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Multi-Environment Evaluation of Egyptian Wheat Cultivars for Adult-Plant Resistance to Stem Rust Using AMMI Stability Analysis

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Abstract: Stem rust, caused by *Puccinia graminis* f. sp. tritici, remains a major threat to wheat production worldwide, particularly under favorable environmental conditions that promote rapid disease development. This study aimed to evaluate the adult-plant resistance and stability of twenty Egyptian wheat cultivars to stem rust across multiple environments and growing seasons. Field experiments were conducted at Ismailia and Sharqia governorates, Egypt, over three successive seasons (2022–2024) using a randomized complete block design under high disease pressure. Disease resistance was assessed using final rust severity (FRS, %) and area under the disease progress curve (AUDPC), while genotype × environment (G×E) interaction and stability were analyzed using the additive main effects and multiplicative interaction (AMMI) model. Significant differences ($P < 0.01$) were detected among genotypes, environments, and their interactions for both FRS and AUDPC. Esmailia exhibited higher disease pressure than Sharkia, allowing clearer discrimination among varietal responses. Cultivars Misr 1 and Misr 2 consistently showed the highest FRS and AUDPC values, indicating high susceptibility across environments. In contrast, Misr 4, Misr 5, Misr 6, and Misr 7 expressed complete resistance, recording zero FRS and AUDPC values across all locations and seasons. Several cultivars, including Misr 3, Giza 171, Sakha 95, Sids 13, and Sids 14, displayed low disease severity and moderate AUDPC values, suggesting effective partial or slow-rusting resistance. AMMI analysis revealed that genotypic effects accounted for the largest proportion of total variation, while the first two interaction principal component axes explained the majority of G×E interaction for both disease parameters. Stability analysis based on AMMI stability value (ASV) and genotype selection index (GSI) identified Sids 12, Sids 13, Sids 14, and Giza 171 as the most stable genotypes with low disease levels across environments. Overall, the

results highlight the presence of substantial genetic variation for stem rust resistance among Egyptian wheat cultivars and emphasize the importance of multi-environment testing combined with robust statistical analysis. The highly resistant and stable cultivars identified in this study represent valuable candidates for cultivation in rust-prone areas and as sources of durable resistance in wheat breeding program.

Key words: Wheat; stem rust, disease parameters; AMMI stability.

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops worldwide, providing a major source of calories and protein for humans and livestock **(Alnusairi *et al.*, 2021 and Khedr *et al.*, 2023)**. In Egypt, wheat is of strategic importanc for national food security, as the country is one of the largest consumers of bread and currently the world's leading wheat importer. Consequently, narrowing the gap between domestic wheat production and consumption remains a major national challenge, requiring intensified research efforts focused on yield stability and stress resilience **(Abdelmageed *et al.*, 2018)**.

Wheat productivity is constrained by multiple abiotic and biotic stresses that vary across agroecological zones. Among the most limiting abiotic factors are water scarcity **(Wang *et al.*, 2024; Li *et al.*, 2024)** and soil salinity **(Zhang *et al.*, 2024)**, while fungal diseases—particularly rusts—represent the most serious biotic threats to wheat production **(Abdelaal *et al.*, 2018; Shahin *et al.*, 2021; Khan *et al.*, 2024; Nazarov *et al.*, 2024)**. Rust diseases are especially damaging under favorable environmental conditions, where they can spread rapidly and cause severe yield reductions.

Stem rust, caused by *Puccinia graminis* f. sp. *tritici*, is regarded as one of the most destructive wheat diseases globally **(Omara *et al.*, 2017; Abdelaal *et al.*, 2018)**. Rust fungi impose severe physiological stress on wheat plants, leading to significant yield losses in susceptible cultivars **(Belayneh and Emebet, 2005)**. Symptoms typically appear on stems and leaf sheaths, but may also affect leaf blades and glumes **(Leonard and Szabo, 2005)**. The pathogen has a complex macrocyclic life cycle involving five spore stages and is heteroecious, requiring alternate hosts—primarily species of *Berberis* and *Mahonia*—to complete its life cycle **(Leonard and Szabo, 2005; Martínez-Moreno and Solís, 2019)**.

Under conducive environmental conditions, *P. graminis* f. sp. *tritici* can rapidly evolve new physiological races capable of overcoming host resistance, resulting in widespread epidemics. In epidemic years, yield losses may reach up to 100% over large production areas. The emergence of the highly virulent Ug99 race group (TTKSK), first detected in Uganda in 1998, shattered the long-held assumption that stem rust had been effectively controlled **(Singh *et al.*, 2008; Jin *et al.*, 2008; Chen *et al.*, 2009)**. Since then, Ug99 and its derivatives have spread across multiple wheat-growing regions, including several African and Middle Eastern countries, as well as Egypt **(Nazari *et al.*, 2009)**.

The deployment of resistant cultivars remains the most effective, economical, and environmentally sustainable approach for managing stem rust **(Singh *et al.*, 2011; Admassu *et al.*, 2012; Regasa *et al.*, 2019)**. Although more than 60 stem rust resistance (Sr) genes have been identified (Chen *et al.*, 2018), resistance based on single major genes is often short-lived due to the rapid evolution of pathogen virulence. Consequently, increasing emphasis has been placed on adult plant resistance and slow-rusting resistance, which tend to be quantitatively inherited, more stable across environments, and more durable over time.

Accurate evaluation of wheat resistance to stem rust requires multi-environment testing and robust statistical approaches capable of dissecting genotype × environment (G×E) interactions. The additive main effects and multiplicative interaction (AMMI) model has been widely adopted for this purpose, as it effectively partitions variation attributable to genotypes, environments, and their interactions, while providing insight into stability and specific adaptation patterns **(Zobel *et al.*, 1988)**.

By combining analysis of variance with principal component analysis, AMMI facilitates the identification of genotypes that not only exhibit low disease severity but also maintain stable performance across diverse environments—an essential criterion for cultivar recommendation and breeding under variable climatic conditions.

In this context, the present study aimed to evaluate the resistance of twenty Egyptian wheat varieties to stem rust at the adult plant stage across multiple environments and growing seasons. Resistance was assessed using two widely accepted parameters for slow-rusting resistance: final rust severity (FRS, %) and area under the disease progress curve (AUDPC). In addition, AMMI analysis was employed to quantify genotype × environment interactions and to identify stable and broadly adapted genotypes with durable stem rust resistance. The outcomes of this study provide valuable information for wheat improvement programs targeting sustainable disease resistance under Egyptian and similar agroecological conditions.

2. Materials and Methods

The current research was conducted at Ismailia and Sharqia governorates in Wheat Disease Research Department, Plant Pathology Research Institute (PPRI), Agricultural Research Center (ARC), Giza, Egypt. The experiments were carried out at three planting dates during of 2022 to 2024 growing seasons. Additionally, the laboratories studies were conducted at the Laboratory at (EPCRS) Excellence Center (certified according to ISO 9001, ISO 14001 and OHSAS 18001) and Plant Pathology and Biotechnology Lab. (certified according to ISO 17025), Department of Agricultural Botany, Faculty of Agriculture, Kafrelsheikh University, Egypt.

Evaluation of Egyptian wheat varieties against stem rust at adult plant stage

A total of 20 wheat cultivars were evaluated under field conditions at Ismailia and Sharqia governorates during of 2022 to 2024 growing seasons (Table 1). These cultivars were sown in complete randomized block design with 3 replicats. The experimental unit consisted of 3 rows (3 m long and 30 cm apart and 5g seed rate for each row). The experiment was surrounded by 1 m allay and 1.5 m belt, served as a spreader of stem rust susceptible entries, i.e. “Morocco and Triticum spleta saharences”. The spreader was artificially inoculated using a mixture of physiological races in addition to the natural infection during late tillering and late elongation stages. The recommended agricultural practices were applied.

Disease severity (DS) was recorded four times, one every 10 days interval, during the two successive seasons expressed as percentage coverage of leaves with rust pustules following the method adopted by **Peterson *et al.* (1948)**. Rust reaction was expressed in five types **(Stakman *et al.* 1962)**, i.e. Immune= (0), resistant= (R), moderately resistant= (MR), moderately susceptible= (MS) and susceptible= (S) (Table 2 and Fig. 1). Then rust reaction was transformed to average coefficient of infection (ACI) values according to the methods adopted by **Saari and Wilcoxson (1974)**. The obtained data served in the determination of final rust severity (FRS) and area under disease progress curve (AUDPC) as follow:

1. Final rust severity (FRS) was recorded as outlined by **Das *et al.* (1993)** as disease severity (%) when the highly susceptible check variety was severely rusted and the disease rate reached the highest and final level of leaf rust severity.

2. Area under disease progress curve (AUDPC) was estimated to compare different responses of the tested cvs. according to **Pandey *et al.* (1989)** using the following equation: -

$$AUDPC = D\,[1/2\,(Y_1 + Y_K) + Y_2 + Y_3 + \ldots Y_{(K-1)}]$$

Where D = days between readings.

Y_1 = first disease record.
Y_k = last disease record.

Table (1). Twenty wheat varieties used in this study with their pedigree

No.	Variety	Pedigree
1	Misr 1	OASIS/SKAUZ//4*BCN/3/2*PASTOR
2	Misr 2	SKAUZ/BAV92
3	Misr 3	ATTILA*2/PBW65*2/KACHU
4	Misr 4	NS-732/HER/3/PRL/SARA/TSI/VEE#5/4/FRET2/5/Wheat/SOKOLL
5	Misr 5	-
6	Misr 6	-
7	Misr 7	-
8	Sakha 93	Sakha 92/TR 810328 S 8871-1S-2S-1S-0S
9	Sakha 94	OPATA/RAYON//KAUZ CMBW9043180-OTOPM-3Y-010M…
10	Sakha 95	OPATA/RAYON//KAUZ CMBW9043180-OTOPM-3Y-010M…
11	Gemmeiza 9	Ald "S"/Huas//CMH74A.630/Sx CG4583-5G-1G-0G
12	Gemmeiza 10	MAYA 74 "S"/ON//1160 − 147/3/BB/GLL/4/CHAT"S"/5/CROW "S"
13	Gemmeiza 11	BOW"S"/KVZ"S"//7C/SERI82/3/GIZA168/SKHA61
14	Giza 168	MRL/BUC//SERI. CM93046-8M-0Y-0M-2Y-0B-0SH
15	Giza 171	Sakha93/Gemmeiza9 S 6-1GZ-2GZ-2GZ-0S
16	Sids 1	HD2172/Pavon‘‘S’’//1158.57/Maya74"S". SD46-4Sd-2SD-1SD-0SD
17	Sids 12	Buc//7c/ald/5/maya74/on//1160 − 147/3/bb/gll/4/chat"s"'
18	Sids 13	AMAZ19 = KAUZ"S"//TSI/SNB"S"
19	Sids 14	Bow"s"/Vee"s"//Bow's'/Tsi/3/BANI SUEF 1 SD293-1SD-2SD-4SD-0SD
20	Shandweel1	SITE/MO/4/NAC/TH.AC//3*PVN/3/MIRLO/BUC

Table (2). The observation of the response of stem rust

Reaction	Observation	Response value
No disease	0	0.0
Resistant	R	0.2
Resistant-Moderately Resistant	R-MR	0.3
Moderately Resistant	MR	0.4
Moderately Resistant-Moderately Susceptible	MR-MS	0.6
Moderately Susceptible	MS	0.8
Moderately Susceptible-Susceptible	MS-S	0.9
Susceptible	S	1.0

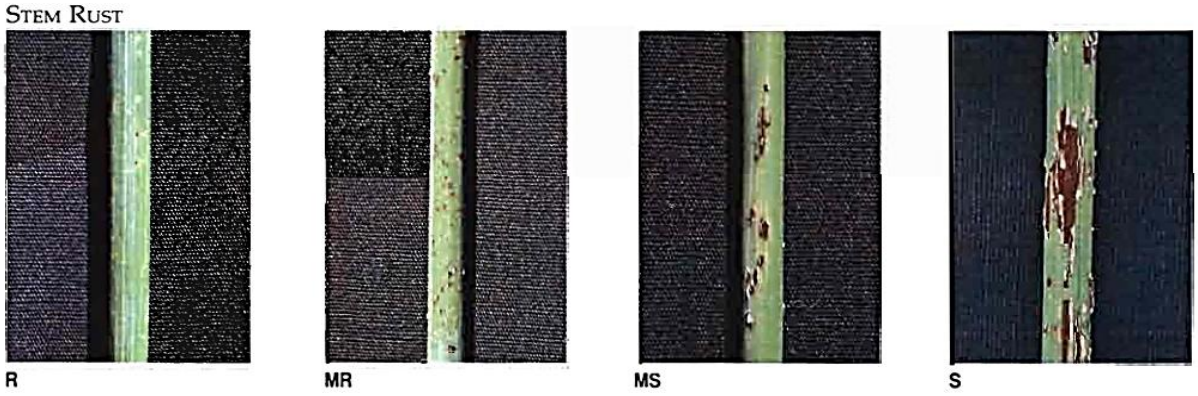


Fig. (1). Adult plant host responses to the stem rust disease (Source: Saari and Wilcoxson, 1974 and Stakman *et al.,* 1962).

AMMI model

Stability analysis of the 20 wheat genotypes was carried out for grain yield/plant across two environments, representing the combinations of two locations × genotypes × 3 years according to the AMMI model. Grain yield data were subjected to multivariate analysis using Additive main effect and multiplicative interaction (AMMI) model as described by **Gauch and Zobel (1996)** to estimate the stability parameters. Additive main effect and multiplicative interaction (AMMI) model is as follows:

AMMI Stability Value (ASV) is the distance from the coordinate point to the origin in a two-dimensional plot of IPCA1 scores (interaction principal component axis 1) against IPCA2 scores (interaction principal component axis 2) in the AMMI model **(Purchase, 1997)**. Because the IPCA1 score contributes more to the G×E interaction sum of squares, a weighted value is needed. This was calculated for each genotype and each environment according to the relative contribution of IPCA1 to IPCA2 as follows:

$$ASVi=\sqrt{(\{SSIPCA1/SSIPCA2(IPCA1\ SCORE)\}2+(IPCA2\ SCORE)2}$$

Where SSIPCA1 / SSIPCA2 was the weight given to the IPCA1-value by dividing the IPCA1 sum of squares by the IPCA2 sum of squares, the larger the ASV value, either negative or positive, the more specifically adapted a genotype was to certain environments. A smaller ASV value indicated a more stable genotype across environments **(Purchase, 1997)**. The AMMI model was performed using the GenStat-v.19. Software

3. Results

Rust severity at Esmailia location

The results obtained at Esmailia revealed pronounced differences in final rust severity among the evaluated wheat varieties over the three growing seasons (2022–2024). Overall, Esmailia exhibited relatively high disease pressure, making it a suitable environment for discriminating varietal responses to rust infection. The highest rust severity was consistently recorded in Misr 1 and Misr 2, with mean values of 75.5 and 59.9%, respectively, indicating high susceptibility under Esmailia conditions. Despite a gradual decline in severity across seasons, these varieties remained highly affected. In contrast, Misr 4, Misr 5, Misr 6, and Misr 7 showed complete resistance, recording zero rust severity in all seasons. Low rust severity levels were observed in Misr 3, Giza 171, Sakha 95, and Sids 14, reflecting a high degree of resistance and stability across seasons. Moderate rust severity was detected in Sakha 93, Sakha 94, Gemmeiza 9, Gemmeiza 11, Sids 1, and Sids 12, suggesting intermediate resistance that may be influenced by seasonal environmental variation (Table 3).

Rust severity at Sharkia location

At Sharkia, final rust severity values were generally lower than those recorded at Esmailia, indicating reduced disease pressure at this location. Nevertheless, varietal responses followed a similar trend. Misr 1 and Misr 2 exhibited the highest rust severity, with mean values of 65.5 and 59.9%, respectively, confirming their susceptibility across environments. The resistant varieties (Misr 4, Misr 5, Misr 6, and Misr 7) maintained complete resistance, with no rust symptoms observed throughout the study period. Several varieties, including Misr 3, Giza 171, Sakha 95, and Sids 14, expressed very low rust severity, while others such as Sakha 93, Sakha 94, Gemmeiza 9, Gemmeiza 11, Sids 1, and Sids 12 exhibited low to moderate infection levels. These findings suggest that Sharkia provides a relatively less conducive environment for rust development compared with Esmailia (Table 3).

Across both locations, wheat varieties exhibited consistent patterns of response to rust infection. Highly susceptible varieties (Misr 1 and Misr 2) showed high rust severity under both environmental conditions, whereas Misr 4, Misr 5, Misr 6, and Misr 7 demonstrated stable and complete resistance. Varieties with low to moderate rust severity generally maintained similar rankings at both locations, indicating stable performance and limited genotype × environment interaction for rust severity. The consistent superiority of resistant varieties across environments highlights their potential value for cultivation in rust-prone areas and for use as genetic sources in wheat breeding programs.

Table (3). Final rust severity (%) for twenty Egyptian wheat varieties at two locations during 2022-2024 growing seasons

Variety	Esmailai				Sharkia			Mean
	2022	2023	2024	Mean	2022	2023	2024	
Misr 1	86.6	73.3	66.6	75.5	76.6	66.6	53.3	65.5
Misr 2	76.6	56.6	46.6	59.9	66.6	56.6	56.6	59.9
Misr 3	2.3	3.3	2.6	2.7	2	2	3.6	2.5
Misr 4	0.0	0	0	0	0	0	0	0
Misr 5	0	0	0	0	0	0	0	0
Misr 6	0	0	0	0	0	0	0	0
Misr 7	0	0	0	0	0	0	0	0
Sakha 93	16.6	16.6	16.6	16.6	8.3	8.3	8.3	8.3
Sakha 94	26.6	26.6	13.3	22.16	13.3	6.6	3.3	7.7
Sakha 95	5	5	5	5	3.3	2.6	4.6	3.5
Gemmeiza 9	16.6	16.6	8.3	13.8	6.6	8.3	4.3	6.4
Gemmeiza 10	10	10	10	10	5	4.3	8.3	5.8
Gemmeiza 11	26.6	23.3	6.6	18.8	16.6	6.6	8.3	10.5
Giza 168	8.3	8.3	8.3	8.3	3.6	2.6	4.3	3.5
Giza 171	3.6	3.6	4.6	3.9	2.3	1.6	2.3	2.06
Sids 1	16.6	16.6	6.6	13.26	13.3	6.6	6.6	8.8
Sids 12	16.6	13.3	8.3	12.73	8.3	10	8.3	8.86
Sids 13	10	10	5	8.3	4	2.6	3.6	3.4
Sids 14	5	5	5	5	3	4.3	2.3	3.2
Shandweel 1	8.3	4.3	8.3	6.9	3.6	3.6	6.6	4.6
$LSD_{0.05}$	2.21	2.54	1.32	-	1.45	2.03	1.65	-

Seasonal variation in rust severity was evident across the three growing seasons. In several susceptible and moderately resistant varieties, a slight reduction in rust severity was observed from 2022 to 2024, particularly at Esmailia. These variations may be attributed to differences in climatic conditions, including temperature, relative humidity, and rainfall patterns. Importantly, varieties exhibiting complete or high resistance maintained stable responses across all seasons, indicating durable resistance. This stability across years underscores the reliability of these varieties under varying environmental conditions (Table 3).

Area Under Disease Progress Curve (AUDPC) at Esmailia location

At Esmailia, significant differences were observed in the AUDPC values across the twenty wheat varieties during the three growing seasons (2022–2024). The highest AUDPC values were recorded in the Misr 1 variety, with mean values of 1711.3, indicating high disease progression and susceptibility across all years. Similarly, Misr 2 also exhibited relatively high AUDPC values (1293.86), indicating moderate susceptibility to rust. In contrast, the Misr 4, Misr 5, Misr 6, and Misr 7 varieties consistently recorded zero AUDPC values (0), reflecting complete immunity to the disease in all three years. These results confirm the excellent resistance of these varieties to rust, consistent with the findings from rust severity data.

Among moderately resistant varieties, Sakha 93 had the highest AUDPC among resistant varieties, with a mean value of 303.6, suggesting some degree of rust progression under the Esmailia conditions. Other moderately resistant varieties such as Sakha 94 and Sakha 95 showed lower AUDPC values (470.7 and 74.7, respectively), indicating moderate disease p rogression. Varieties like Sakha 93 and Gemmeiza 9 exhibited noticeable disease progression, with mean AUDPC values of 303.6 and 284.16, respectively, indicating some level of susceptibility, though still less than highly susceptible varieties (Table 4).

Area Under Disease Progress Curve (AUDPC) at Sharkia location

At Sharkia, the rust disease pressure was generally lower than at Esmailia, reflected in the lower AUDPC values across all wheat varieties. Misr 1 still exhibited the highest AUDPC values at Sharkia, though these were lower compared to Esmailia (1286.3), further confirming the reduced disease pressure in this region.

The Misr 4, Misr 5, Misr 6, and Misr 7 varieties maintained zero AUDPC values (0), confirming their strong and consistent resistance across both locations and all years. Other varieties, such as Misr 2 (1129.1) and Sakha 93 (154.17), demonstrated low to moderate disease progression, reflecting their resistance but with some vulnerability under favorable disease conditions.

Gemmeiza 10, Sakha 94, and Sids 1 showed low AUDPC values (93.067, 124.73, and 214.63, respectively), indicating their relatively low susceptibility. Giza 168 and Sids 14, with mean AUDPC values of 67.2 and 53.3, respectively, also demonstrated very low disease progression, suggesting strong resistance (Table 4).

The data from both locations, clear patterns emerged. The highly susceptible varieties, including Misr 1 and Misr 2, showed the highest AUDPC values at both Esmailia and Sharkia, with significant disease progression across all years. These varieties can be classified as highly susceptible under various environmental conditions. On the other hand, the completely resistant varieties, Misr 4, Misr 5, Misr 6, and Misr 7, maintained zero AUDPC values across both locations and all years, confirming their strong resistance to rust. Varieties such as Sakha 93, Sakha 94, Gemmeiza 9, and Sids 1 displayed moderate disease progression, as indicated by intermediate AUDPC values. These varieties exhibited resistance but still allowed some disease development, especially in high-disease-pressure environments like Esmailia (Table 4).

Seasonal fluctuations were observed in the AUDPC values for several varieties. For example, Misr 1 and Misr 2 exhibited a decrease in AUDPC values over the years, reflecting a potential gradual adaptation or reduction in disease severity due to environmental factors. However, the trends in the highly resistant varieties (Misr 4, Misr 5, Misr 6, Misr 7) remained stable, with zero AUDPC values across all seasons.

In general, most varieties showed stable patterns of disease progression over the three growing seasons, with minor seasonal fluctuations that could be attributed to the variation in environmental conditions, such as temperature and humidity, between 2022 and 2024 (Table 4).

The analysis of the area under disease progress curve (AUDPC) revealed that the Egyptian wheat varieties exhibited substantial variation in their susceptibility to rust. Highly susceptible varieties such as Misr 1 and Misr 2 displayed the highest disease progression, as reflected by high AUDPC values, while completely resistant varieties (Misr 4, Misr 5, Misr 6, Misr 7) showed no disease progression across both locations and all years (Table 4).

Table (4). Area under disease progress curve (AUDPC) for twenty Egyptian wheat varieties at two locations during 2022-2024 growing seasons

Variety	Esmailai				Sharkia			
	2022	2023	2024	Mean	2022	2023	2024	Mean
Misr 1	2245.3	1545.6	1343	1711.3	1745.6	1067.6	1045.6	1286.3
Misr 2	1942.6	1144	795	1293.86	1097	1145.6	1144.6	1129.1
Misr 3	53	98.6	41.3	64.3	37.3	35.3	81	51.2
Misr 4	0	0	0	0	0	0	0	0
Misr 5	0	0	0	0	0	0	0	0
Misr 6	0	0	0	0	0	0	0	0
Misr 7	0	0	0	0	0	0	0	0
Sakha 93	320.6	319	271.3	303.6	141.6	160.3	160.6	154.17
Sakha 94	496.3	596.6	319.3	470.7	183.6	104.3	86.3	124.73
Sakha 95	87.3	86	51	74.7	41.6	32	57.3	43.633
Gemmeiza 9	271.6	420.6	160.3	284.16	163	163.6	74	133.53
Gemmeiza 10	160.3	158	142	153.4	79.6	87	112.6	93.067
Gemmeiza 11	504.6	317.6	160.6	327.6	261	160.6	159.6	193.73
Giza 168	158	218.3	210	195.4	85	31	85.6	67.2
Giza 171	100	89	64	84.3	43	42.6	30	38.533
Sids 1	319.3	270.6	210	266.6	322.3	161.6	160	214.63
Sids 12	267.3	157.3	163	195.86	222.3	152	142.6	172.3
Sids 13	160.3	108.6	91.3	120.06	88.3	51.6	69.6	69.833
Sids 14	84.6	118.6	85.6	96.26	57.3	52.3	50.3	53.3
Shandweel 1	211	105.6	149	155.2	43.6	85.6	161.6	96.933
$LSD_{0.05}$	8.65	9.54	5.64	-	7.68	8.35	9.32	-

AMMI analysis of variance for final rust severity (%) and AUDPC

The AMMI analysis of variance revealed highly significant ($P \leq 0.01$) differences among treatments, genotypes, environments, and genotype × environment interactions (GEI) for both final rust severity (%) and area under disease progress curve (AUDPC) (Table 5). Treatments explained 98.2% and 99.9% of the total variation for final rust severity and AUDPC, respectively. Genotypic effects were the major source of variation, accounting for 92.2% of treatment variation for final rust severity and 88.5% for AUDPC, indicating substantial genetic variability among wheat genotypes in their response to rust disease. Environmental effects, although significant ($P \leq 0.01$), contributed a relatively small proportion of the total variation (2.0% for final rust severity and 2.7% for AUDPC). The GEI effect was significant ($P \leq 0.01$) for both traits, contributing 4.0% of the total variation for final rust severity and 8.8% for AUDPC, indicating differential genotypic responses across environments. Decomposition of GEI showed that the first interaction principal component axis (IPCA1) explained the largest proportion of GEI variation, accounting for 67.4% and 73.7% for final rust severity and AUDPC, respectively. IPCA2 accounted for an additional 21.0% and 16.8% of GEI variation, while the residual interaction explained a smaller proportion, suggesting that the first two IPCAs adequately captured the interaction pattern.

Table (5). Additive Main effect and Multiplicative Interaction (AMMI) analysis of variance for Final rust severity (%) and Area under disease progress curve (AUDPC) for 20 wheat varieties

Source	Final rust severity (%)				Area under disease progress curve (AUDPC)			
	D.F.	M.S.	Explained %	GEI %	D.F.	M.S.	Explained %	GEI %
Total	359	366.9			359	167297		
Treatments	119	1087.1**	98.2		119	504623**	99.9	
Genotypes	19	6392.4**	92.2		19	2795825**	88.5	
Environments	5	519.3**	2		5	326426**	2.7	
Block	12	36.4**	0.3		12	183**	0.003	
Interactions	95	55.9**	4		95	55761**	8.8	
IPCA 1	23	155.5**		67.4	23	169732**		73.7
IPCA 2	21	53.2**		21	21	42359**		16.8
Residuals	51	12.1*		11.6	51	9882**		9.5
Error	288	8.4	1.5		228	33	0.012	

* and ** Significant at 0.05 and 0.01 probability levels, respectively.

AMMI stability parameters for final rust severity

Significant variation was observed among wheat genotypes for final rust severity, interaction principal component scores, AMMI stability value (ASV), and genotype selection index (GSI) (Table 6). Final rust severity ranged from 0.0% to 70.56%. Genotypes Misr 4, Misr 5, Misr 6, and Misr 7 recorded zero disease severity, indicating complete resistance. Genotypes Misr 3, Giza 171, and Sids 14 also exhibited low rust severity values. In contrast, Misr 1 and Misr 2 showed the highest disease severity and ranked lowest in disease resistance. Stability analysis revealed substantial differences among genotypes. Sids 12 recorded the lowest ASV (0.198) and the lowest GSI (12), indicating high

stability combined with favorable disease performance. Sids 13 and Giza 171 also showed low ASV and GSI values, reflecting stable resistance across environments. Conversely, Misr 1, Misr 2, and Sakha 94 exhibited high ASV and GSI values, indicating strong interaction effects and poor stability.

Table (6). IPCAg1, IPCAg2 scores, AMMI stability value and Genotype Selection Index of 20 wheat varieties for Final rust severity (%)

No.	varieties	FDS	RYi	IPCAg1	IPCAg2	ASV	RASV	GSI
G1	Misr 1	70.56h	17	-3.03402	0.04117	9.721	20	37
G2	Misr 2	60g	16	-2.27835	3.14603	7.949	19	35
G3	Misr 3	2.66ab	2	1.12913	0.36078	3.636	16	18
G4	Misr 4	0a	1	1.02352	0.49016	3.316	12	13
G5	Misr 5	0a	1	1.02352	0.49016	3.316	13	14
G6	Misr 6	0a	1	1.02352	0.49016	3.316	14	15
G7	Misr 7	0a	1	1.02352	0.49016	3.316	15	16
G8	Sakha 93	12.5ef	13	0.29627	-1.39985	1.691	3	16
G9	Sakha 94	15f	15	-2.1233	-2.15922	7.138	18	33
G10	Sakha 95	4.28b	5	0.96716	0.17828	3.104	10	15
G11	Gemmeiza 9	10.17de	10	-0.52525	-0.92402	1.92	4	14
G12	Gemmeiza 10	7.94cd	9	0.84861	-0.42394	2.752	8	17
G13	Gemmeiza 11	14.72f	14	-2.12246	-0.22881	6.804	17	31
G14	Giza 168	5.94bc	8	0.63499	-0.57159	2.113	5	13
G15	Giza 171	3.06ab	3	0.94609	0.03829	3.032	9	12
G16	Sids 1	11.11de	12	-0.74753	-0.01179	2.395	6	18
G17	Sids 12	10.83de	11	-0.05168	0.10786	0.198	1	12
G18	Sids 13	5.89bc	7	0.09582	-0.40374	0.507	2	9
G19	Sids 14	4.11b	4	0.84317	0.0581	2.702	7	11
G20	Shandweel1	5.83bc	6	1.02724	0.23179	3.3	11	17

FDS = Final rust severity (%), RYi= rank of disease incidence, IPCA1,2= interaction principal component axis 1 and 2, ASVi= AMMI stability value, RASVi= rank of AMMI stability value, GSIi= genotype selection index.

AMMI stability parameters for AUDPC

AUDPC values varied widely among genotypes, ranging from 0.0 to 1498.8 (Table 7). Genotypes Misr 4, Misr 5, Misr 6, and Misr 7 showed zero AUDPC values, indicating complete suppression of disease development across environments. Low AUDPC values were also observed for Misr 3, Sakha 95, and Giza 171. Based on stability analysis, Sids 1 recorded the lowest ASV (2.93) and ranked first in stability, followed by Gemmeiza 9 and Sids 12. These genotypes combined low disease progression with high stability across environments. In contrast, Misr 1 and Misr 2 exhibited

the highest AUDPC values, large IPCA scores, high ASV, and high GSI values, reflecting severe disease development and strong genotype × environment interaction.

AMMI biplot analysis

The AMMI biplot analysis illustrated the relationship between mean disease response and genotype × environment interaction for final rust severity and AUDPC (Figure 2). In the AMMI1 biplot for final rust severity (Figure 2A), genotypes positioned close to the origin of the IPCA1 axis exhibited minimal interaction effects and greater stability across environments, whereas genotypes located farther from the origin showed stronger interaction and environmental sensitivity. The IPCA1 versus IPCA2 biplot for AUDPC (Figure 2B) further demonstrated differential genotypic responses across environments. Genotypes clustered near the origin were more stable, while those distributed farther along the axes contributed most to GEI. The biplots confirmed the effectiveness of the AMMI model in identifying stable and high-performing genotypes under varying environmental conditions.

Table (7). IPCAg1, IPCAg2 scores, AMMI stability value and genotype selection index of area under disease progress curve (AUDPC) for 20 wheat varieties

No.	varieties	AUDPC	RYi	IPCAg1	IPCAg2	ASV	RASV	GSI
G1	Misr 1	1498.8n	17	-24.3902	-9.65144	107.47	20	37
G2	Misr 2	1211.5m	16	-18.1273	16.61248	81.27	19	35
G3	Misr 3	57.8b	2	4.59923	1.32462	20.23	18	20
G4	Misr 4	0a	1	4.53118	1.60395	19.95	14	15
G5	Misr 5	0a	1	4.53118	1.60395	19.95	15	16
G6	Misr 6	0a	1	4.53118	1.60395	19.95	16	17
G7	Misr 7	0a	1	4.53118	1.60395	19.95	17	18
G8	Sakha 93	228.9i	12	1.69229	-2.12112	7.72	4	16
G9	Sakha 94	297.8l	15	-3.54299	-10.2235	18.61	12	27
G10	Sakha 95	59.2b	3	3.56648	1.1028	15.69	10	13
G11	Gemmeiza 9	208.9h	11	0.97517	-4.57056	6.26	2	13
G12	Gemmeiza 10	123.3e	7	3.51949	0.39631	15.45	8	15
G13	Gemmeiza 11	260.7k	14	-4.26831	0.62766	18.74	13	27
G14	Giza 168	131.3f	9	3.42611	-3.90328	15.53	9	18
G15	Giza 171	61.4b	4	3.19561	0.49662	14.03	7	11
G16	Sids 1	240.7j	13	0.5385	-1.7306	2.93	1	14
G17	Sids 12	184.1g	10	1.46517	1.47622	6.6	3	13
G18	Sids 13	95d	6	2.28187	0.71695	10.04	5	11
G19	Sids 14	74.8c	5	4.01059	-0.20527	17.6	11	16
G20	Shandweel1	126.1ef	8	2.93355	3.23631	13.27	6	14

AUDPC= Area under disease progress curve, RYi= rank of disease incidence, IPCA1,2= interaction principal component axis 1 and 2, ASVi= AMMI stability value, RASVi= rank of AMMI stability value, GSIi= genotype selection index.

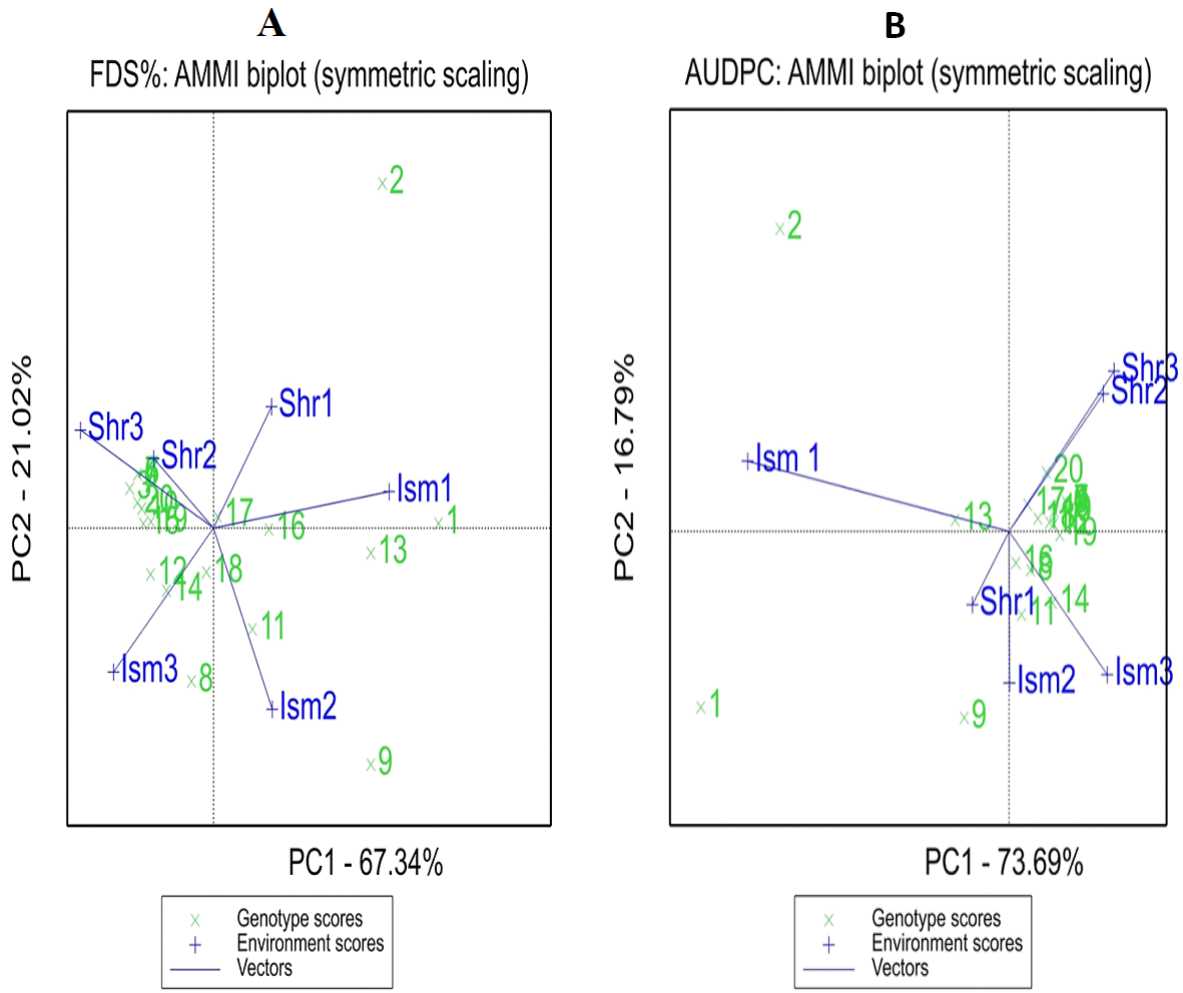


Fig. (2). AMMI1 biplot illustrating genotype performance and genotype × environment interaction based on IPCA1 scores for final rust severity (%) (A) and area under disease progress curve (AUDPC) (B) among 20 wheat genotypes across six environments.

4. Discussion

Stem rust caused by *Puccinia graminis* f. sp. *tritici* is still considered one of the most destructive diseases threatening wheat production in Egypt and worldwide, particularly under favorable climatic conditions that enhance pathogen development and spread **(Park *et al.*, 2007; El-Naggar *et al.*, 2020)**. The results of the present study clearly demonstrated wide variability in disease response among the evaluated Egyptian wheat genotypes across locations and seasons, emphasizing the strong influence of genetic constitution, environment, and their interaction on stem rust development.

The consistently higher final rust severity (FRS) and AUDPC values recorded at Esmailia compared with Sharkia indicate that Esmailia represents a highly conducive environment for stem rust epidemics. Such environments are crucial for effective screening, as high disease pressure enhances the ability to discriminate between resistant and susceptible genotypes **(Van der Plank, 1963)**. Under these conditions, Misr 1 and Misr 2 repeatedly exhibited the highest FRS and AUDPC values across seasons, confirming their high susceptibility and poor field resistance. Similar patterns of high disease expression in susceptible wheat cultivars under favorable environments have been widely reported **(Mabrouk *et al.*, 2019; Omara *et al.*, 2021)**.

In contrast, Misr 4, Misr 5, Misr 6, and Misr 7 consistently showed complete resistance, with zero disease severity and no disease progression across all environments and years. This stable response strongly suggests the presence of effective adult-plant resistance or a combination of resistance genes conferring durable protection. Durable resistance is particularly valuable because it tends to remain effective over time and exerts lower selection pressure on pathogen populations compared with race-specific resistance **(Parlevliet and Kuiper, 1977; Marais *et al.*, 2003)**. Such genotypes represent excellent candidates both for direct cultivation and as resistance donors in breeding programs **(Bartos *et al.*, 2002; Nzuve *et al.*, 2012)**.

Several genotypes, including Misr 3, Giza 171, Sakha 95, Sids 13, and Sids 14, exhibited very low rust severity and relatively low AUDPC values across both locations, indicating effective partial resistance. Partial or slow-rusting resistance, characterized by reduced disease development despite a susceptible infection type, is considered more durable and environmentally stable than complete hypersensitive resistance **(Parlevliet and Kuiper, 1977; Marais *et al.*, 2003)**. The relatively consistent performance of these genotypes across environments supports their classification as stable and broadly adapted under Egyptian field conditions.

Seasonal variation in disease intensity was observed, particularly among susceptible and moderately resistant genotypes, with a general decline in rust severity and AUDPC values from 2022 to 2024, especially at Esmailia. Such fluctuations are expected because rust epidemics are highly dependent on climatic variables such as temperature, humidity, and rainfall, which influence spore germination, infection efficiency, and epidemic rate **(Van der Plank, 1963)**. Importantly, highly resistant genotypes maintained stable responses across all seasons, reinforcing the concept that durable resistance is less sensitive to environmental variation **(Simmonds, 1988)**.

The strong agreement between FRS and AUDPC rankings further validates the robustness of genotype classification in this study. While FRS reflects the final outcome of disease expression, AUDPC integrates disease intensity over time and provides a comprehensive assessment of epidemic development and host response **(Van der Plank, 1963)**. Genotypes with high final severity also showed high AUDPC values, whereas resistant genotypes exhibited minimal or zero disease progression, a relationship that has been consistently reported in wheat rust studies **(Ali *et al.*, 2008; Safavi *et al.*, 2010)**.

AMMI analysis confirmed that genotypic effects accounted for the largest proportion of variation in both FRS and AUDPC, highlighting the dominant role of genetic resistance. Nevertheless, the highly significant genotype × environment interaction indicates that environmental conditions still modulate disease expression and that stability must be considered alongside mean performance. The concentration of interaction variance within the first two IPCAs demonstrates that most interaction patterns were systematic rather than random, supporting the effectiveness of AMMI biplots and stability parameters for identifying broadly adapted genotypes **(Zobel *et al.*, 1988)**. Accordingly, genotypes such as Sids 12, Sids 13, Sids 14, and Giza 171 combined low disease levels with favorable stability indices, making them suitable for cultivation across diverse environments.

From a breeding perspective, the coexistence of immune genotypes (Misr 4–Misr 7) and stable low-disease genotypes (particularly Sids 13 and Giza 171) provides valuable opportunities for improving stem rust resistance. Given the continuous evolution of new virulent races of *P. graminis* f. sp. *tritici*, reliance on single resistance sources is risky, and pyramiding multiple resistance genes remains essential for sustainable wheat production **(Bartos *et al.*, 2002; Omara *et al.*, 2021)**. Overall, the present findings underscore the importance of multi-environment testing and integrated statistical approaches for identifying wheat genotypes that combine low disease severity, slow rusting behavior, and high stability under rust-prone conditions.

5. Conclusion

The results of this study revealed clear differences among Egyptian wheat genotypes in their response to stem rust across locations and growing seasons, confirming the strong influence of genetic background, environment, and their interaction. Final rust severity and AUDPC were effective indicators for distinguishing resistant, moderately resistant, and susceptible genotypes. Esmailia

provided higher disease pressure than Sharkia, enabling better discrimination of varietal responses. Genotypes Misr 4, Misr 5, Misr 6, and Misr 7 showed complete and stable resistance across all environments, while Sids 13 and Giza 171 combined low disease levels with high stability according to AMMI analysis. These genotypes are therefore recommended for cultivation in rust-prone areas and as valuable sources of resistance in wheat breeding programs aimed at achieving durable stem rust resistance.

References

Abdelaal, K. A. A., Omara, R. I. and Abd El-Moneim, M. A. (2018). Evaluation of wheat resistance to stem rust using disease severity and molecular markers. J. Plant Diseases and Protection, 125, 189–198. https://doi.org/10.1007/s41348-017-0133-9

Abdelmageed, K., Ali, M. and El-Bassiouny, H. (2018). Improving wheat productivity under Egyptian conditions. Egyptian J. Agronomy, 40, 1–15.

Admassu, B., Lind, V., Friedt, W. and Ordon, F. (2012). Genetic variation and association mapping of resistance to stem rust in bread wheat. Theoretical and Applied Genetics, 125, 105–116. https://doi.org/10.1007/s00122-012-1824-7

Ali, S., Shah, S.J.A. and Khalil, I. H. (2008). Assessment of wheat breeding lines for slow rusting resistance against leaf rust. Pakistan J. Botany, 40(1), 87–96.

Alnusairi, G. S. H.; Al-Taweel, S. S.; Hassan, M. A. and Ali, A. K. (2021). Wheat production and food security challenges. Sustainability, 13, 12345.

Bartos, P., Sip, V., Chrpova, J. and Stuchlikova, E. (2002). Achievements and prospects of wheat breeding for disease resistance. Czech j. Genetics and Plant Breeding, 38, 16–28.

Belayneh, A. and Emebet, F. (2005). Physiological specialization of *Puccinia graminis* f. sp. *tritici* in Ethiopia. Phytopathologia Mediterranea, 44, 313–318.

Chen, S., Rouse, M. N. and Dubcovsky, J. (2018). Stem rust resistance in wheat. Theoretical and Applied Genetics, 131, 181–195. https://doi.org/10.1007/s00122-017-3011-9

Chen, X. M.; Lin, F.; Xu, S.; Jin, Y. and Singh, R. P. (2009). Race dynamics, evolution and spread of Ug99 lineage. Plant Disease, 93, 111–124.

Das, M.K.; Rajaram, S.; Ktonstad, W.K.; Mundt, C.C. and Singh, R.P. (1993). Association and genetics of three components of slow rusting in leaf rust of wheat. Euphytica, 68:99-109.

El-Naggar, D. R., Elkot, A. F. and Abd El-Latif, A. M. (2020). Evaluation of Egyptian wheat cultivars for resistance to stem rust under field conditions. Egyptian J. Phytopathology, 48(2), 145–158.

Gui, D.; Zhang, H.; Liu, J. and Wang, Y. (2024). Impact of water scarcity on wheat growth and yield. Agricultural Water Management, 291, 108580.

Jin, Y.; Singh, R. P.; Ward, R. W.; Jin, Y.; Singh, R. P. and Ward, R. W. (2008). Characterization of Ug99 stem rust race group. Plant Disease, 92, 923–926. https://doi.org/10.1094/PDIS-92-6-0923

Khan, M. A.; Ali, S.; Ahmed, H.; Iqbal, M. and Shah, S. J. A. (2024). Climate-driven dynamics of wheat rust diseases. Crop Protection, 176, 106467.

Khedr, R. A.; Elbeltagi, A.; El-Shamy, M.; Abd El-Rahman, M. and Hassan, M. (2023). Wheat yield stability under biotic and abiotic stresses. Field Crops Research, 293, 108823.

Leonard, K. J. and Szabo, L. J. (2005). Stem rust of small grains and grasses caused by *Puccinia graminis*. Molecular Plant Pathology, 6, 99–111. https://doi.org/10.1111/j.1364-3703.2005.00273.x

Li, X.; Wang, Y.; Zhang, H.; Liu, J.; Chen, Z. and Zhao, L. (2024). Drought stress and wheat productivity under climate change. Environmental and Experimental Botany, 215, 105538.

Mabrouk, O. I., Omara, R. I., Abd El-Moneim, M. A. and El-Naggar, D. R. (2019). Partial resistance to stem rust in Egyptian wheat cultivars. J. Plant Protection Research, 59, 343–352. https://doi.org/10.24425/jppr.2019.129747

Marais, G. F., Pretorius, Z. A., Wellings, C. R., McCallum, B. and Marais, A. S. (2003). Leaf rust and stripe rust resistance genes transferred to common wheat from *Triticum dicoccoides*. Euphytica, 133, 145–153. https://doi.org/10.1023/A:1025638513389

Martínez-Moreno, F. And Solís, I. (2019). Life cycle and epidemiology of wheat rust fungi. European J. Plant Pathology, 154, 1–14.

Nazari, K.; Hodson, D. P.; Huerta-Espino, J.; Singh, R. P. and Jin, Y. (2009). Spread of Ug99 stem rust race group. Euphytica, 165, 1–14.

Nazarov, A.; Ivanov, S.; Petrov, D.; Smirnova, E. and Kuznetsov, V. (2024). Emerging rust pathogens under climate variability. Plant Pathology, 73, 456–468.

Njau, P. N.; Jin, Y.; Huerta-Espino, J.; Singh, R. P. and Keller, B. (2010). Virulence of Ug99 lineage in East Africa. Plant Disease, 94, 413–419.

Nzuve, F. M., Tusiime, G., Bhavani, S. and Njau, P. (2012). Evaluation of bread wheat for slow rusting resistance to stem rust. African Crop Science J. 20(2), 83–92.

Omara, R. I., Abd El-Moneim, M. A., El-Naggar, D. R. and Mabrouk, O. I. (2021). Virulence analysis of *Puccinia graminis* f. sp. *tritici* populations in Egypt. J. Plant Diseases and Protection, 128, 1019–1030. https://doi.org/10.1007/s41348-021-00474-5

Omara, R. I., Abd El-Moneim, M. A., El-Naggar, D. R. and Mabrouk, O. I. (2017). Evaluation of wheat genotypes for stem rust resistance in Egypt. Egyptian J. Phytopathology, 45, 29–45.

Pandey, H.N.; Menon, T.C.M., and Rao, M.V. (1989). A simple formula for calculating area under disease progress curve. Rachis, 8(2):38-39.

Park, R. F., Fetch, T., Hodson, D. (2007). International surveillance of wheat rust pathogens. Euphytica, 179, 109–117. https://doi.org/10.1007/s10681-010-0300-4

Park, R. F., Fetch, T., Hodson, D., Jin, Y., Nazari, K., Prashar, M. and Pretorius, Z. A. (2007). International surveillance of wheat rust pathogens: Progress and challenges. Euphytica, 179, 109–117. https://doi.org/10.1007/s10681-010-0300-4

Parlevliet, J. E. and Kuiper, H. J. (1977). Partial resistance of barley to leaf rust, *Puccinia hordei*. II. Effect of partial resistance on epidemic development. Euphytica, 26, 249–255. https://doi.org/10.1007/BF00026986

Peterson, R.F.; Compbell, A.B. and Hamah, A.E. (1948). A diagrammatic scale for estimating rust intensity on leaves and stems. Cereal Can. J. Res., 60:496-500.

Purchase, J.L. (1997). Parametric analysis to describe genotype × environment interaction and yield stability in winter wheat. Ph.D. Thesis, University of the Free State, Bloemfontein, South Africa.

Regasa, T.; Fetch, T.; Singh, R. P. and Huerta-Espino, J. (2019). Breeding strategies for durable stem rust resistance. Crop Science, 59, 1–14.

Saari, E.E. and Wilcoxson, R.D. (1974). Plant disease situation of high-yielding durum wheat in Asia and Africa. Annual Review Phytopathol., 2:49-68

Safavi, S. A., Ahari, A. B., Afshari, F. and Arzanlou, M. (2010). Slow rusting resistance in wheat lines to yellow rust in Iran. Pakistan J. Biological Sciences, 13, 240–244.

Shahin, A. A.; El-Orabey, W. M.; Omara, R. I. and Abd El-Moneim, A. M. (2021). Response of Egyptian wheat cultivars to rust diseases. Archives of Phytopathology and Plant Protection, 54, 1211–1225.

Simmonds, N. W. (1988). Principles of Crop Improvement. Longman Scientific & Technical, London.

Singh, R. P., Hodson, D. P., Huerta-Espino, J., Jin, Y., Njau, P., Wanyera, R., Herrera-Foessel, S. A. and Ward, R. W. (2008). Will stem rust destroy the world's wheat crop? Advances in Agronomy, 98, 271-309

Singh, R. P., Huerta-Espino, J. and Rajaram, S. (2011). Achieving near immunity to rusts in wheat. Euphytica, 179, 95–108.

Stakman, E.C.; Stewart, D.M. and Loegering, W.Q. (1962). Identification of physiologic races of *Puccinia graminis* var. *tritici* A.R.S. USDA. Agric. Res. Serv. Bull. E. 617- 53 pp.

Van der Plank, J. E. (1963). Plant Diseases: Epidemics and Control. Academic Press, New York.

Zhang, Z., Zhang, Y., Li, X., Liu, J., Wang, H. and Chen, Y. (2024). Salinity stress and wheat tolerance mechanisms. Plant Physiology and Biochemistry, 208, 108332**.**

Zobel, R. W., Wright, M. J. and Gauch, H. G. (1988). Statistical analysis of a yield trial. Agronomy Journal, 80, 388–393. https://doi.org/10.2134/agronj1988.00021962008000030002.

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