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ORIGINAL PAPER

Partial Resistance of Late Wilt Disease Caused by *Magnaporthiopsis maydis* in Certain Egyptian Maize Hybrids

Abdelghany, W.R*; EL-Sayed, A.B.B.; Kafsheer, D.A.; Ata, A.A. and Omara, R.I.*

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ABSTRACT

Late wilt, triggered by *Magnaporthiopsis maydis*, is threatening maize productivity in temperate countries. The disease is mostly managed by genetic resistance, which is frequently exhibited partially in the field. Fifteen maize hybrids were investigated for their partial resistance to late wilt disease in two Agricultural Research Stations, Gemmeiza and Sids in the 2021 and 2022 growing seasons. Two epidemiological parameters were used to characterize this type of resistance in the examined maize hybrids at the adult plant stage: final disease incidence (FDI%) and area under disease progress curve (AUDPC). The hybrids HYTECH-TWC1100, PIONEER-SC30K9, and HYTECH-SC2031 exhibited slower disease progression (less than 7.67%) throughout the plant cycle in all trials compared with the check hybrid Boushy (above 54.63%). The genetic composition of the examined maize hybrids was responsible for more than 80% of the variability in how the hybrids responded to late wilt. In the changes of FDI (%) and AUDPC, the relative contribution of the environment (locations) was relatively low (less than 1%). Due to strong heritability estimates (up to 99%) and high values of genetic progress of more than 80% of the two parameters under the 2021 and 2022 growing seasons, the phenotypic changes were attributed to the genetic structures of the genotypes. The agronomic characteristics of the evaluated hybrids demonstrated a significant positive relationship between LWD resistance and grain yield per plant, as well as hundred kernel weight, plant height, and ear length. The principal component analysis demonstrated the significance of FDI (%) and 100 kernel weight as appropriate evidence for assessing these materials for late wilt disease.

Keywords: Maize, *Zea mays*, Genotypes, *Magnaporthiopsis maydis*, Partial resistance (PR), AUDPC, Genetic advance, Heritability, Principal component analysis.

***Correspondence: Abdelghany, W.R.**
E-mail: walaa.rabie@arc.sci.eg
***Correspondence: Omara, R.I.**
E-mail: redaomara43@arc.sci.eg
Walaa R. Abdelghany
https://orcid.org/0000-0002-2259-2110
Abdelnasser B.B. EL-Sayed
Doaa A. Kafsheer
Abed A. Ata
Reda I. Omara
https://orcid.org/0000-0002-9776-0238
Plant Pathology Research Institute, Agricultural Research Center, 12619, Giza, Egypt.

INTRODUCTION

Maize (*Zea mays* L.) is a major grain crop in Egypt, ranking second to wheat in terms of production and cultivated area. The most devastating disease in maize fields is late wilt disease (LWD), which lowers crop potential yield and reduces the quality and amount of grain produced (El-Shehawy *et al*., 2014 and El-Naggarr *et al*., 2015). LWD was first reported and described as a vascular wilt disease of maize in 1960 (Samra *et al*., 1962). The maize LWD has been recorded in many countries, including Egypt (Sabet *et al*.,1961), India (Ward and Bateman, 1999), Portugal (Molinero-Ruiz *et al*., 2010), Israel (Drori *et al*., 2013), and Spain (Ortiz-Bustos *et al*., 2015). The disease is triggered by the seed-borne and soil-borne fungus *Magnaporthiopsis maydis* (Samra, Sabet and Hing.) Klaubauf, Lebrun and Crou (synonym *Cephalosporium maydis* Samra, Sabet and Hing.; *Harpophora maydis* (Samra, Sabet and Hing.) (Gams, 2000). The genus *Magnaporthiopsis* was introduced by Luo and Zhang, 2013 and *M. maydis* was recently reassigned to this genus from *Harpophora* (Klaubauf *et al*., 2014). The phytopathogen can endure as sclerotia for a very long time in the soil and infects maize seedlings through their roots or mesocotyl (El-Assiuty *et al*., 1999), expanding on roots epiphytically, creating short, robust hyphae with swollen cells resembling *Gaeumannomyces* hyphopodia leading to root necrosis and impairing sprout development emergence (Tej *et al*., 2018). Symptoms occur before tasseling and continue until just before maturity (Sabet *et al*., 1970), and are distinguished by the initial dull green color of the leaves. It usually signifies a lack of water and dryness, before becoming yellow and seeming dried up and withered (Abd EL-Rahim *et al*, 1982). While this happened, elongated streaks of color ranging from yellow to brown to reddish brown started appearing on the still-green stalks. *Magnaporthiopsis maydis* moves upward inside the plant's vascular system as the growth session progresses (Zeller *et al*., 2000), disrupting the water supply and causing dehydration. If an infected stalk were sliced open longitudinally at this stage, yellow to brown streaks spreading through several internodes would be visible (EL-Shafey and Claflin, 1999). In severe infection cases, the lowest internodes become hollow and wither. In the last stages of the disease, the damaged maize crops suffer from extreme dehydration, resulting in serious economic losses, where incidence scored 50-100% and high yield losses in areas with sensitive maize hybrids (El-Shahawy and El-Sayed, 2018). Even if ears grow, the infection is present and the kernels are stunted (Drori *et al*., 2013) and may be infected with the pathogen.

In Egypt, the fungal pathogen population has four lineages that varied in colonization capability and pathogenicity on maize. Three of the lineages are extensively dispersed across the country (Saleh *et al*., 2003). Disease incidence is affected by host-pathogen interactions, pathogen population, degree of soil infestation, maize genotype, plant age at infection, and geographical circumstances (Sabet *et al*., 1966; Agag *et al*., 2021 and Degani *et al*., 2021). Drought stress is thought to be a crucial limiting factor in a plant's capacity to deal with disease (Abd El-Rahim *et al*., 1998). Likewise, soil moisture is critical to late wilt epidemics and severity (Ali *et al*., 2011 and Ortiz-Bustos *et al*., 2019).

Although the disease can be treated using biological and chemical fungicides (Gordani *et al*., 2023), sustainable crop disease prevention methods are being promoted in agriculture (El-Shahawy and Abd El-Wahed, 2022). Indeed, genetic resistance and the use of tolerant maize varieties appear to be the best effective ways to manage LWD and reduce yield loss from the disease (El-Shenawy *et al*., 2022). However, this alternative is restricted due to the presence of a variety of aggressive strains within *M. maydis* populations (Ortiz-Bustos *et al*., 2016) and, in certain cases, a partial development of resistance that is highly dependent on environmental factors (Nyanapah *et al*., 2020). The enhancement of quantitative features resistant to late wilt disease may assist in stabilizing the yields of maize in sensitive areas. However, varied symptom expression in developed hybrids has been reported, implying variation in disease resistance (Degani *et al*., 2022). There is agreement that symptoms develop relatively quickly around 20 to 32 °C, with 28 to 30 °C being the ideal air temperature for the disease (Ortiz-Bustos *et al*., 2019). The performance of each genotype is determined by the selection of the most suited variety in line with the current environment (Abd El-Rahim *et al*., 1998).

Estimates of epidemiological parameters as partial expression of resistance and genetic parameters as variances, heritability, phenotypic, genotypic, and environmental correlations, provide an understanding of the genetic variability of a population (Bello *et al*., 2012). The knowledge of heritability enables us to decide the course of the selection procedure to be followed in a given situation (Bartaula *et al*., 2019). The estimates of genetic parameters like heritability and genetic advance help in forecasting LWD resistance (El-Lakany *et al*., 2009). Consequently, this study aimed to explore the heritability, genetic advance, and genetic variability among maize genotypes by estimating the two main epidemiological indicators of resistance: final disease incidence (FDI%) and area under disease progress curve (AUDPC) under disease stress of the field conditions at two different hot-spot locations.

MATERIALS AND METHODS

Magnaporthiopsis maydis inoculum:

Isolates of *M. maydis* were kindly obtained from the Maize and Sugar Crops Department, Plant Pathology Research Institute, ARC, Giza, Egypt. These isolates came from maize fields in different governorates, including Kafr El-Sheikh, Gharbia, Menofia, Giza, Beni-Suef and Fayoum, where they were recovered from maize plants exhibiting typical late wilt symptoms. Based on culture and microscopic traits, all isolates were previously classified as *M. maydis* and tested for pathogenicity (Samra *et al*., 1963).

Inoculum preparation:

In a 500-mL glucose glass bottle, 150 gm of clean grain sorghum seeds were steeped in water overnight. The next day, the extra water was decanted, and the bottle was autoclaved for one hour. Each bottle was inoculated with agar mycelial disc from *M. maydis* culture that had been growing at 27 °C for seven days on PDA with 0.2% yeast extract (El-Shabrawy and Shehata, 2018). The fungus was allowed to develop for 15 days at this temperature before being detected. Thereafter, the contents of the bottles of each fungal isolate were poured out and the inoculum from each governorate was divided into two groups: group1 (Kafr El-Sheikh, Gharbia, and Menoufia) and group 2 (Giza, Beni-Suef and Fayoum) were mixed separately to get homogenized inoculum. Afterward, soil infestation was carried out using the mixed inoculum (Sabet *et al*., 1966).

Maize hybrids:

Fifteen maize hybrids were grown to determine how they would respond to *M. maydis*. Eight hybrids were kindly obtained from Maize Research Department, Field Crops Research Institute, ARC, Giza, three from HYTECH company, and three from PIONEER company.

Field experiment:

Assessment of resistance levels of 15 maize hybrids to late wilt was done in two nursery fields of Agricultural Research Stations, Gemmeiza and Sids, Plant Pathology Research Institute, Agricultural Research Centre, Egypt during the 2021 and 2022 growing seasons. The Gemmeiza nursery field (30° 79' 58" N; 31° 12' 09" E) was infested artificially with *M. maydis* group 1, while the Sids nursery field (28° 87' 63" N; 30° 88' 62" E) was infested by *M. maydis* mixed inoculum group 2. Three replicates of the experiment were run using a randomized complete block design. Each replication consists of 4 rows that are 6m long, 80 cm apart, and have a 20 cm plant spacing. Rows were infested by adding *M. maydis* mixed inoculum of sorghum seeds inside the rows and sown by 2 grains/hill, thinned to one plant/hill after three weeks. In accordance with a growth regimen suggested by the Maize Research Department at the Field Crops Research Institute, fields were irrigated, treated with pesticides, and fertilized. Sowing of the two tested nursery fields was conducted at the beginning of June, and germination occurred a few days later, and the fruit ripening stage in most hybrids was set 60 days after planting.

Disease assessment:

Based on typical maize late wilt symptoms, which included the following: Infected plants' leaves turn pale green as if they are suffering from a lack of water and eventually become dry. The level of resistance to late wilt in cultivated maize hybrids was evaluated as disease incidence (DI%) and monitored at 76, 83, 90, 97, 104, and 111 days after planting (DAP). The stems' color turns yellow-brown as the drying symptoms go upward.

$$\textbf{DI (\%)} = \frac{\textbf{Number of infected plants}}{\textbf{Total number of maize plants}} \times \mathbf{100}$$

Final disease incidence (FDI%) was measured as a percentage of disease incidence for 15 maize hybrids under study when the highly susceptible check hybrid reached the highest final disease level (115 days after planting). The area under disease progress curve (AUDPC) value was determined for 15 maize hybrids under study using the equation of Pandey *et al*. (1989) in order to more precisely quantify the level of partial resistance (PR) in the tested maize hybrids under field conditions.

Genetic components:

Heritability (h^2) for FDI (%) and AUDPC was estimated according to the following formula of Miller *et al*. (1958):

$$\textbf{\% Heritability } (\mathbf{h^2}) = \frac{\textbf{Genotypic variance } (\boldsymbol{\sigma^2}\mathbf{g})}{\textbf{Phenotypic variance } (\boldsymbol{\sigma^2}\mathbf{ph})} \times \mathbf{100}$$

Where:

$\boldsymbol{\sigma^2}\mathbf{g} = [(\sigma^2 e + r\sigma^2 g) - \sigma^2 e]/r$

$\boldsymbol{\sigma^2}\mathbf{ph} = (\sigma^2 e + r\sigma^2 g)/r$

Genetic advance (GA%) was also estimated for FDI (%) and AUDPC based on the formula of Miller *et al*. (1958):

$$\textbf{Genetic advance} = (\boldsymbol{\sigma^2 g/\sigma^2 ph})\ \boldsymbol{k} \times \sqrt{\boldsymbol{\sigma^2 ph}}$$

Where:

k = 2.06 at 5% selection intensity.

Yield components:

Fifteen maize hybrids were evaluated to late wilt and estimated their yield components during the harvest period, such as ear length (cm), ear diameter (cm), 100-kernel weight (g), plant height (cm), ear height (cm), and harvested ears yield per plot (kg/plot) at the two study locations and seasons.

Statistical analysis:

SPSS software version 25.0 was used to statistical analysis the data. The one-way analysis of variance (ANOVA) was performed on each comparison first and the LSD was determined at p = 0.05. Also, principal component analysis (PCA) was used between FDI (%) and yield components.

RESULTS

Variance analysis:

The degree of partial resistance (PR) of the tested maize hybrids was determined using a combined analysis of the variance of the two locales throughout the course of the 2021 and 2022 growing seasons. There were significant differences in FDI (%) and AUDPC across locales (L) and maize hybrids (H) (Table 1). The interaction between the tested maize hybrids (H) and locales (L) also revealed a significant difference. Due to the significance of the interaction between hybrids and locales (H x L), the LSD values were used to examine the differences in FDI (%) and AUDPC means of any two hybrids within each environment.

Table (1): Analysis of variance for FDI (%) and AUDPC combined across the two locations.

S.O.V.	Df.	FDI (%) Mean Square (M.S.)		AUDPC Mean Square (M.S.)	
		2021	2022	2021	2022
Location (L)	1	184.642*	150.311**	23778.070**	1319.741**
Hybrids (H)	14	1814.498**	1180.121**	229024.371**	176708.388**
L × H	14	58.913*	40.730*	7247.160**	15893.329**
Error	60	31.574	12.550	11.071	5.809

FDI (%) = Final disease incidence; AUDPC = Area under disease progress curve; * = significant, ** = highly significant

Disease development:

Typical late wilt infection signs were noted, commencing with the formation of brown necrotic bands on the first internode and progressing to adjacent internodes until the plant was completely dehydrated. The epidemiological characteristics related to maize genetic resistance to LWD, as well as disease-progress curves for the fifteen hybrids in Gemmeiza and Sids locations over the two growing seasons 2021 and 2022, are depicted in Figs. 1 and 2 (A, C). In all studies, the hybrids HYTECH-TWC1100, PIONEER-SC30K9, and HYTECH-SC2031 demonstrated slower disease progression throughout the plant cycle. During the two seasons, disease incidence (DI%) stayed below 3.18 and 5.51% for hybrid HYTECH -TWC1100, 3.12 and 7.67% for hybrid PIONEER-SC30K9, as well as 2.22 and 7.52% for hybrid HYTECH-SC2031 (Tables 2 and 3). The rate of disease progression increased 90 days after planting (90 DAP), coinciding with the blooming and grain-filling periods of the examined genotypes (Figs. 1 and 2 A, C). The check cultivar Boushy had the quickest disease development rate, followed by the sensitive hybrid PIONEER-SC3062. During growing seasons 2021 and 2022, the rate of disease incidence of the check cultivar Boushy climbed steadily from 8.81 to 63.22% and from 16.58 to 54.63% in Gemmeiza (Tables 2,3 and Fig. 1 A, C) and from 12.99 to 74.45% and 10.24 to 67.12% in Sids location (Tables 2, 3 and Fig. 2 A, C). The meteorological data collected during the growing seasons are shown in detail in Figs. 1 and 2 (B, D). During the seasons 2021 and 2022, the average daily air temperature (31.54°C, 32.05°C) and soil temperature (32.11°C, 32.18°C) in Sids were higher than the Gemmeiza air temperature (29.03°C, 29.29°C) and soil temperature (31.36°C, 31.62°C). Furthermore, the Gemmeiza location has a higher average relative humidity (53.82, 52.29%) than Sids station (39.10, 39.22%).

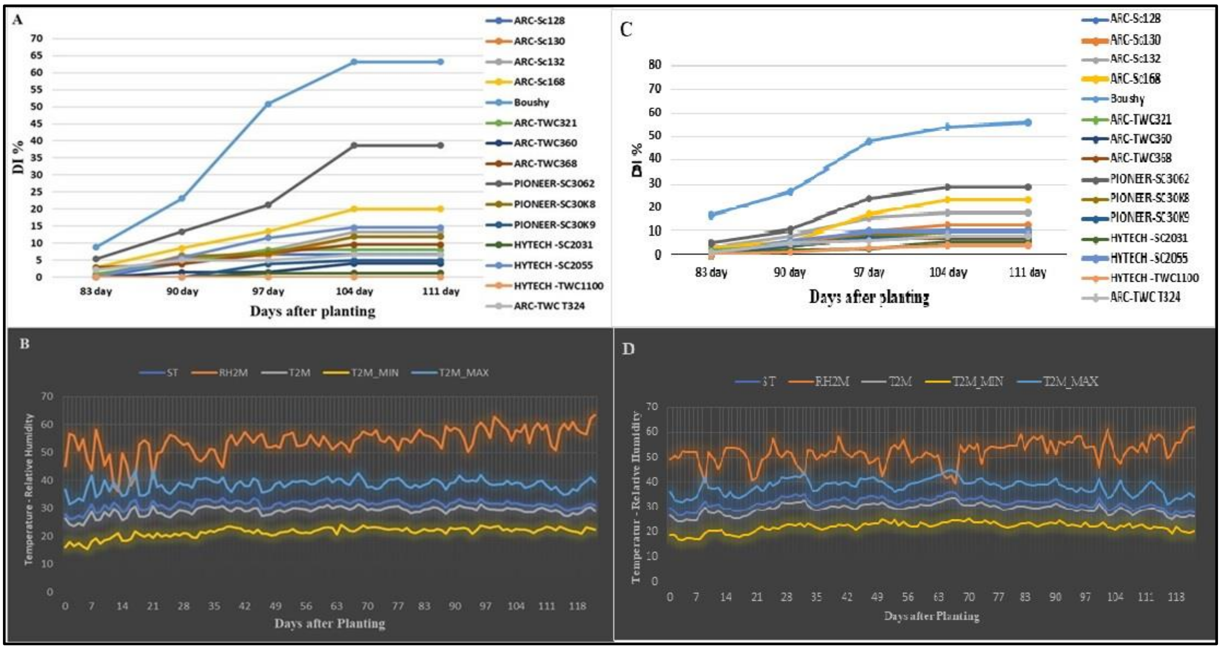

Fig. (1): Maize late wilt disease progress in 15 maize hybrids in a field trial during growing seasons 2021 (A) and 2022 (C) in Gemmeiza station. Metrological parameters during growing seasons 2021 (B) and 2022 (D) in Gemmeiza station; soil temperature (ST), relative humidity at 2 meters (RH2M), temperature at 2 meters (T2M), maximum temperature at 2 meters (T2M_MAX) and minimum temperature at 2 meters (T2M_MIN).

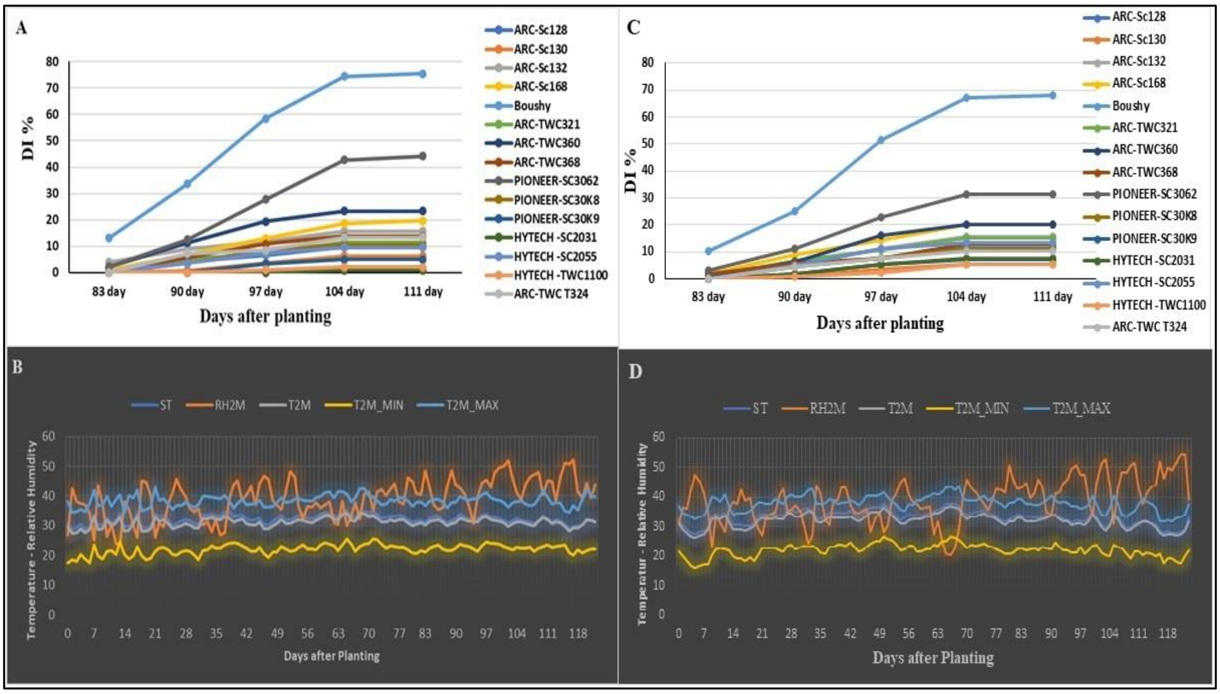

Fig. (2): Maize late wilt disease progress in 15 maize hybrids in a field trial during growing seasons 2021 (A) and 2022 (C) in Sids station. Metrological parameters during growing seasons 2021 (B) and 2022 (D) in Sids station; soil temperature (ST), relative humidity at 2 meters (RH2M), temperature at 2 meters (T2M), maximum temperature at 2 meters (T2M_MAX) and minimum temperature at 2 meters (T2M_MIN).

The degree of partial resistance to late wilt was estimated for each hybrid by estimating the two main parameters of resistance, final disease incidence (FDI%) and area under the disease progress curve (AUDPC), based on the disease pressure of the field conditions at two separate locales in the 2021 and 2022 seasons. Environmental factors were generally more favorable for the onset and progression of disease during the first season (2021) than they were during the second (2022).

Final Disease Incidence (FDI%):

To limit the final level of disease incidence (%) attained individually, it was calculated that the PR hybrids' ability to reduce or limit the spread and quantity of late wilt infections in fields, also known as FDI (%) (Tables 2, 3 and Figs. 3, 4). In contrast to Sids' location and second season (2022), a significant late wilt epidemic was often documented in Gemmeiza's location and first season (2021). As a result, during the two growing seasons, the highly susceptible maize hybrids showed high levels of FDI (more than 29.88%), such as Boushy and PIONEER-SC3062 (Figs. 3 and 4). While the lowest values of FDI (less than 7.67%) were recorded with HYTECH-TWC1100, PIONEER-SC30K9, and HYTECH-SC2031 hybrids at the Gemmeiza and Sids locations (Tables 2, 3 and Figs. 3, 4).

Area Under Disease Progress Curve (AUDPC):

All investigated hybrids might be broadly characterized into two groups based on AUDPC estimates at Gemmeiza and Sids locations during the 2021 and 2022 seasons (Tables 2, 3 and Figs. 3 and 4). In the 2021 season (Table 2 and Fig. 3), the first group includes ARC-SC128, ARC-SC130, ARC-TWC321, ARC-TWC368, PIONEER-SC30K8, PIONEER-SC30K9, HYTECH-SC2031, HYTECH-TWC1100, and ARC-TWC324 maize hybrids with the lowest AUDPC values (less than 184.86) at Gemmeiza and Sids locations. While the second group included ARC-SC132, ARC-SC168, Boushy, ARC-TWC360, PIONEER-SC3062, and HYTECH-SC2055 hybrids, with the highest values of AUDPC (more than 184.86) at the two locations. In the 2022 season (Table 3 and Fig. 4), ARC-SC128, ARC-SC130, ARC-TWC321, ARC-TWC368, PIONEER-SC30K8, PIONEER-SC30K9, HYTECH-SC2031, HYTECH-TWC1100, ARC-TWC324 and HYTECH-SC2055 hybrids fall in the first group, which recorded the lowest values of AUDPC (less than 184.86). While the second group recorded the highest AUDPC values (more than 184.86), for such hybrids as ARC-SC132, ARC-SC168, Boushy, ARC-TWC360, and PIONEER-SC3062 hybrids at the Gemmeiza and Sids locations.

Table (2): Final disease incidence (FDI%) and area under disease progress curve (AUDPC) of the 15 maize hybrids, under field conditions at Gemmeiza and Sids locations, during 2021 growing season.

Maize hybrid		Disease parameters/locations			
		FDI (%)		AUDPC	
		Gemmeiza	Sids	Gemmeiza	Sids
ARC-SC128		9.78	10.73	124.58	135.26
ARC-SC130		12.91	7.33	146.34	72.74
ARC-SC132		14.37	16.73	153.83	235.73
ARC-SC168		20.04	18.58	233.79	207.00
Boushy		63.22	74.45	769.86	950.43
ARC-TWC321		9.09	12.48	139.23	147.68
ARC-TWC360		5.11	24.49	54.35	324.52
ARC-TWC368		10.58	14.87	138.91	184.86
ARC-TWC T324		7.63	14.45	120.38	177.03
PIONEER-SC3062		39.70	43.84	416.14	460.04
PIONEER-SC30K8		12.93	11.67	153.44	142.73
PIONEER-SC30K9		5.95	6.12	64.38	62.66
HYTECH -SC2031		2.22	1.95	32.25	24.34
HYTECH -SC2055		15.62	10.58	192.07	131.54
HYTECH -TWC1100		0.00	3.18	0.00	35.93
LSD at 0.05	Hybrids (H)	5.42		3.21	
	Locations (L)	2.42		1.43	
	H × L	7.66		4.53	

Table (3): Final disease incidence (FDI%) and area under disease progress curve (AUDPC) of the 15 maize hybrids, under field conditions at Gemmeiza and Sids locations, during 2022 growing season.

Maize hybrid		Epidemiological parameters/locations			
		FDI (%)		AUDPC	
		Gemmeiza	Sids	Gemmeiza	Sids
ARC-SC128		9.95	11.80	117.48	138.95
ARC-SC130		12.49	5.60	154.54	51.16
ARC-SC132		17.50	15.82	235.23	177.24
ARC-SC168		23.32	19.99	249.23	238.24
Boushy		54.63	67.12	773.47	804.75
ARC-TWC321		10.12	15.32	119.78	179.48
ARC-TWC360		7.39	20.37	105.10	232.25
ARC-TWC368		7.22	12.91	104.35	147.30
ARC-TWC T324		7.97	10.22	108.63	121.85
PIONEER-SC3062		29.88	31.48	358.62	359.46
PIONEER-SC30K8		10.14	11.13	123.11	123.97
PIONEER-SC30K9		7.67	7.35	107.33	75.52
HYTECH -SC2031		5.46	7.52	50.83	79.66
HYTECH -SC2055		9.99	13.59	146.77	162.09
HYTECH -TWC1100		4.15	5.51	45.46	41.86
LSD at 0.05	Hybrids (H)	3.41		2.32	
	Locations (L)	1.52		1.03	
	H × L	7.66		4.53	

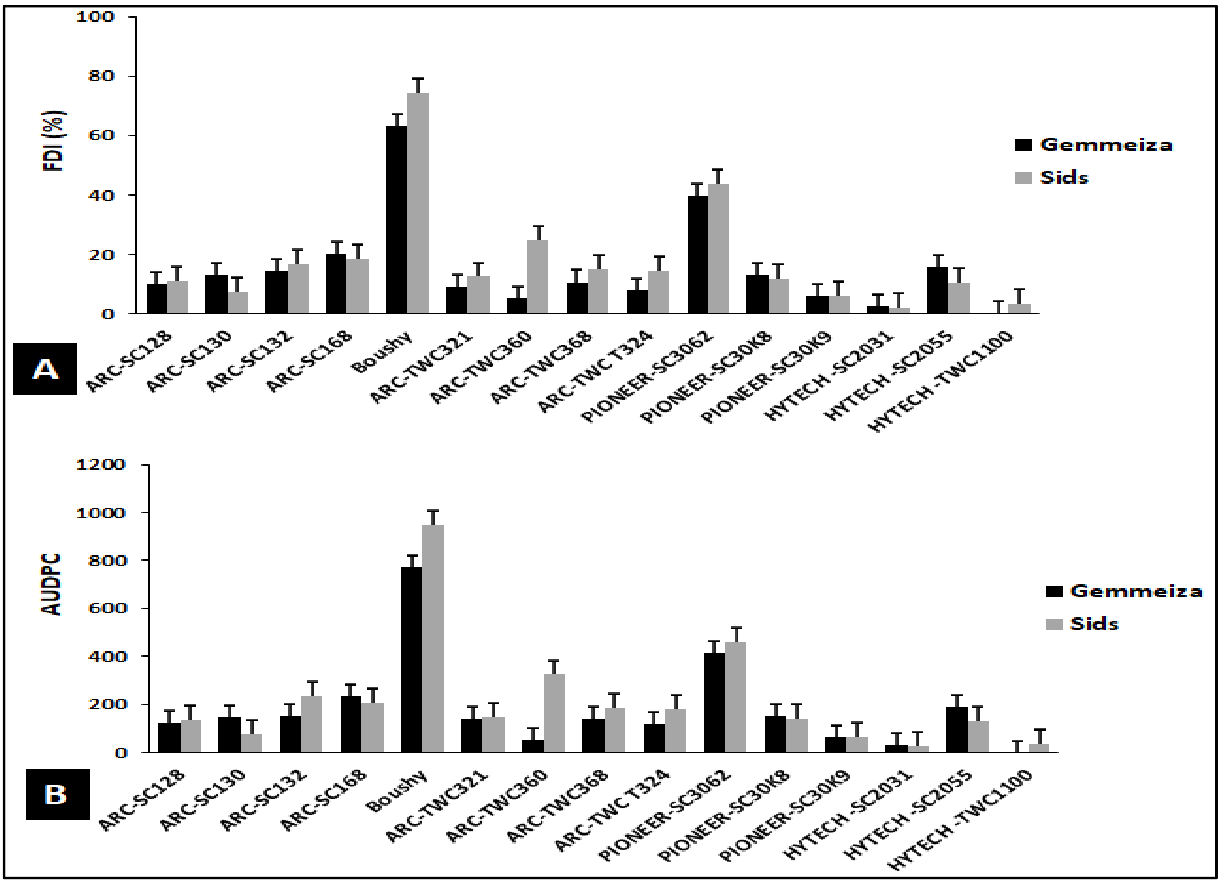

Fig. (3): Late wilt disease, expressed as FDI% (A) and AUDPC (B) of 15 maize hybrids, under field conditions at Gemmeiza and Sids locations, during 2021 growing season.

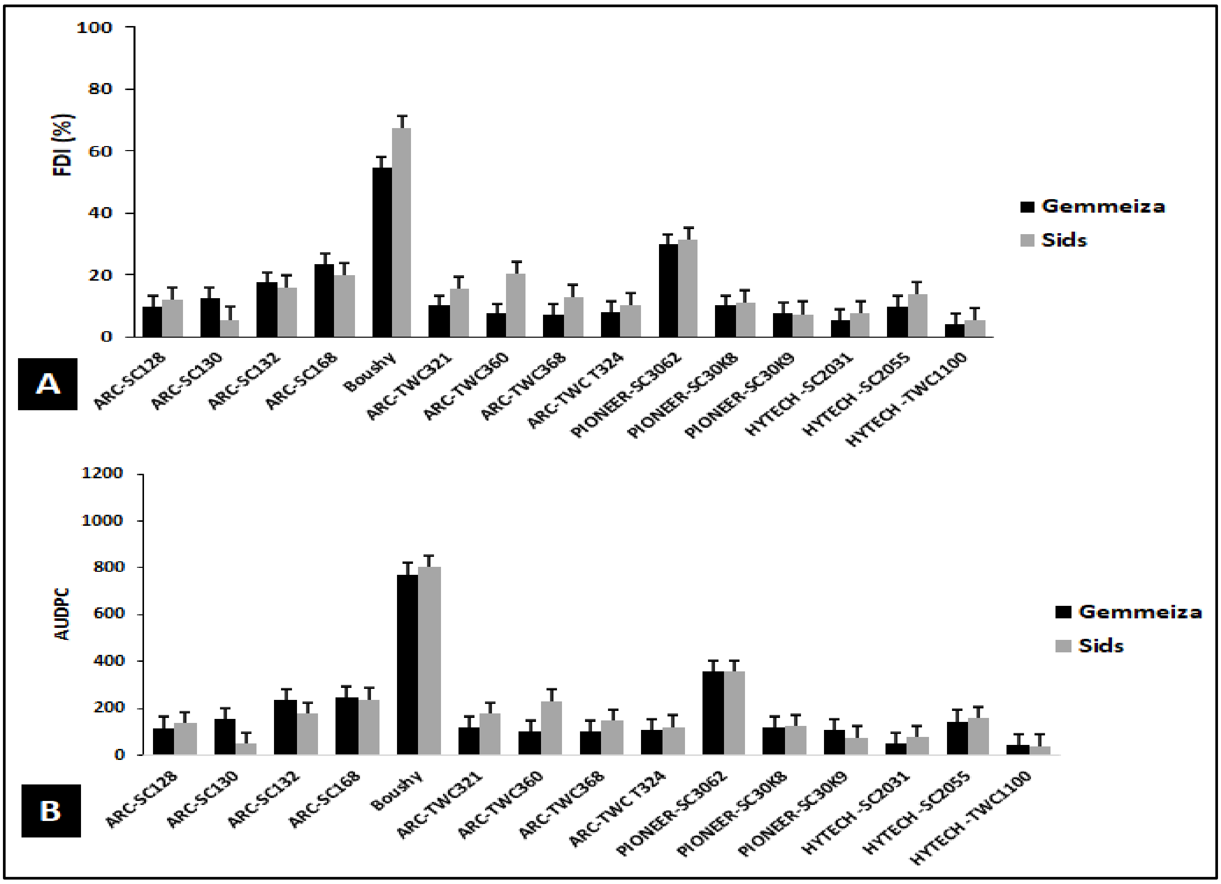

Fig. (4): Late wilt disease, expressed as FDI% (A) and AUDPC (B) of 15 maize hybrids, under field conditions at Gemmeiza and Sids locations, during 2022 growing season.

Relative contribution (%):

Based on the data in Table (4), it is clear that the genetic makeup of the tested maize hybrids was primarily responsible for more than 80% of the variations in how the hybrids responded to late wilt. In the variations of FDI (%) and AUDPC (Table 4), the genetic structure of the investigated hybrids contributed comparatively by 89.74 and 96.20% (2021) and 91.81 and 91.69% (2022), respectively. In contrast, during the study's 2021 and 2022 seasons, the percentage contribution of the locations was relatively low (less than 1%).

Table (4): Relative contribution (%) of the environment, maize hybrids, and their interaction on variance analysis of two variables tested for late wilt.

S.O.V.	FDI (%)		AUDPC	
	2021	2022	2021	2022
Environment (L)	0.65	0.84	0.71	0.09
Hybrid (H)	89.74	91.81	96.20	91.69
Interaction (L×H)	2.92	3.17	3.04	8.25

FDI (%) = final disease incidence; AUDPC = area under disease progress curve.

Genetic nature of PR to late wilt:

Genetic advance (GA%) and heritability (h^2%) were computed for the two parameters, namely FDI (%) and AUDPC (Table 5). For the FDI (%) and AUDPC, the heritability values (up to 99%) were attained, with values of 99.42 and 99.79% in 2021 and 99.76 and 99.89% in 2022, respectively. Also, genetic advance was more than 80% of the two parameters under the 2021 and 2022 growing seasons.

Table (5): Heritability (h^2%) and genetic advance (GA%) for 15 maize hybrids of two variables tested for late wilt.

S.O.V.	FDI (%)		AUDPC	
	2021	2022	2021	2022
Heritability in broad sense (h^2)	99.42	99.76	99.79	99.89
Genetic advance (GA)	87.49	87.64	87.66	87.70

FDI (%) = final disease incidence; AUDPC = area under disease progress curve.

Yield components:

The performance of fifteen hybrids for grain production and related agronomic components in the two testing locations over the two seasons of 2021 and 2022 is depicted in Tables 6, 7 and Figs. 5, 6. A perusal of the results revealed that the values of all attributes varied substantially among the hybrids studied. The plant height average was 212 cm, with the largest value of 248 cm recorded in the HYTECH-SC2031 hybrid and the lowest value of 169 cm shown in the sensitive check variety Boushy (Tables 6, 7 and Fig. 5B). Likewise, the average ear height was 107 cm, reaching 124 cm for HYTECH-SC2055 and 92 cm for Boushy (Tables 6, 7 and Fig. 5B). The harvested grains per plot varied significantly across the tested hybrids, ranging from 3.25 kg in Boushy to 8.17 kg in HYTECH-SC2031, with an average of 5.08 Kg/plot. Four hybrids possess high grain yield with an average of more than 6.16 kg/plot: HYTECH-SC2031, ARC-SC130, HYTECH-SC2055, and PIONEER-SC30K9 (Tables 6, 7 and Fig. 5C). In the same circumstances, the hundred kernel average weight (Tables 6, 7 and Fig. 6A) was 34.58 gm, and the hybrids HYTECH-SC2031 (39.47 gm), HYTECH-TWC1100 (39.41 gm), and PIONEER-SC30K9 (39.31 gm) generated the heaviest kernel index, while hybrid Boushy achieved the lightest kernels (24.83 g). The average ear length was 20.66 cm, and the ARC-Sc132 hybrid was the longest (23.5 cm), while the susceptible hybrid Boushy recorded the shortest ear length (Tables 6, 7 and Fig. 6B). On the other hand, there is no significance in ear diameter amongst maize hybrids throughout the two growing seasons (Tables 6, 7 and Fig. 6C). As a result, a substantial positive relationship was found between grain yield/plant and each of the hundred kernel weight, plant height, and ear length. Furthermore, a substantial positive relationship was found between resistance to LWD and the harvested grain yield per plant.

Principal Component Analysis (PCA):

Final disease incidence (FDI) and yield factors, including 100 kernel weight, ear length, ear diameter, plant height, ear height and harvested yield per plot, were all subjected to principal component analysis (Figs. 7A and B). The first two components, FDI (%) and 100 kernel weight, have eigenvalues greater than one, as can be seen from the scatter plot graph and loadings (Figs. 7A and B). As a result, from the combined data of the 2021 and 2022 seasons of Gemmeiza and Sids locations, two components were derived that together described about 93.99% of the data. These two variables had a substantial positive correlation (0.8667) compared to another variable, for which the correlation was weekly (0.0457) (Fig. 7B). In light of this, principal component analysis demonstrated the significance of FDI (%) and 100 kernel weight, which were regarded as excellent and more trustworthy indicators for evaluating the items under research.

Table (6): Effect of late wilt disease in the yield components of the fifteen maize hybrids at the two locations during the growing season 2021.

Maize hybrid	100 Kwt (g)		Ear length (cm)		Ear diameter (cm)		plant height (cm)		Ear height (cm)		Harvested ears/plot (Kg)	
	Gemm.	Sids	Gemm.	Sids	Gemm.	Sids	Gemm.	Sids	Gemm.	Sids	Gemm.	Sids
ARC-Sc128	40.6	33.1	22.17	20.42	5.3	5.3	212	220	92	100	5.78	5.38
ARC-Sc130	38.1	30.7	21.17	19.57	5.1	5.0	208	221	106	103	6.91	6.53
ARC-Sc132	38.0	25.2	23.50	20.58	5.0	4.9	194	188	97	97	4.73	4.35
ARC-Sc168	35.0	31.9	22.00	20.33	5.3	5.2	192	188	98	100	4.17	3.32
Boushy	27.7	24.0	19.17	18.25	4.9	4.8	187	170	97	115	3.55	3.28
ARC-TWC321	38.7	35.2	21.00	19.08	4.8	5.1	213	218	109	113	3.87	3.48
ARC-TWC360	40.3	26.7	22.33	20.17	5.1	5.1	218	205	98	98	5.27	3.25
ARC-TWC368	39.3	27.5	21.50	20.50	5.6	5.4	222	197	103	108	5.50	5.15
ARC-TWC T324	38.6	31.2	20.67	20.44	5.0	4.9	217	213	102	102	3.64	3.25
PIONEER-SC3062	33.9	29.3	20.33	19.03	5.0	5.0	225	222	120	120	4.56	4.22
PIONEER-SC30K8	37.1	28.6	19.00	18.47	5.1	5.0	202	234	103	105	6.12	5.75
PIONEER-SC30K9	42.4	37.1	21.67	19.92	5.1	5.1	234	215	104	115	6.62	6.19
HYTECH -SC2031	41.1	37.1	22.00	20.02	5.1	5.2	243	235	111	118	8.05	7.64
HYTECH -SC2055	37.5	34.1	22.33	20.25	5.1	5.1	218	215	124	118	6.14	5.77
HYTECH -TWC1100	44.5	35.6	21.00	22.17	6.8	6.5	233	225	118	118	4.64	4.19
LSD at 0.05	1.25	2.11	1.01	1.03	ns	ns	3.21	4.31	3.56	2.67	0.52	0.43

ns* = non-significant

Table (7): Effect of late wilt disease in the yield components of the fifteen maize hybrids at the two locations during the growing season 2022.

Maize hybrid	100 Kwt (g)		Ear length (cm)		Ear diameter (cm)		plant height (cm)		Ear height (cm)		Harvested ears/plot (Kg)	
	Gemm.	Sids	Gemm.	Sids	Gemm.	Sids	Gemm.	Sids	Gemm.	Sids	Gemm.	Sids
ARC-Sc128	40.2	31.8	21.89	20.06	4.9	4.6	212	192	96	99	5.63	5.24
ARC-Sc130	38.2	30.2	21.89	20.02	5.0	5.0	235	201	110	99	7.08	6.21
ARC-Sc132	38.4	25.8	23.33	20.44	4.6	4.6	189	189	101	94	4.70	4.17
ARC-Sc168	34.3	32.7	22.33	20.61	5.0	4.7	202	189	98	103	3.79	3.36
Boushy	27.9	23.6	18.39	18.00	5.2	5.0	169	170	96	93	3.77	3.32
ARC-TWC321	38.5	34.1	20.50	18.69	4.7	4.7	221	214	108	118	4.03	3.43
ARC-TWC360	39.1	27.6	22.11	20.06	4.9	4.7	208	207	97	101	4.98	4.06
ARC-TWC368	38.7	28.1	21.33	20.58	4.6	4.9	201	201	114	100	5.69	5.11
ARC-TWC T324	38.7	31.3	20.89	20.67	4.9	4.2	215	213	101	104	3.98	3.55
PIONEER-SC3062	34.0	29.5	20.78	19.31	4.9	4.5	219	224	123	118	5.19	4.44
PIONEER-SC30K8	37.1	28.0	19.50	18.82	5.0	4.8	206	222	103	108	6.20	5.81
PIONEER-SC30K9	41.8	35.9	21.72	19.97	5.0	4.6	210	246	106	113	6.65	6.21
HYTECH -SC2031	40.6	39.0	22.00	19.97	4.9	5.0	244	248	113	119	8.17	7.36
HYTECH -SC2055	37.4	36.2	23.11	20.67	4.9	4.8	213	218	123	121	6.51	6.21
HYTECH -TWC1100	43.1	34.5	20.67	22.22	5.2	4.8	233	223	115	123	4.64	4.10
LSD at 0.05	2.04	2.76	1.01	0.91	ns	ns	4.32	3.25	3.07	2.94	1.02	0.95

ns* = non-significant

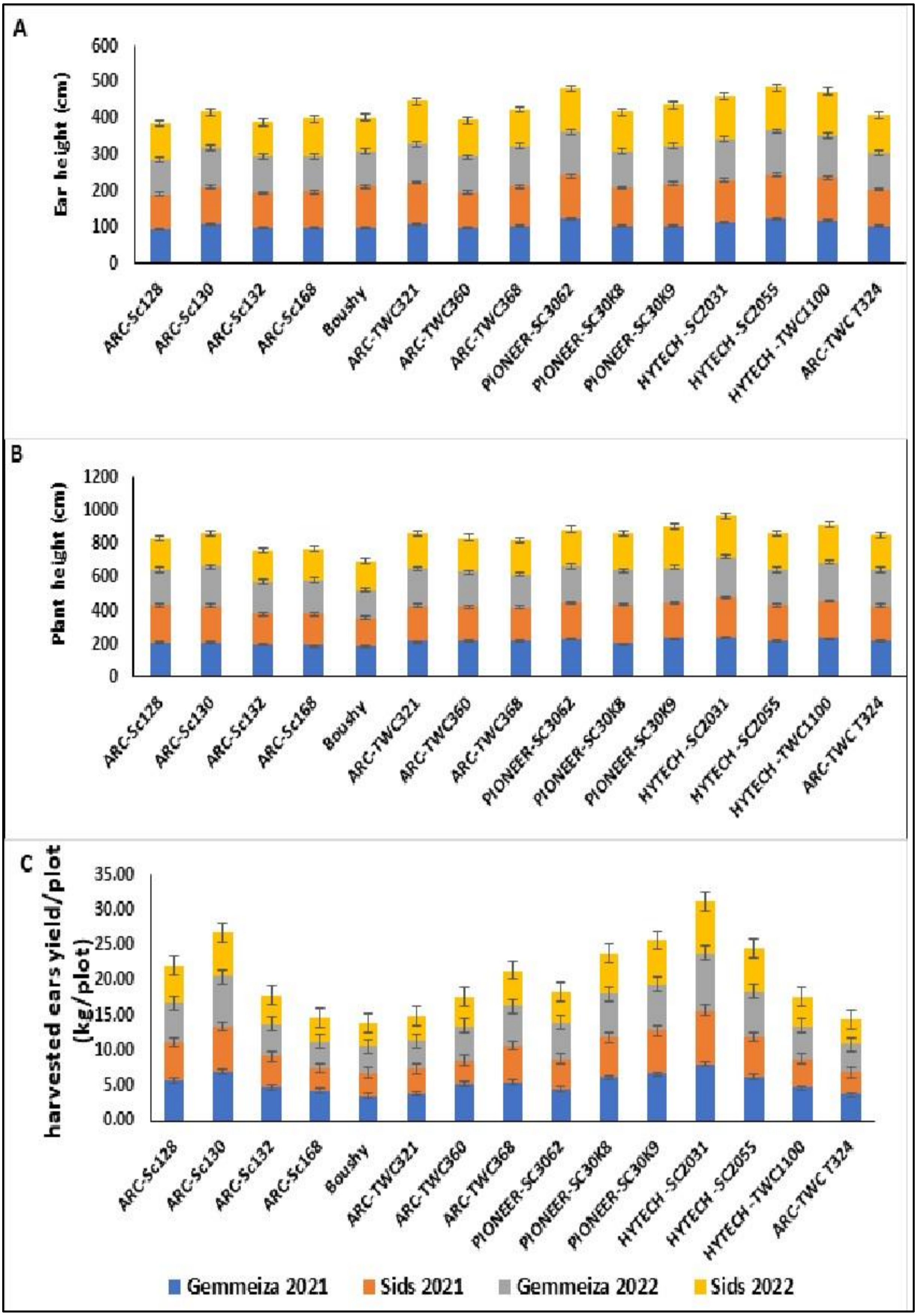

Fig. (5): Mean performance of the fifteen hybrids for agronomic characteristics over two locales and two seasons; (A) Ear height (cm), (B) Plant height (cm), (C) harvested ears yield per plot (Kg/plot).

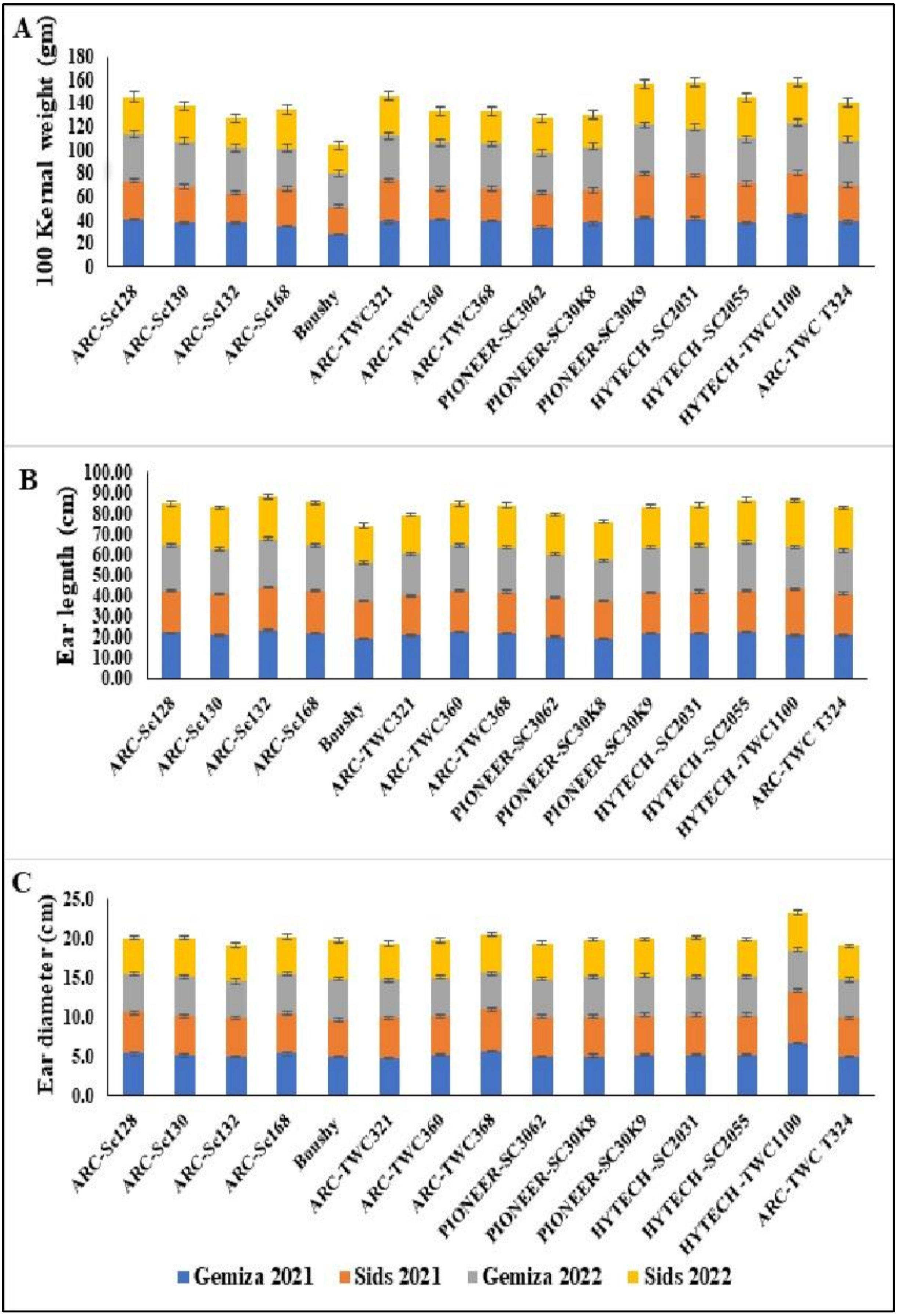

Fig. (6): Mean performance of the fifteen hybrids for grain yield and agronomic characteristics over two locales and two seasons; (A) 100 kernel weight (gm), (B) ear length (cm), (C) ear diameter (cm).

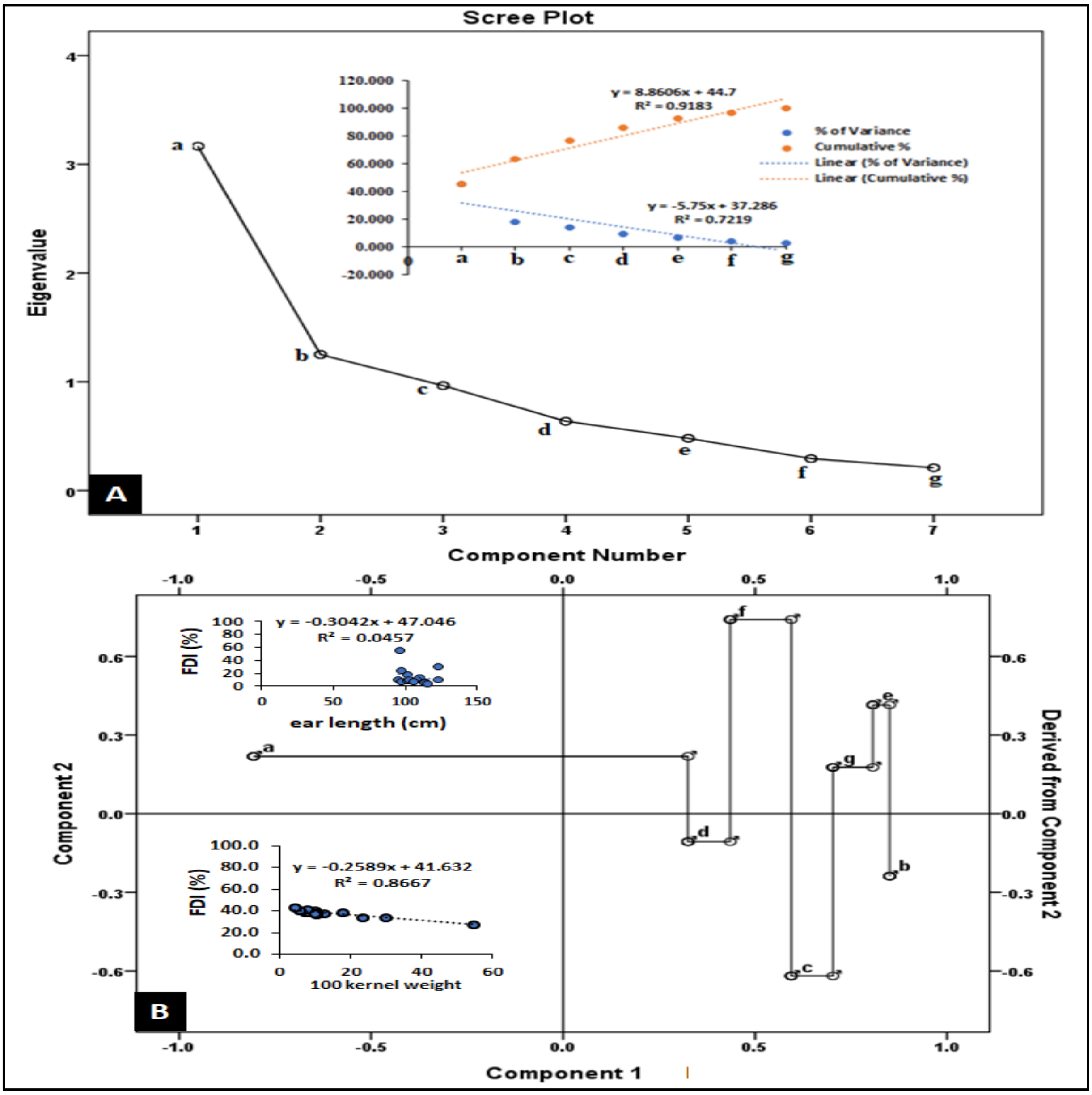

Fig. (7): Scree plot graph (A) and loadings plot (B) of final disease incidence (a), 100 kernel weight (b), ear length (c), ear diameter (d), plant height (e), ear height (f) and harvested yield per plot (g) for maize over two locales and two seasons.

DISCUSSION

Late wilt disease is a serious danger to the maize economy in heavily infected areas. Screening for late wilt disease resistance necessitates the evaluation of genotyping arrays with the purpose of categorizing maize hybrids into certain categories of disease response. The symptoms seen on infected plants were identical to those described by El-Shafey and Claflin, 1999. The observation that all of the examined hybrids exhibited LWD symptoms immediately after fruit ripening indicates the fact that there was no immunity against *M. maydis* in the evaluated genotypes. This finding supports the findings of El-Naggarr (2019), who stated that *M. maydis* infects all maize hybrids under fungus inoculum stress and colonizes all maize plant parts that emerge throughout the growing season. Pathogen migration and accumulation in plants, on the other hand, are mostly determined by the genetic makeup of the attacked plant, with the outcome of their interactions determining pathogen concentration in the host (Wang, 2018).

Annual field evaluations of maize hybrids have been done to determine their degree and level of partial resistance (PR) to late wilt disease by assessing the two primary epidemiological indices of resistance: final disease incidence (FDI%) and area under disease progress curve (AUDPC) under disease stress of field circumstances at two separate hotspot locations over the study's two seasons. The check hybrid Boushy had the highest and fastest disease development rate, followed by hybrid PIONEER-SC3062, indicating that these genotypes are the most sensitive to LWD among the genotypes tested; therefore, they characterized fast disease development. Since they recorded the highest percentages of FDI%, they ranged from 54.63 to 74.45 and from 29.88 to 43.84 for Boushy and PIONEER-SC3062, respectively, at both locations *i.e*., Gemmieza and Sids, during the two growing seasons. Nevertheless, under the same climatic circumstances of the two locations, maize hybrids ARC-SC132, ARC-SC168, ARC-TWC321, ARC-TWC368, PIONEER-SC30K8, and HYTECH-SC2055 displayed appropriate moderate levels of adult plant resistance to LWD. Meanwhile, the excellence of the three hybrids; HYTECH-TWC1100, PIONEER-SC30K9, and HYTECH-SC2031, as they exhibited the greatest resistance rate (FDI% is not surpassed up to 7.67%) and a sufficient degree of resistance in adult plants or partial resistance (PR) under disease stress in the identical field circumstances at the two sites over the two seasons of the research. As a result, it was determined that each of these maize genotypes had the capacity to limit the development of LWD infection over the study's two years. Niks *et al*. (2011) found similar findings, justifying and describing partial resistance broadly as a lower rate of epidemic growth and/or accumulation in the field, regardless of a susceptible infection type or in the absence of a suitable host-pathogen interaction (Nyanapah *et al*., 2020). Moreover, the maize response to LWD in each of the 15 hybrids varied from site to site and season to season, indicating different levels of resistance. This is consistent with the findings of El-Itriby *et al*. (1984) investigation. The resistance of ARC-TWC360, ARC-TWC368, ARC-TWC T324, PIONEER-SC3062, and Boushy was higher in Sids than in Gemmeiza. It has been generally proven that resistance to diseases in plant species is not a permanent feature, and the explanation for this phenomenon is due to the self-regulating nature of genetic variety in host-parasite interactions (King and Lively, 2012). Moreover, the relevance of disease resistance in maize has long been appreciated, although maize strains typically range in degree of resistance and do not demonstrate a clear distinction between resistant and susceptible varieties (El-Shafey *et al*., 1988). Meanwhile, many corn diseases, such as root, stalk, and ear rots, are inherited in a complicated way rather than by simple single or complementary gene inheritance (Poehlman, 2005). The genetic heterogeneity makes it easier to identify preferred genes and hence prospective genotypes according to agronomic productivity and LWD resistance (Kamara *et al*., 2021). Similarly, El-Hosary and El-Fiki (2015) and Mosa *et al*. (2017) reported genetic variations in maize hybrids for grain yield and LWD resistance. Moreover, the presence, prevalence, and severity of plant pathogens are influenced by climate change. Since world temperatures rise by 2-4°C creates an environment favorable to pest migration and establishment (Shekhar *et al*., 2010). The considerable variation found might be attributed to differences in soil and climatic conditions between the two locations. Similar findings were reported by other studies, such as Ajala *et al*. (2020). The interplay of genotype and environment has frequently been characterized as persistent differences between genotypes from one environment to another. Several attempts have already been performed in this area to investigate the link between genotype and environmental conditions (Song *et al*., 2020 and Zhang *et al*., 2022) .

To estimate the degree of partial resistance (PR) of the tested maize hybrids, a combined analysis of the variance of the two sites was used across the two growing seasons of 2021 and 2022. There were significant disparities in FDI (%) and AUDPC between locations (L) and maize hybrids (H). Furthermore, when the tested maize hybrids and locations (L) interacted, there was a significant difference. Because the interaction between hybrids and locations is essential, values were used to explore differences in FDI% and AUDPC means of any two hybrids within each location (H x L). The degree of PR to late wilt was assessed for each hybrid by evaluating the two key epidemiological measures of resistance, FDI%, and AUDPC, under disease tension at two distinct sites over the study's two growing seasons. When comparing the first and second seasons (2021 and 2022), environmental circumstances were typically more favorable to the onset and progression of the disease. AUDPC was estimated for each genotype under investigation in order to provide further data on the variance for PR to LWD in the hybrids studied and therefore a more precise description of this type of resistance. AUDPC, on the other hand, has been widely utilized and previously utilized as a reputable and more trustworthy source by many investigators' estimators for evaluating and characterizing PR for many diseases (Nyaga *et al*., 2020). They all agreed that AUDPC is a more reliable and straightforward method of estimating PR than other parameters. since it may represent both the amount of infection and the rate at which it occurs (Omara *et al*., 2018). Furthermore, the widespread usage of AUDPC for calculating PR rather than other epidemiological measures is due to its inclusion of all components that impact or alter disease development. Based on AUDPC estimations at Gemmeiza and Sids sites throughout the 2021 and 2022 seasons, the examined hybrids may be categorized into two main groups. The maize hybrids with the lowest AUDPC values characterized by PR include ARC-SC128, ARC-SC130, ARC-TWC321, ARC-TWC368, PIONEER-SC30K8, PIONEER-SC30K9, HYTECH-SC2031, HYTECH-TWC1100, and ARC-TWC324 (less than 184.86). The second group, however, consisted of hybrids with the highest AUDPC values (more than 184.86) at the two sites: ARC-SC132, ARC-SC168, Boushy, ARC-TWC360, PIONEER-SC3062, and HYTECH-SC2055. The high correlation between LWD scores and AUDPC indicated that AUDPC is a reliable measure of resistance and ought to be utilized regularly for disease resistance screening. In addition, rather than other epidemiological parameters, individual disease ratings at the adult stage of plant growth were nearly identically effective as AUDPC in ranking inbred lines for disease resistance (Nyanapah *et al*., 2020). It should be emphasized that this is the first attempt to identify this type of resistance (partial resistance and AUDPC) to LWD on maize genotypes in Egypt.

According to the findings of relative contribution (%), the genetic composition of the studied maize genotypes was responsible for more than 80% of the variability in how the hybrids responded to late wilt. The genetic structure of the investigated hybrids contributed comparatively by 89.74 and 96.20% (2021) and 91.81 and 91.69% (2022), respectively, in the variations of FDI (%) and AUDPC. Meanwhile, during the 2021 and 2022 seasons under consideration, the environment's (locations') relative contribution was quite small (less than 1%). As a result, it is reasonable to believe that the variation in the examined disease parameters displayed on the tested hybrids may be attributed to their genetic makeup or genetic composition. Similarly, Omara *et al*. (2020) observed that heterogeneity in the intensity of adult plant response to stem rust infection across stem rust lines was mostly attributable to genetic structure rather than differences in environmental variables among the three research locations. High estimates of broad-sense heritability up to 99% were achieved for FDI (%) and AUDPC, in the two locations under study throughout the two seasons, accordingly. This finding suggests that the phenotypic variances were triggered by the genetic structure of the maize hybrids investigated. Furthermore, the diversity in disease response to late wilt response in the explored genotypes was less affected by climate change from one location to another. These results are in accordance with many studies, such as El-Lakany *et al*. (2009). The findings might also be used to identify the most efficient and desired genes for LWD resistance in future generations. Nevertheless, genetic advancement accounted for more than 80% of the two characteristic parameters in the 2021 and 2022 seasons. Estimates of high heritability (%) obtained over the two growing seasons and at both research sites suggested that most of the phenotypic changes in these PR components were mostly attributable to genetic factors in maize genotypes. Moreover, the high heritability estimation of these characteristics suggested that any of these investigated measures might be extensively employed as a feasible criterion for assessing and choosing PR genotypes in the field. Furthermore, slight differences in environmental factors between locations or seasons had less of an influence on the manifestation of these feat criteria for assessing and selecting PR genotypes under field conditions (Ali *et al*., 2011; Omara *et al*., 2018 and Nyaga *et al*., 2020). Consequently, quick and significant improvement in breeding for PR to LWD would be predicted in present breeding efforts utilizing these lucrative disease parameters (Omara *et al*., 2018; Nyaga *et al*., 2020 and Aruna *et al*., 2021). According to the PCA study, FDI (%) and 100 kernel weight were given considerable importance as two of the best and most accurate indicators for assessing the field resistance of hybrid maize against late wilt. As a result, using FDI (%) will make it simpler to choose among a vast array of maize materials. Similar outcomes were previously noted by (Kamel *et al*., 2017; Essa *et al*., 2018; Omara *et al*., 2018, 2020 and Derbalah *et al*., 2022).

CONCLUSION

The current study displayed considerable partial resistance variation across fifteen maize hybrids, which ensures that these genotypes have adequate amounts of this form of resistance. Low disease progression ARC-SC128, ARC-SC130, ARC-TWC321, ARC-TWC368, PIONEER-SC30K8, PIONEER-SC30K9, HYTECH-SC2031, HYTECH-TWC1100, and ARC-TWC324 showed great performance and resistance to LWD, as well as high yield across the two sites. Due to high heritability estimates and high levels of genetic progress, the phenotypic variances were attributed to hybrid genetic architecture. The principal component analysis revealed the importance of FDI (%) and 100 kernel weight as acceptable evidence for assessing these materials for late wilt disease, which were regarded as excellent and more reliable indicators for evaluating the items under investigation.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

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