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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 infected plants. The highest 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 Gameda 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 million tons annually, Egypt faces a persistent production gap, leaving the country vulnerable to global grain market fluctuations (FAO, 2024 and Mabrouk *et al.*, 2025).

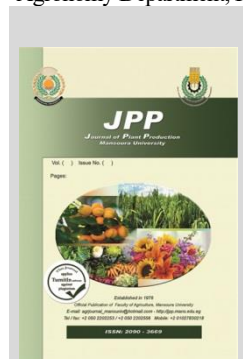
Among the most serious biotic constraints to wheat yield, and quality are rust diseases, leaf rust (*Puccinia triticina*), stem rust (*P. graminis* f. sp. *tritici*), and stripe rust (*P. striiformis* f. sp. *tritici*). Leaf rust is the most widespread and can reduce kernel weight and photosynthetic 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; Gemedu 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	<i>Triticum aestivum</i> L.	HdHD2172/Pavon"S"/1158.57/Maya74"S" SD46-4SD-2SD-1SD-0SD	1996
2	Sids 12	<i>Triticum aestivum</i> 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	<i>Triticum aestivum</i> L.	CMH 74A.360 / SX // SERI 8213 / AGENT CGM4611-2GM-3GM-1GM-0GM	1999
4	Gemmeiza 11	<i>Triticum aestivum</i> L.	BOW"S"/KVZ"S"/7C/SERI82/3/GIZA168/SAKHA61GM5820- 3GM-1GM-2GM-0GM	2011
5	Misr 3	<i>Triticum aestivum</i> L.	ATTILA*2/PBW65*2//KACHUCMSS06Y00582T-099TOPM- 099Y-099ZTM-099Y-099M-10WGY-0B-0EGY	2021
6	Line Shadweel 2	<i>Triticum aestivum</i> L.	QUAIU/5/FRET2*2/4/SNT/TRAP#1/3/HAUZ*2/TRAP//	2011
7	Line Nubaria 2	<i>Triticum aestivum</i> L.	FRET2*2/4/SNT/TRAP#1/3/KAUZ*2/TRAP//KAUZ*2/5/BOW/U RES//2*WEAVER/3/CROC 1/AESQUARROSA (213)/POG	2005
8	Giza 171	<i>Triticum aestivum</i> L.	SAKHA 93 / GEMMEIZA 9 S.6-1GZ-4GZ-1GZ-2GZ-0S	2013
9	<i>Triticum spelta saharinsis</i> (T.S.S)	<i>Triticum spelta</i> 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 severity 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): $AUDPC = D [1/2 (Y_1 + Y_k) + \sum Y_2 \dots Y_{k-1}]$, 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):

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

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 (Y_s) 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 <i>et al.</i> , 2009)
3	Geometric Mean Productivity (GMP)	$(Y_n * Y_s)^{0.5}$	(Fernandez, 1992)
4	Stress Tolerance Index (STI)	$(Y_n * Y_s) / (Y_n)^2$	(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

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
Misir 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			Location= 83.76			Location= 6.95		
	Genotype = 5.616			Genotype = 82.96			Genotype = 6.91		
	Genotype*Location = Ns			Genotype*Location= Ns			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
Misir 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			Location= 98.976			Location= 7.643		
	Genotype = 5.988			Genotype = 98.976			Genotype = 7.857		
	Genotype*Location = Ns			Genotype*Location= Ns			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 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*	135000*	110523*	132066*	129389*	78750*
(R) ^B	4	92.59	92.59	12289	17157	8448	10231
(G) ^C	8	368588**	379074*	723305**	752814**	512857**	448898**
(L×G) ^D	8	208 ^{NS}	82 [*]	3182 ^{NS}	7057 ^{NS}	3891 ^{NS}	4208 ^{NS}
Error	32	2280	2593	4977	7485	3448	4463

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.

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 Gemmeiza 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 Gemmeiza 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 Gemmeiza 7 (22.13% and 23.49%) and Gemmeiza 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 Gemmeiza 7, Gemmeiza 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.

SOV	df	Meansquaresofyieldcomponentparameters																	
		1000kernelweight(gm)						Numberofkernelsperspike(K/S)						Grainyield/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	261 ^{ns}	189 ^{ns}	1819 ^{**}	1376 ^{ns}	1119 ^{ns}	1119 ^{ns}	13251 ^{ns}	4572 ^{ns}	7814 ^{**}	11152 ^{ns}	07337 ^{ns}	3494 ^{**}	12382 ^{**}	55838 ^{**}	67197 ^{**}	54734 ^{**}	31804 ^{**}	3178 ^{**}
(R) ^B	4	60	837	016	789	012	0824	740	854	01684	748	101679	0988	0280	0804	0406	0179	0198	025
(G) ^C	8	4478 ^{**}	6153 ^{**}	13536 ^{**}	4648 ^{**}	021 ^{**}	1397 ^{**}	112996 ^{**}	31294 ^{**}	1301 ^{**}	114853 ^{**}	3160140 ^{**}	136 ^{**}	217401 ^{**}	112651 ^{**}	304098 ^{**}	228887 ^{**}	113408 ^{**}	30857 ^{**}
(L×G) ^D	8	079 [*]	018 ^{ns}	0297 ^{ns}	0178 ^{**}	0184 ^{ns}	071 ^{**}	079 ^{ns}	028 ^{**}	0229 ^{**}	0861 ^{**}	110945 ^{**}	0805 ^{**}	0160 ^{ns}	0788 ^{ns}	1245 ^{**}	01257 ^{ns}	10827 ^{ns}	120 ^{**}
Error	32	081	041	024	0188	0120	0172	0141	0112	01862	016	01974	01654	0808	0889	0142	04567	0882	013

(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
Gemmiza 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
Gemmiza 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			Location=NS			Location=0301			Location=2132			Location=NS			Location=0430		
	Genotype=0208			Genotype=0239			Genotype=0544			Genotype=0216			Genotype=0175			Genotype=0331		
	Location*Genotype=1908			Location*Genotype=NS			Location*Genotype=NS			Location*Genotype=NS			Location*Genotype=NS			Location*Genotype=0550		
	Number of kernels per spike (K/S)																	
Sids1	6204	63.14	62.59	6694	6890	6792	732	835	784	6243	6283	6263	6795	6991	6893	812	1012	912
Sids12	6303	6402	63.53	6996	7194	7095	990	1101	1046	6346	6346	6346	7153	7278	7215	1128	1281	1205
Gemmiza7	5567	5689	56.28	7096	7314	7205	2156	2221	2189	5605	5506	5555	7285	7285	7285	2306	2443	2374
Gemmiza11	5850	5980	59.15	6905	7155	7030	1528	1643	1585	5934	5815	5874	7104	7104	7104	1647	1815	1731
Misr3	6420	6523	64.72	7021	7192	7107	856	927	891	6490	6325	6408	7111	7111	7111	873	1105	989
LionShandweel2	6655	6705	66.80	7192	7291	7241	747	804	775	6747	6598	6673	7295	7295	7295	751	955	853
LionNubaria2	6627	6720	66.73	7155	7295	7225	738	789	763	6705	6613	6659	7297	7297	7297	811	937	874
Giza171	6099	6189	61.44	7071	7271	7171	1375	1488	1431	6186	6000	6093	7198	7100	7149	1406	1550	1478
TSS	2238	2332	22.85	4880	5082	4981	5413	5411	5412	2249	2200	2225	5031	5017	5024	5528	5616	5572
Mean	57.74	58.73	58.23	67.79	69.65	68.72	1615	1691	1653	5834	5743	5788	6919	6942	6930	1696	1857	1776
LSD0.05	Location=NS			Location=NS			Location=0310			Location=NS			Location=Ns			Location=0162		
	Genotype=0237			Genotype=0167			Genotype=0280			Genotype=0224			Genotype=0311			Genotype=0299		
	Location*Genotype=NS			Location*Genotype=2214			Location*Genotype=0439			Location*Genotype=2000			Location*Genotype=2379			Location*Genotype=0414		

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
Sids1	1416	1516	1466	1510	1642	1576	625	765	695	1690	1746	1718	1850	1924	1887	867	924	896
Sids12	1346	1423	1384	1716	1854	1785	2159	2325	2242	1396	1449	1423	1860	1974	1917	2495	2659	2577
Gemmiza7	1171	1272	1222	1755	2003	1879	3329	3648	3488	1345	1372	1358	2079	2237	2158	3532	3868	3700
Gemmiza11	1300	1436	1368	1799	2059	1929	2770	3026	2898	1345	1455	1400	1968	2187	2078	3170	3345	3258
Misr3	2116	2205	2161	2355	2552	2453	1015	1359	1187	2220	2265	2242	2595	2684	2639	1445	1562	1504
LineShandweel2	2137	2289	2213	2344	2533	2438	882	964	923	2223	2308	2266	2484	2605	2544	1052	1137	1095
LineNubaria2	1720	1809	1765	1832	1977	1905	611	848	729	1797	1897	1847	1988	2115	2051	961	1027	994
Giza171	1725	1812	1769	2333	2502	2418	2605	2759	2682	1816	1875	1845	2532	2668	2600	2827	2971	2899
TSS	227	267	247	988	1342	1165	7702	8013	7858	222	257	239	1094	1438	1266	7975	8213	8094
Total	1462	1559	1510	1848	2051	1950	2411	2634	2523	1561	1625	1593	2050	2204	2127	2703	2856	2780
LSD005	Location=0361 Genotype=0726			Location=0539 Genotype=0900			Location=0496 Genotype=0453			Location=0076 Genotype=0390			Location=0105 Genotype=1096			Location=0379 Genotype=0428		
	Location*Genotype=NS			Location*Genotype=NS			Location*Genotype=0708			Location*Genotype=NS			Location*Genotype=NS			Location*Genotype=0634		

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 kernels). 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.

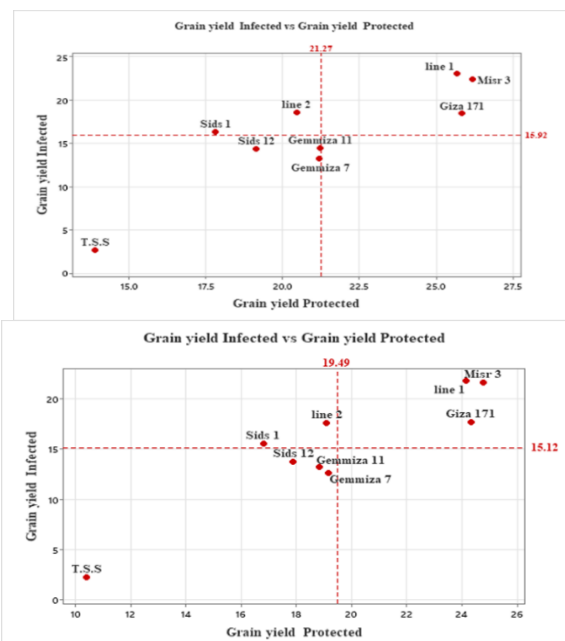


Figure 1. Interaction effect of wheat genotypes under protected vs. unprotected conditions on grain yield at Sids and Itay Elbaroud locations across two growing seasons.

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.

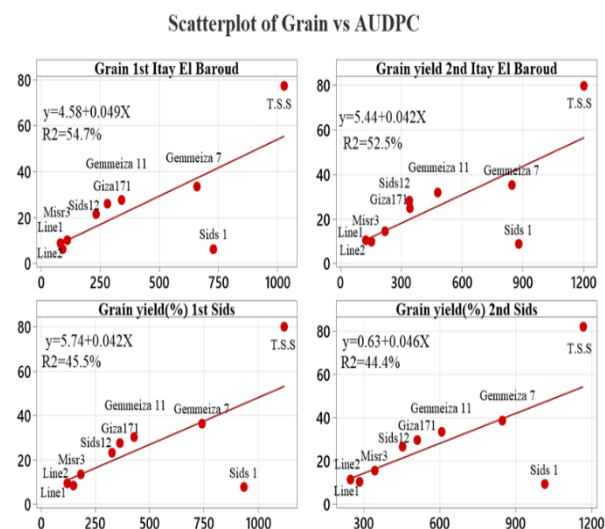


Figure 2. Relationship between AUDPC and yield loss in wheat cultivars at Sids and Itay El Baroud across two growing seasons.

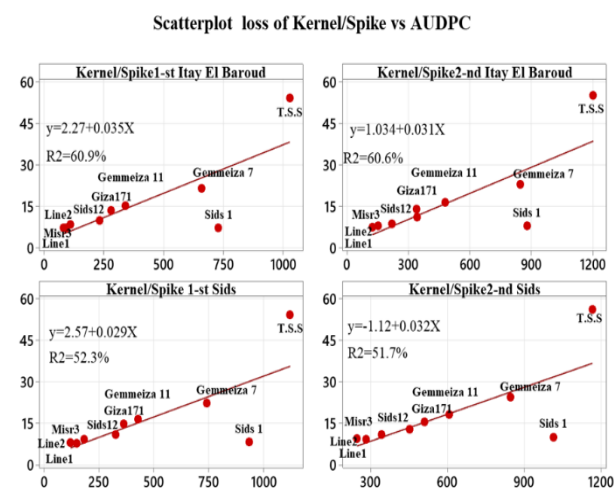


Figure 3. Relationship between AUDPC and number of kernels per spike in wheat cultivars at Sids and Itay El Baroud across two growing seasons.

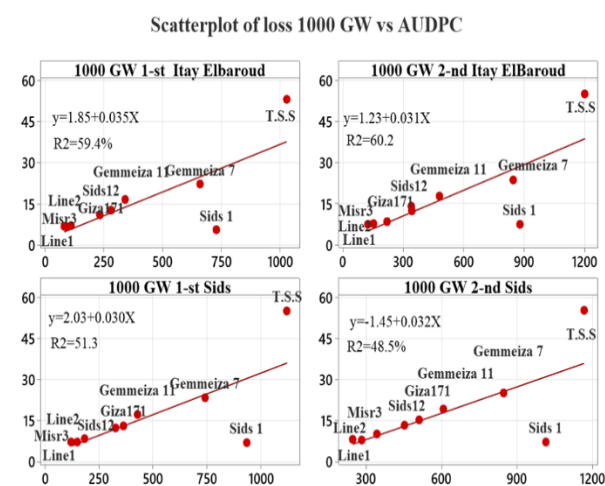


Figure 4. Relationship between AUDPC and 1000 grain weight in wheat cultivars at Sids and Itay El Baroud across two growing seasons.

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 (النتيجة عن صدى الأوراق في مواسم وبيئات مختلفة)

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الملخص

في ظل التغيرات المناخية وتطور سلالات مسببات المرضية، يعد صدى أوراق القمح (*Puccinia triticina*) من أخطر الأمراض التي تصيب القمح عالمياً، 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 و ٢٠٢٤-٢٠٢٥) 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 السنبل، غلة الحبوب في الحوض) بين النباتات المحمية والمصابة. سجلت الأصناف سدس ١، 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 كنوات مؤثرة في انتخاب الأصناف المقاومة ودعم برامج التربية والإدارة المتكاملة للأمراض.

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