	12.40
7	Sids 1	16.80	15.53	16.17	16.14	16.16	0.69	7.58
8	Sids 12	17.88	13.71	15.80	15.52	15.66	0.65	23.34
9	T.S.S	10.41	2.24	6.33	3.69	4.83	0.06	78.45
			Corresponding ranks					
1	Gemmeiza 11	6	7	6	6	6	6	7
2	Gemmeiza 7	4	8	7	8	8	8	8
3	Giza 171	2	3	3	3	3	3	6
4	Line 1 (Shandweel 2)	3	1	2	2	2	2	3
5	Line 2 (Nubaria 2)	5	4	4	4	4	4	2
6	Misr 3	1	2	1	1	1	1	4
7	Sids 1	8	5	5	5	5	5	1
8	Sids 12	7	6	8	7	7	7	5
9	T.S.S	9	9	9	9	9	9	9

5. Linear Regression Analysis of AUDPC and Yield Loss

The relationship of the relevant area under the disease progress curve (rAUDPC) to yield loss was positive for all traits (grain yield, number of kernels per spike, and 1000 grain weight) under evaluation in both locations, and seasons as shown in Figures 2, 3 and 4.. The nine wheat cultivars included Sids 1, Gemmeiza 7, Gemmeiza 11, Giza 171, Misr 3, Sids 12, Line 1, Line 2, and T.S.S exhibited a linear relationship with increasing yield loss corresponding to increasing rAUDPC.

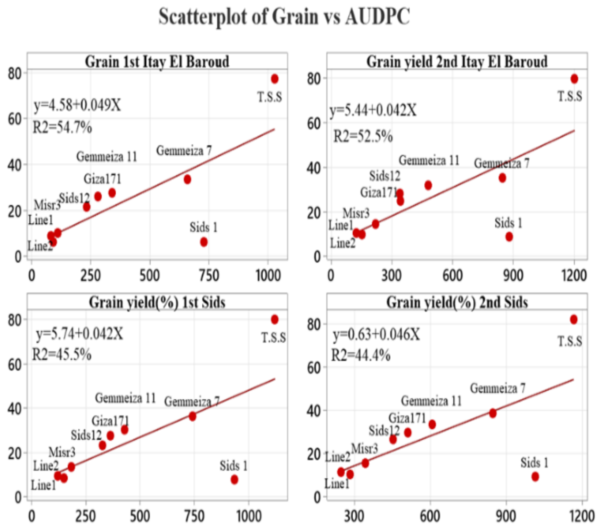

Figure 2. Relationship between AUDPC and yield loss in wheat cultivars at Sids and Itay El Baroud across two growing seasons.

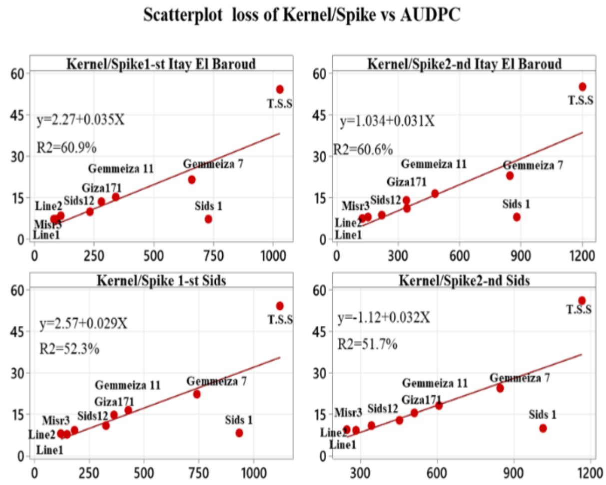

Figure 3. Relationship between AUDPC and number of kernels per spike in wheat cultivars at Sids and Itay El Baroud across two growing seasons.

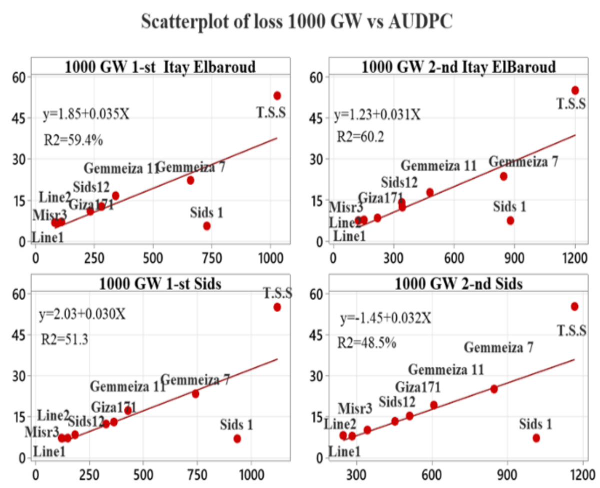

Figure 4. Relationship between AUDPC and 1000 grain weight in wheat cultivars at Sids and Itay El Baroud across two growing seasons.

The coefficient of determination (R^2) for each regression model was calculated to examine the strength of these relationships. As illustrated in Figure 2, Line 1, Line 2, and Misr 3 all showed substantial tolerance to leaf rust of low rAUDPC and lower yield losses; Gemmeiza 11, Giza 171, and Sids 12 showed moderate tolerance; while Sids 1 appeared more sensitive with higher grain yield losses similar to the susceptible check genotype T.S.S.

The linear relationship between rAUDPC and loss in yield components(Figure 3 and 4),, especially kernel number per spike and 1000-kernel weight, was evident at both locations of Sids and Itay El Baroud in both years. In particular, Line 1, Line 2, and Misr 3 maintained their tolerance, while Sids 1 showed some promise due to its relatively low losses in kernel number per spike, despite its susceptibility.

Discussion

In light of climate change and shifting *Puccinia triticina* populations, wheat leaf rust remains a major worldwide problem for wheat production. According to El-Orabey *et al.* (2020) and Yadav *et al.* (2025), under ideal circumstances, it can result in yield losses of up to 40%. Changes in temperature regimes, humidity patterns, and wind-driven spore dispersal have been shown to increase both the frequency and aggressiveness of rust, making the deployment of cultivars with durable resistance an urgent breeding priority (Omara *et al.,* 2021 and Zhang *et al.,* 2022). Managing leaf rust requires combined strategies. This includes the development of and use of resistant or tolerant varieties, responsible fungicide application, and utilizing production practices that will minimize the spread of disease. However, breeding for durable resistance represents the most sustainable long-term solution. Where it is possible, it is critical to evaluate wheat genotypes for resistance or tolerance under field conditions to identify high-yielding lines that can maintain yield under disease pressure (Mapuranga *et al.,* 2022 and Mabrouk *et al.,* 2025).

This study assessed nine bread wheat cultivars across two consecutive growing seasons (2023–2024 and 2024–2025) in two Egyptian agro-climatic zones. Disease progress was monitored through final rust severity (FRS%), the area under the disease progress curve (AUDPC), and relative AUDPC (rAUDPC), while yield losses in 1000-kernel weight, kernels per spike, and grain yield per plot were determined by comparing protected and infected plants (Paraschivu *et al.,* 2023 and Saranya *et al.,* 2025).

Significant distinctions in susceptibility to rust were found. Sids 1, Gemmeiza 7, and Gemmeiza 11 had the highest disease pressure (FRS up to 41.67%, AUDPC > 500, rAUDPC > 60%) and yield reductions above approximately 35% on some yield components. On the contrary, Shandweel 2 (FRS 10–18.33%, rAUDPC < 25%), Nubaria 2 (FRS 12.5–21.67%, rAUDPC 18–30%), and Misr 3 (FRS 18.33–28.33%, rAUDPC 25–35%) exhibited the lowest levels of disease severity and minimal yield loss demonstrating moderate partial resistance. With the increase in diseases, yield components (kernel number per spike and 1000-kernel weight) consistently declined, showing that rust negatively impacted important agronomic traits. This aligns with other studies (Srinivas *et al.,* 2023; Paraschivu *et al.,* 2023 and Mabrouk *et al.,* 2025) that reported similar disease-yield associations in varying agro-ecological situations.

The important correlations indicate that AUDPC, rAUDPC, and yield losses can be used with confidence as reliable measures of resistance in screening cultivars, which is consistent with Mabrouk *et al.* (2022) and Ashmawy *et al.* (2024) who reported slow-rusting components were reliable measures of durability. Our data also reflect findings of Omara *et al.* (2021) and Ali *et al.* (2022) that the combination of epidemiological data and yield loss provides a more accurate evaluation of cultivars when evaluated in field conditions. This implies that the tolerance or resistance genotypes under investigation can be distinguished using an equivalent strategy (Darwish *et al.,* 2017; Gaballa *et al.,* 2019; Selim *et al*., 2021 and Yadav *et al.,* 2025). Understanding these correlations can help make selection easier in breeding programs by cutting down on redundant evaluation criteria.

By integrating multi-parameter disease assessment with yield performance across diverse environments, this work provides a modern and field-relevant framework for identifying high-yielding, rust-resistant cultivars. The discovery of three promising genetic materials (Shandweel 2, Nubaria 2, and Misr 3) is increasingly important to breeding programs looking to obtain sustained productivity, in light of current and future climate conditions.

CONCLUSION

In summary, this study furthers our understanding of the type of wheat rust resistance and tolerance Rs from wheat genotypes under field conditions in Egypt and provides valuable evidence to base decisions on improving wheat productivity. The combined use of measurements for disease severity, tolerance indices, and regression models offers a framework to pursue in breeding programs around the world. Future research should involve more molecular characterizations of the resistant genotypes and evaluating their gene by environment interactions to find durable resistance against evolving rust populations.

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تقييم خسائر محصول قمح الخبز (الناتجة عن صدأ الأوراق في مواسم وبيئات مختلفة

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الملخص

في ظل التغيرات المناخية وتطور سلالات المسببات المرضية، يعد صدأ أوراق القمح (*Puccinia triticina*) من أخطر الأمراض التي تصيب القمح عالميًا، حيث يتسبب خسائر كبيرة في كمية المحصول وجودته. هدفت هذه الدراسة إلى تقييم العلاقة بين شدة الإصابة وخسائر المحصول في تسعة أصناف من قمح الخبز خلال موسمين متتاليين (٢٠٢٣–٢٠٢٤ و٢٠٢٤–٢٠٢٥) وفي موقعين مختلفين. تم قياس تطور المرض باستخدام شدة الإصابة النهائية(FRS%) ، والمساحة تحت منحنى تطور المرض (AUDPC) ، والمساحة النسبية تحت المنحنى .(rAUDPC) كما قورنت مكونات المحصول (وزن الألف حبة، عدد الحبوب في السنبلة، غلة الحبوب في الحوض) بين النباتات المحمية والمصابة. سجلت الأصناف سدس١ , جميزه ٧ و جميزه ١١ أعلى مستويات للمرض FRS) حتى ٤١,٦٧%، AUDPC > 500، (rAUDPC > 60%مع خسائر تجاوزت ٣٥٪ في بعض الصفات. بينما أظهرت شندويل ٢ FRS 10–18.33%) ، (rAUDPC < 25% ونوبارية ٢ FRS 12.5–21.67%)، (rAUDPC 18–30% ومصر ٣ FRS 18.33–28.33%)، (rAUDPC 25–35% أقل شدة مرضية وخسائر محدودة، ما يدل على مقاومتها الجزئية. أظهرت التحليلات وجود ارتباطات معنوية بين مؤشرات شدة المرض وخسائر المحصول، مما يبرز أهميتها كأدوات موثوقة في انتخاب الأصناف المقاومة ودعم برامج التربية والإدارة المتكاملة للأمراض.

الكلمات الدالة: القمح، صدأ الأوراق، خسائر المحصول، مؤشرات التحمل.