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A Predictive Study of the Redistribution of Some Bread Wheat Genotypes in Response to Climate Change in Egypt

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Abstract: Climate change and global warming have become the most significant challenges to the agricultural production worldwide, especially in arid and semiarid areas. The main purpose of plant breeding programs now is to produce a genetically wide range of genotypes that can withstand the adverse effects of climate change. Moreover, farmers have to reallocate their cultivars due to their ability to tolerate unfavorable conditions. During this study, two field experiments and climate analysis based on 150 years of data are conducted to reallocate some genotypes of bread wheat in respect to climate change based on their performance under drought stress conditions. Climatic data indicate that there is an increase in temperature over all Egyptian sites coupled with some changes in rain amount. Among the tested cultivars, cultivar Giza 160 was the perfect one, while cultivar Masr 03 was the weakest one. Susceptibility indices are a good tool for discovering the superior genotypes under unfavorable conditions and, interestingly, some of the cultivars with high performance were among the superior cultivars in more than one of the tested traits in this study. Finally, combining the climatic data and the experimental data, we can conclude that cultivars Giza 160 and Sakha 94 are suitable for growning in zones with harsh environments, such as the eastern desert and southern Egypt, while cultivars Gemmeza 11, Sahel 01, Sakha 98, Sids 12, and Sakha 93 are suitable for growning in zones with good growing conditions, such as the Nile Delta region and northern Egypt.

Keywords: global warming; susceptibility indices; abiotic stresses

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1. Introduction

Climate change and global warming are the biggest problems facing all the world due to their enormous effect on life resources. Its effect becomes more severe when it occurs in a place with limited initial resources. Egypt's ordinary climate is a semiarid climate with very little rainfall accompanied by hot, dry summers and moderate winters. The temperature the last summer exceeded 45 °C in the experimental site while it reached 41 °C in April during the wheat grain filling stage [1], resulting in a signifiant reduction in the grain yield [2]. Egypt has a rare and irregular rainfall during the winter season (from October to April). The annual rainfall varies from 200 mm as a maximum value in the northern coastal regions, then decreases to about 50–100 mm in the Nile Delta region, and reaches a minimum of almost zero in the south, such as Assiut (the experimental site) [3]. The River Nile is the only primary source of water supply and it supplies over 95% of the country's water needs. The Nile waters originate outside Egypt, flowing through nine countries. Egypt's part of the Nile water is controlled by an international agreement.

Recently, Egypt's climate became more severe due to global warming, with unlikely high temperatures and high gusty winds, which make a significant impact on the process of drought change and the expansion of the drought area. The severe climate harmed crop productivity due to abiotic stresses that affect plants' growth, leading to a reduction in crop output [4,5].

Moreover, abiotic stress, such as heat and drought, could reduce germination and seedling growth, cell turgidity, and plant water-use efficiency [6]. Moreover, abiotic stresses could reduce photosynthesis and deactivate photosynthetic enzymes [7]. In addition, abiotic stress reduces grain number and size by affecting grain settings, assimilating translocation and duration, and growth rate of grains [8–10]. Heat stress combined with drought may cause a considerable reduction in the grain yield of wheat, exceeding 50% depending on the durability and the stage of occurrence [2]. Under the current conditions in Egypt, wheat yield reduction will reach 12% with each 1.5 °C increase, and this decrease may reach 27% with the increase in temperature by 3.5 °C [11].

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops globally, providing about 20.0% of total food calories for the world's population [12]. In Egypt, wheat is the most strategic cereal crop as it is the main component in the Egyptian daily meals and its straw is used for animal nutrition. The Egyptian population reached 100 million people without a significant increase in agricultural land, making the gap between wheat production and consumption approach 53.67% [13]. Climate change has recently impacted all agricultural processes in Egypt, from cultivar selection to harvest time [14]. The commercial wheat cultivars in the Egyptian agrarian system differ in their yield production, quality, and response to biotic and abiotic stresses. The time has come to rearrange or redistribute the commercial cultivars along the Egyptian map in response to climatic change to obtain the maximum productivity of them by matching each genotype with the best environmental conditions. This study aims to create a precise distribution of the different commercial bread wheat cultivars on the Egyptian map in view of climatic change.

2. Materials and Methods

2.1. Climatic Analysis

The whole area of Egypt was selected in this study to reallocate the bread wheat cultivars based on the long-term change of climate and experimental analysis of the abiotic stress on some commercial wheat cultivars. The Housing and Building Research Centre (HBRC) divides the country into eight different climatic design regions as reported by [15]. We followed their classification except in the eastern and western desert as they are considered as one zone, however, divided them into two different zones. From our point of view, we studied 9 zones (Figure 1).

In this study, we used the HighResMIP experiments conducted by the Atmospheric General Circulation Model (AGCM) v 3.2 at Meteorological Research Institute (MRI) (MRI-AGCM3.2S) at a20 km spatial resolution [16] over the continuous long-term period of 150 years (1950–2099). This model gives historical data for the period 1950–2014 and future data for the period 2015–2099 with RCP8.5 future scenarios. To understand the spatial and temporal climatic variability and its link with agricultural activities, we stylistically analyzed the present climatic data from 1950–2014 (about 65 years), and the future climatic data from 2015–2099 (about 85 years). For instance, the whole of Egypt was classified into 9 spatial areas based on the climatic condition as well as the distribution of urban and agricultural regions. Both rainfall and temperature parameters were considered in the analysis. The monthly weighted average of temperature and rainfall over each zone were estimated using zonal analysis tools in ArcGIS 10.8. These data then were used for the comparison between the present climate conditions for the period (1950–2014) and the future scenarios of climate for the period (2015–2099).

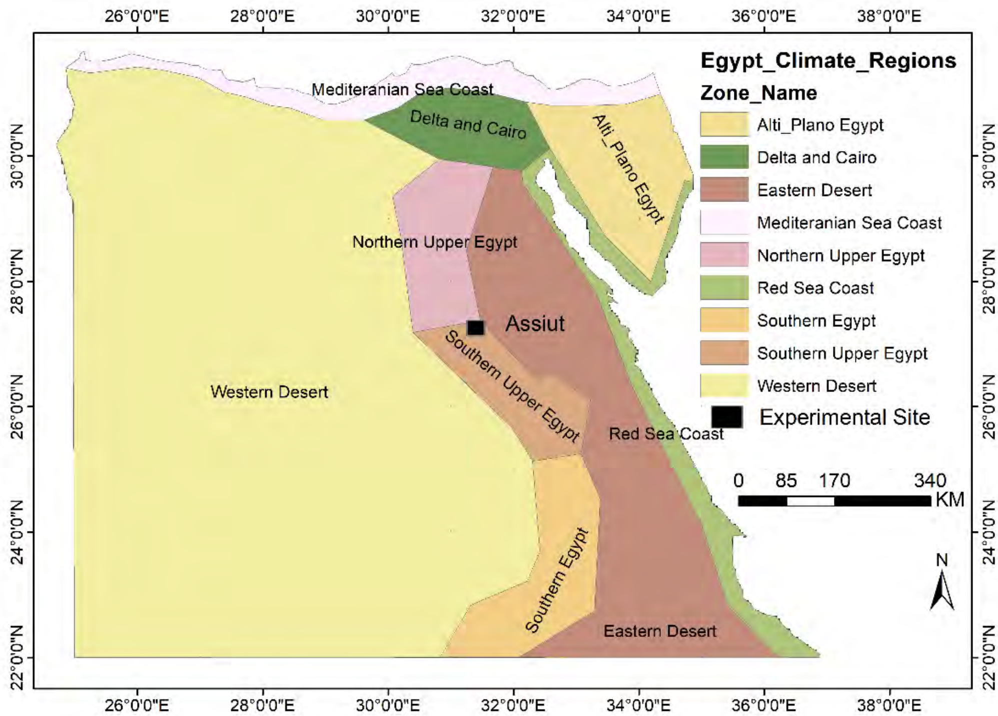

Figure 1. Experimental site and climatic zones of Egypt.

2.1.1. Rainfall

Temporal and spatial analysis for the rainfall changes in the future were discussed in this paper. Temporally, annual, and seasonal changes were investigated, and spatially, 9 climatic regions were considered in the analysis to show the extent of the difference in the rainfall amount.

2.1.2. Temperature

The temperature was also considered as one of the important climatic parameters in this study. Both temporal and spatial analyses were addressed in this section. Temporally, annual, and seasonal changes were investigated, and spatially, 9 climatic regions were considered in the analysis to show is the extent of the difference in temperature.

2.2. Experiment Procedures

Two field experiments were conducted during the 2018/2019 and 2019/2020 seasons to study the effect of two irrigation levels using a drip irrigation system on the productivity of most of the bread wheat commercial cultivars.

2.2.1. Plant Material

In this study, we used a set of 23 Egyptian local bread wheat cultivars, which included both some modern and old cultivars developed by the agricultural research center and distributed as commercial cultivars across the Egyptian agrarian map.

2.2.2. Experimental Site

All cultivars were grown at the Cemex company farm (about 17 km from Assiut University), Assiut Governorate (lat. 27°18′ N, long 31°03′, and alt. 53 m asl). This site is located in Assiut, western desert, as the soil type is sandy (Figure 1). The mechanical and chemical analyses of the experimental site are shown in Table 1.

Table 1. Summary of the physical and chemical properties of the experimental site.

Test Type	Properties	2018/2019	2019/2020
Mechanical analysis	Sand	86.4	85.3
	Silt	7.4	8.2
	Clay	6.2	6.5
	Soil Type	Sandy	Sandy
Chemical analysis	pH	8.1	8.3
	Organic matter %	0.093	0.099
	Total N%	0.019	0.017
	Total $CaCO_3$%	20.5	19.75

2.2.3. Climatic Data of the of Experimental Site

The climatic data were obtained from the Central Laboratory for Agricultural Climate (CLAC) and shown in Table 2. Assiut weather has high temperatures during summer, a short winter, high-sunshine duration hours, and low humidity. Cropwat 8.0 is a program developed by FAO to calculate evapotranspiration (ET0) and irrigation water requirement based on climatic data [17]. We used this program to calculate the optimum irrigation water requirements.

Table 2. Average maximum (T_{Max}) and minimum (T_{Min}) temperature, relative humidity (RH), wind speed (WS), and calculated evapotranspiration (ETo) during the 2018/2019 and 2019/2020 growing seasons.

Month	T_{Max}	T_{Min}	RH %	ETo (mm) Cropwat Result	WS (km h^{-1})
December 2018	13	20	53	4.27	18.1
January 2019	11	20	35	4.79	15.3
February 2019	12	22	36	5.96	19.7
March 2019	15	25	29	8.05	22.4
April 2019	19	30	24	10.32	23.3
December 2019	10	22	51	3.82	18.2
January 2020	8	18	52	3.46	19.3
February 2020	11	22	46	4.67	20.9
March 2020	16	27	32	7.47	24.2
April 2020	19	31	26	9.29	24.2

Rainfall was discarded from the two growth seasons.

2.2.4. Experimental Setup

The experiment was laid out in a randomized complete block design in a strip plot arrangement with three replications. Two irrigation treatments were conducted in each season as follows:

1. Normal condition: all cultivars were subjected to the optimum amount of irrigation water requirements (IR) under these conditions, which were 6529 m^3 ha^{-1} and 5244 m^3 ha^{-1} for the 2018/2019 and 2019/2020 seasons, respectively.
2. Stress conditions: all cultivars were subjected to 70% of the optimum amount of irrigation water requirements in the previous treatment, which were 4570.3 m^3 ha^{-1} and 3670.8 m^3 ha^{-1} for the 2018/2019 and 2019/2020 seasons, respectively, and the treatment started 15 days after transplanting.

In both treatments, the irrigation was conducted using a drip irrigation system and the plants were irrigated every three days. Dripper laterals were installed 0.5 m apart, and emitters were spaced 0.30 m apart with a flow rate of 2.1 L h^{-1}. Wheat grains of each cultivar were germinated in foam trays and transplanted after 15 days from germination. Seedlings were transplanted beside the dripper's line and on the two sides with a single seedling, and the distance between plants was 25 × 25 cm. The transplanting date was 1 December in both seasons, and plants were harvested on 15 May 2019 and 10 May 2020 in the first and second seasons, respectively. The experimental unit was 2 m^2 (1 × 2 m). All other cultural practices, including fertilizers and weed management, were conducted according to the standard recommendations for sowing wheat in this area.

2.2.5. Phenotypic Evaluation

After maturity, a sample of ten guarded plants was used to measure the phenotypic data for yield and its attributes, including plant height in (cm) (PH; the height of the main stem), spike length (SL; cm); length from neck node to the tip of the spike at maturity), number of grains per spike (GN), the weight of grains per spike in gram (GW), and seed index (SI; 1000 kernel weight in gram). Finally, we harvested one-meter square guarded plants for biological (above-ground dry matter) yield/m^2 in Kg (BY), and grain yield/m^2 in kg (GY).

In addition, the average over the two growing seasons for some mathematical formulas of tolerance and susceptibility indices was calculated for grain yield, as shown in Table 3.

Table 3. Some mathematical formulas of tolerance and susceptibility indices for grain yield.

Index	Formula	Reference
Stress susceptibility index	$SSI = \frac{1-(Y_s/Y_P)}{1-(\bar{Y}_s/\bar{Y}_P)}$	[18]
Relative stress index (RSI)	$RSI = \frac{(Y_s/Y_P)}{(\bar{Y}_s/\bar{Y}_P)}$	[19]
Tolerance index (TI)	$TI = Y_P - Y_s$	[20]
Mean productivity (MP)	$MP = \frac{(Y_p+Y_s)}{2}$	[20]
Yield stability index (YSI)	$YSI = Y_s/\ Y_P$	[21]
Harmonic mean (HM)	$HM = \frac{2(Y_p \times Y_s)}{(Y_p+Y_s)}$	[22]
Yield reduction ratio (YRR)	$YRR = 1-(Y_S/Y_P)$	[23]
Geometric mean productivity (GMP)	$GMP = \sqrt{Ys \times Yp}$	[24]
Stress tolerance tndex (STI)	$STI = \frac{(Y_s \times Y_P)}{(\bar{Y}_p)^2}$	[24]
Yield index (YI)	$YI = Y_s/\bar{Y}_s$	[25]

Ys and Yp are the stress and non-stress potential yield of a given cultivar, respectively; Ȳs and Ȳp are the average yield of all genotypes under stress and non-stress conditions, respectively.

2.2.6. Data Analysis

Separate and combined analyses of variance were performed using Proc Mixed of SAS package version 9.2 [26], and means were compared by revised least significant difference (LSD) at 5% level of significance [27]. Ward's hierarchical cluster analysis was performed by PAST software [28] to unify groups such that the variation inside these groups is not increased too drastically based on the average of the two seasons grain yield and stress tolerance index.

3. Results

3.1. Climatic Change

3.1.1. Rainfall

The annual changes over the whole of Egypt (Figure 2) between the past period (1950–2014) and the future period (2015–2099) were about 16.83% as a result of an increase in future rainfall. The future period under consideration is very long, of about 85 years; therefore, we classified this time into three periods (2015–2050, 2051–2075, and 2076–2099), and the results show that the rainfall is also increasing by 13.60%, 5.54%, and 33.44% in the future, respectively. The maximum increase was recorded in the last period (2076–2099).

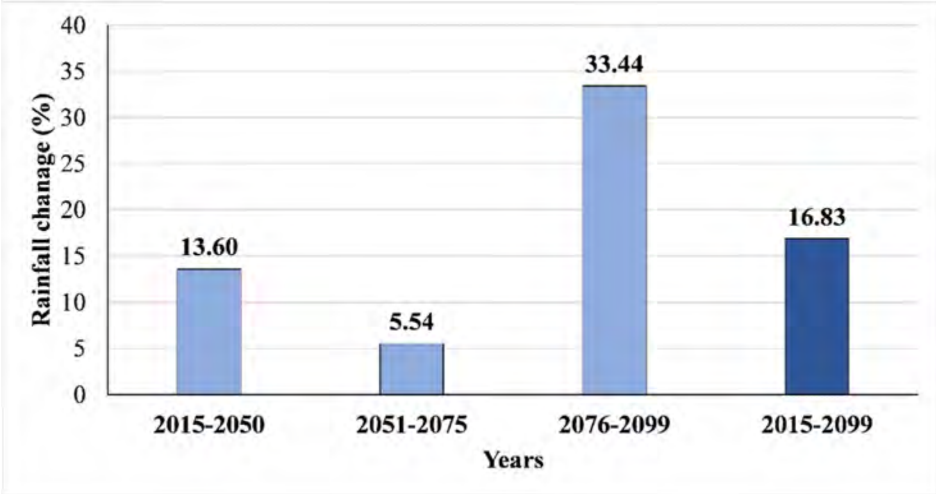

Figure 2. The annual rainfall changes in Egypt between the past period (1950–2014) and the future period (from 2015 to 2099).

Spatially, the average changes across Egypt show a 16.83% increase in rainfall. However, it is highly different from one region to the others. The region of Southern Egypt (See Figure 1 for regions) shows an increase of about 87.48% in the rainfall amounts in the future period. The areas of southern Egypt, Eastern Desert, Sothern Upper Egypt, Western desert, and Red Sea Coast show the highest percentage of increase in rainfall in the future (Figure 3). It is well known the Mediterranean Sea Coast receives the highest rate of rainfall in Egypt; however, this rate will decline in the future. This indicates the spatial changes and shifts from the current condition in the future. Moreover, the Delta and Sinai will increase slightly in the future.

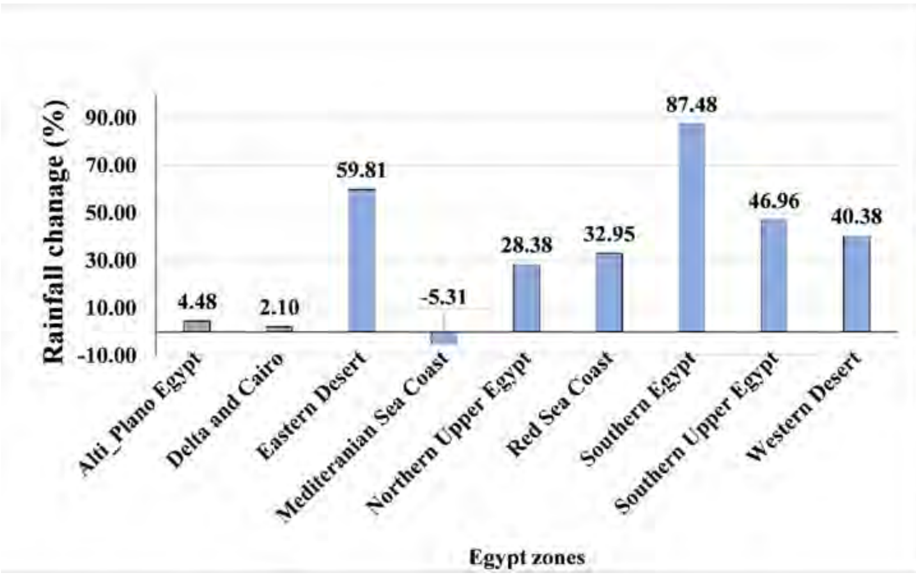

Figure 3. The zonal rainfall changes in Egypt between the past period (1950–2014) and the future period (2015–2099).

In this study, we focus on different wheat cultivars and their relation with climatic impacts, such as rainfall and temperature, in the present and future. This is very important in terms of allocation of the cultivars in the future based on the climate of each zone and which zone will be more suitable for each cultivar. Accordingly, we have investigated the rainfall changes over the wheat crop season in March, April, and May, the most important three months in wheat production as the most sensitive growth stages usually happen during these months. So, only the data of these three months were used in the analysis and we found that, temporally, the annual change shows (see Figure 4) an increase in rainfall of about 47.06% in the future period (2015–2099). In the case of the classified periods, as we stated earlier, there is an increase of about 18.17%, 8.95%, and 130.09% in the periods of 2015–2050, 2051–2075, and 2076–2099, respectively. The last period of 2076–2099 shows a dramatic increase in the average rainfall in the future.

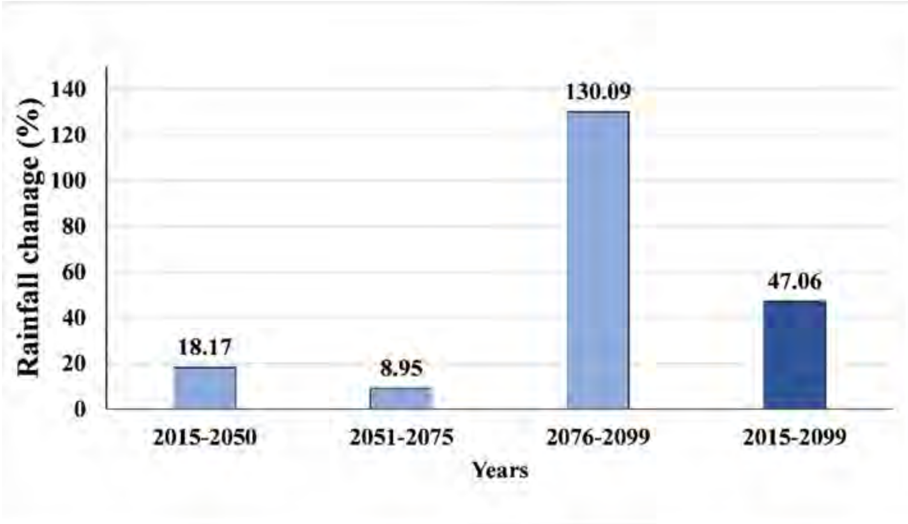

Figure 4. The rainfall changes in Egypt between the past period (1950–2014) and the future period (from 2015 to 2099), considering only the months from March to May.

Spatially, the average rainfall increases in the future in all zones except the Mediterranean Sea Coast area, which shows a decrease of about 6.25% in the future in the considered three months. Southern Egypt, Southern Upper Egypt, and the Eastern Desert show a significant increase in rainfall in the future of over 100% (Figure 5). However, we should notice that these zones in the present time did not receive enough water for the cultivation of wheat and, even if this amount was increased to over 100%, it would still not be enough. So, we should keep in mind that all agricultural areas in Egypt depend on irrigation.

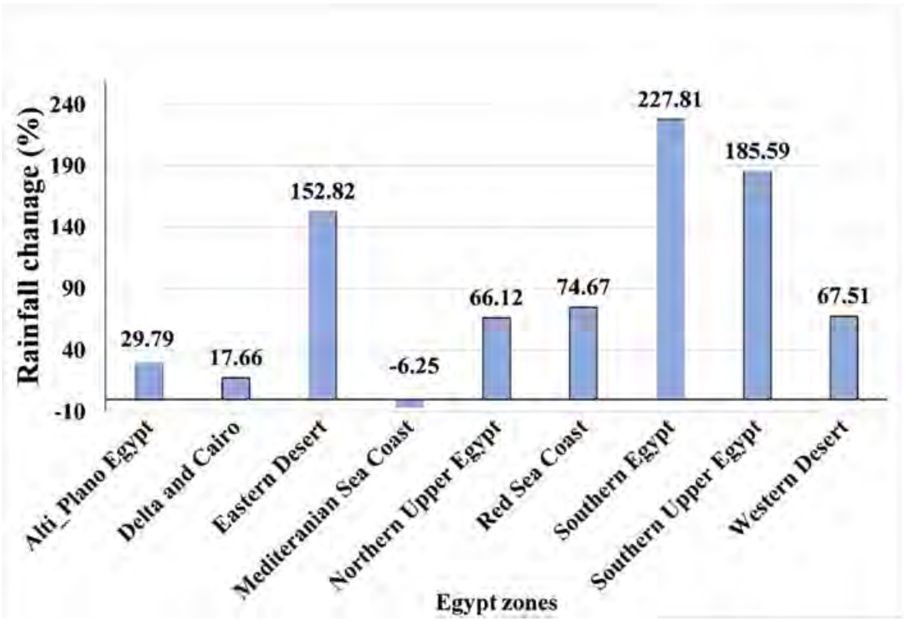

Figure 5. The zonal rainfall changes in Egypt between the past period (1950–2014) and the future period (2015–2099), considering only the months from March to May.

3.1.2. Temperature

The results show that the annual temperature changes from the 1950–2014 period and the future period 2015–2099 positively based on the period, for instance, there is an increase in the temperature of about 7.99% (1.8 degrees), 13.8% (3.2 degrees), and 18.5% (4.26 degree) in the periods of 2015–2050, 2051–2075, and 2076–2099, respectively (Figure 6). The average increase over the entire future time from 2015–2099 is about 12.7% (2.9 degrees).

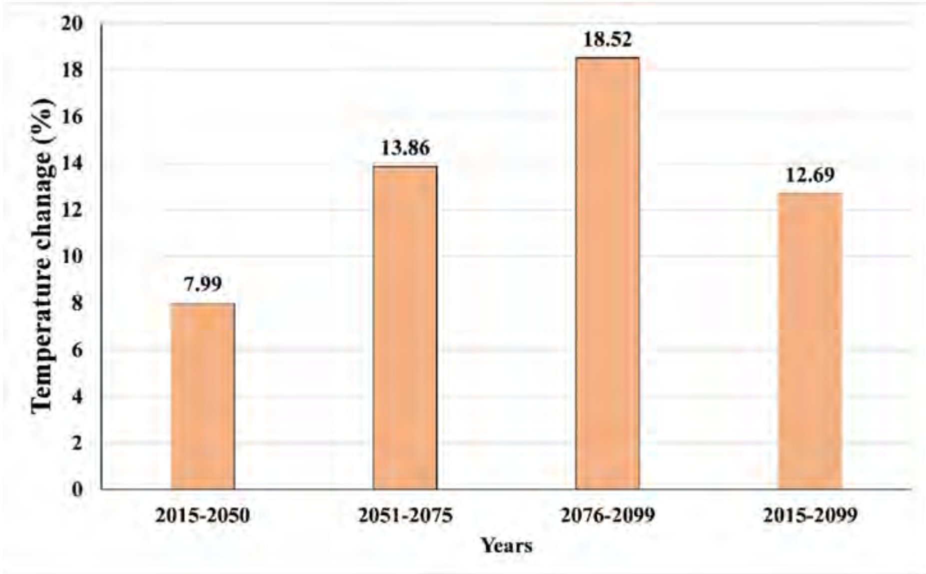

Figure 6. The annual temperature changes in Egypt between the past period (1950–2014) and the future period (from 2015 to 2099).

Spatially, the average temperature changes over the whole of Egypt showing an increase in the future with no significant changes between the different areas. All zones are in the range of 15.1% at Alti Plano Egypt, and the lowest is about 11.8% at the Southern Egypt region, indicating that most of the zones experience an increase in temperature from 2.6–3.15 degrees (Figure 7).

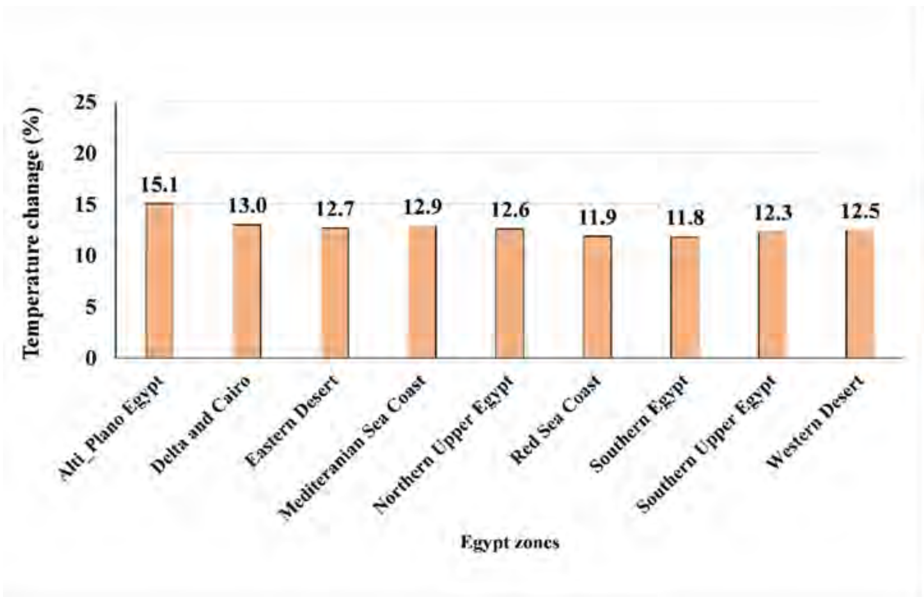

Figure 7. The zonal temperature changes in Egypt between the past period (1950–2014) and the future period (2015–2099).

As we performed for the rain analysis, we have investigated the temperature changes especially over March, April, and May, the most important three months in wheat production as this is when flowering and grain filling occurs. So, only the data of these three months were considered in the analysis and we found that, temporally, the annual change shows (see Figure 8) an increase in the temperature of about 15.85% (3.6 degrees) in the future time (2015–2099). In the case of the classified periods, as we stated earlier, there is an increase of about 14.68% (3.37 degrees), 12.81% (2.94 degrees), and 20.78% (4.77 degrees) in the periods of 2015–2050, 2051–2075, and 2076–2099, respectively. The last period of 2076–2099 shows the highest rate of temperature change in the future.

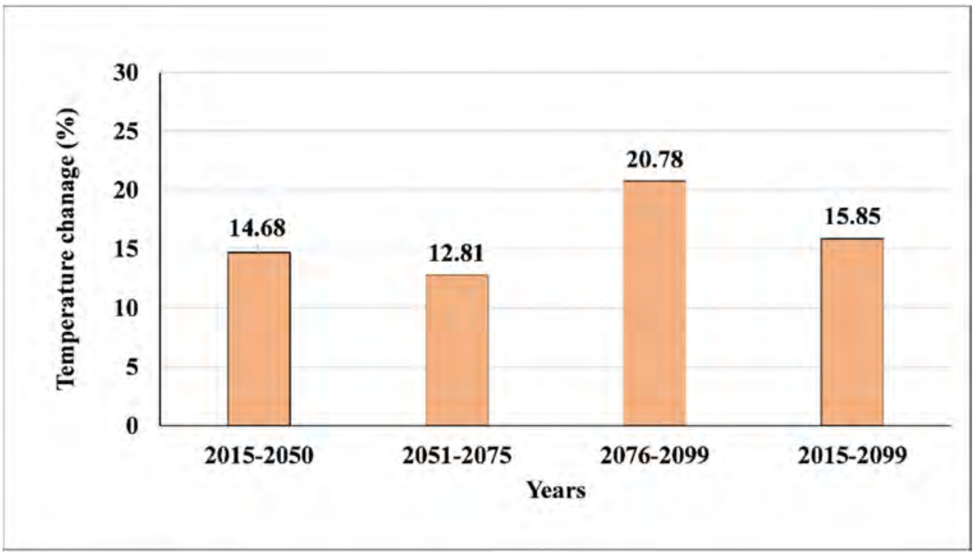

Figure 8. The annual temperature changes in Egypt between the past period (1950–2014) and the future period (2015–2099), considering only the months from March to May.

Spatially, the average rainfall increases in the future at all zones with no distinctive changes (Figure 9) from 3.9 degrees to 3.2, which means all the zones show an increase of more than 3 degrees. The highest change was recorded in Alti Plano Egypt.

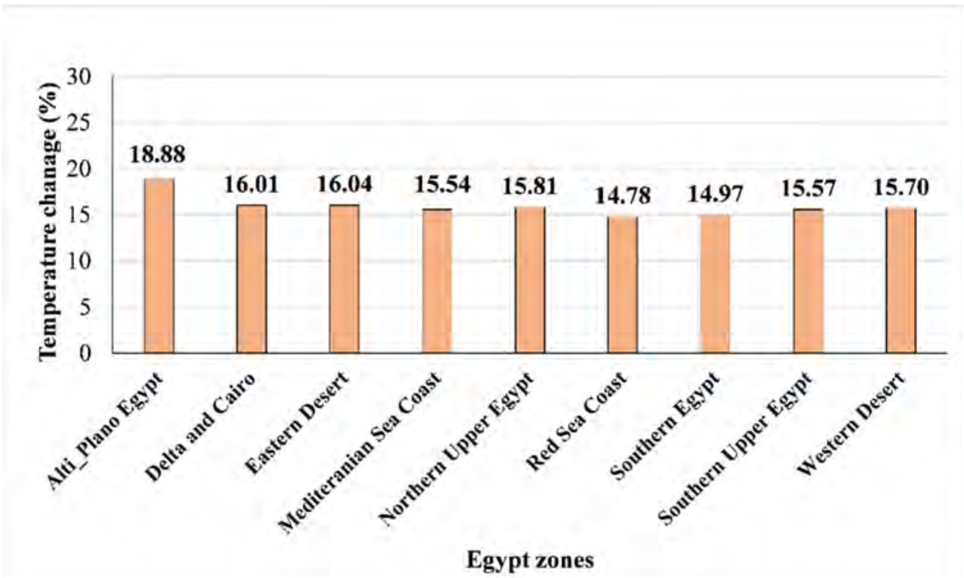

Figure 9. The zonal temperature changes in Egypt between the past period (1950–2014) and the future period (2015–2099), considering only the months from March to May.

Considering only the months from March to May, we should also mention that the recent temperature is severe in some zones, especially in southern Egypt, and affects wheat cultivation in these locations as an increase in temperature increases the degree of stress in these zones.

3.2. Phenotypic Evaluation

The analysis of variance showed significant and highly significant differences amongst cultivars for all agronomic traits evaluated due to water stress (Table 4). Moreover, highly significant differences were detected for the effect of cultivars on all studied traits. In addition, the impact of seasons was not significant for SL, GN, and GY.

Table 4. Analysis of variance and mean square of all studied traits.

Source of Variance	D.F	Mean Square						
		PH	SL	GN	GW	SI	BY	GY
Season (S)	1	139.19 **	0.01NS	226.94NS	3.87 *	716.99 *	2.11 *	0.08NS
Error S	2	0.89	1.3	15.69	0.09	15.94	0.04	0.01
Treatment (T)	1	5331.05 **	154.13 **	7998.45 **	51.33 **	4696.78 **	23.62 **	4.16 **
S*T	1	0.61 *	3.43NS	130.95NS	0.03NS	10.008NS	0.08NS	0.01NS
Error T	2	0.03	0.25	7.13	0.08	7.42	0.02	0.01
Cultivar (C)	22	520.85 **	7.13 **	802.37 **	2.98 **	737.84 **	1.88 **	0.26 **
Y*C	22	2.39NS	0.73NS	35.84 **	0.03 **	36.98 **	0.01NS	0.01NS
Error C	44	1.14	0.5	0.88	0.02	7.42	0.01	0.01
T*C	22	165.77 **	3.09 **	331.02 **	0.52 **	84.80 **	0.89 **	0.13 **
Y*T*C	22	7.64 **	0.55NS	35.09 **	0.07 **	6.08NS	0.01NS	0.01NS
Error	134	139.19	0.48	0.37	0.01	5.11	0.01	0.01

NS = nonsignificant; * and **, significant at 0.05 and 0.01 probability levels, respectively.

3.2.1. Plant Height (PH)

As revealed by ANOVA, drought stress conditions led to a highly significant reduction in plant height (Table 4). Cultivar Sakha 69 recorded the tallest plants under normal conditions (111.50 and 114.00 cm, in the first and second growing seasons, respectively). On the other hand, the shortest plants were recorded by the cultivar Shandaweel1 (70.50 and 75.00 cm, in the first and second growing seasons, respectively) under drought conditions. Cultivar Gemmeza11 gave the lowest reduction in plant height (0.49%) in the first season, and cultivar Sids12 gave the lowest reduction (1.62%) in the second season due to drought treatment as compared with the normal one (Supplementary Table S1).

3.2.2. Spike Length (SL)

Spike length was significantly affected by drought stress as the reduction was of about 11.86% of the overall cultivar's mean compared with normal conditions (Table 4, Supplementary Table S1). Cultivar Shandaweel1 surpassed all other cultivars as the mean of the two seasons and generated the longest spike (13.44 cm). Cultivar Giza164 recorded the lowest reduction (4.17%) in the first season, whereas cultivar Gemmeza10 recorded the lowest reduction (1.26%) in the second season. Under drought conditions, the lowest spike length was recorded by cultivar Gemmeza7 (9.50 and 9.00 cm in the first and second growing seasons, respectively).

3.2.3. Number of Grains per Spike (GN)

Drought stress led to a highly significant effect on the number of grains per spike, which caused a reduction by 20.09% and 16.58% as a general mean of all cultivars in the first and second seasons, respectively (Table 4, and Supplementary Table S1). Moreover, cultivars significantly differ from each other, and cultivar Sakha94 surpassed all other cultivars (65.36) in the first season, whereas cultivar Sids12 recorded the highest mean (70.29) in the second season and overall the two seasons (67.37). Furthermore, the reduction in the number of grains per spike differs from one cultivar to another cultivar, and Shaka93 recorded the minimum reduction (1.49%) in the first season, whereas Sids4 recorded the lowest decrease (1.36%) in the second season. On the other hand, cultivar Sakha92 recorded the highest reduction (52.12% and 52.84% in the first and second growing seasons, respectively).

3.2.4. Weight of Grains per Spike (GW)

In the same trend of the number of grains per spike, drought stress had a highly significant effect on the weight of grains per spike. It caused a reduction calculated by 34.47% and 30.21% as a general mean of all cultivars in the first and second seasons, respectively (Table 4 and Supplementary Table S1). Cultivar Gemmeza11 surpassed all other cultivars (3.14 and 3.48 g in the first and second growing seasons, respectively). Sids12 recorded the minimum reduction in the first season and Gemmeza9 in the second season, whereas Sakha92 recorded the highest reduction in the first season and Shandaweel1 in the second season.

3.2.5. Seed Index (SI)

Drought stress has a severe impact on the seed index. The mean reduction of all cultivars over the two seasons was about 18.70% (Table 4 and Supplementary Table S1). In the first season, the cultivar Gemmeza11 surpassed all other cultivars (56.00 g), while in the second season, the cultivar Sids4 was the superior one (61.18 g) under normal conditions. On the other hand, the cultivar Sakha92 was the lowest one (20.67 and 21.65 g in the first and second growing seasons, respectively). Furthermore, the cultivar Sids14 recorded the lowest reduction in 1000 grain weight (2.36%) than normal in the first season. However, in the second season, the cultivar Gemmeza9 was the superior one (0.50%).

3.2.6. Biological Yield kg/m^2 (BY)

A highly significant impact was found on biological yield due to drought stress. It causes a reduction calculated by 26.49% and 27.02% in the first and second growing seasons, respectively, as the mean overall cultivars (Table 4 and Supplementary Table S1). Cultivars differed significantly, and the cultivar Giza160 surpassed all other cultivars (2.52 and 2.78 kg/m^2 in the first and second growing seasons, respectively). On the other hand, the cultivar Masr03 recorded the lowest biological yield between all cultivars (1.10 and 1.19 kg/m^2 in the first and second growing seasons, respectively). Under normal conditions, the cultivar Giza160 surpassed all other cultivars (2.66 and 2.93 kg/m^2 in the first and second growing seasons, respectively). Under drought stress conditions, the cultivar Shandaweel1 was the most recessive one (0.27 and 0.29 kg/m^2 in the first and second growing seasons, respectively). The highest reduction in biological yield was found in the cultivar Shandaweel1 in both seasons, while the cultivar Sakha94 recorded the lowest decrease in both seasons.

3.2.7. Grain Yield kg/m^2 (GY)

Drought stress has a highly significant effect on grain yield, and the reduction was 34.73% and 35.97% in the first and second growing seasons, respectively (Tables 4 and 5), compared with normal irrigation treatment. The cultivar Giza 160 was superior among other cultivars under normal irrigation (0.83 and 0.90 kg/m^2 in the first and second growing seasons). On the other hand, regarding mean value cultivars, Masr03 and Giza 171 had the lowest grain yield in the first and second growing seasons, respectively. The most reduction due to drought was found in the cultivar Shandaweel 01 (93.97% and 90.17% in the first and second growing seasons, respectively). The lowest reduction was recorded by the cultivar Giza 160 (2.02% and 2.08% in the first and second growing seasons, respectively).

Table 5. Effect of drought stress on grain yield kg/m^2 (means ± SD) of some Egyptian cultivars.

Seasons (S)	Season 2018/2019			Season 2019/2020			Combined		
Treatment (T) / Cultivar (C)	Normal	Drought	Mean	Normal	Drought	Mean	Normal	Drought	Mean
Gemmeza 07	0.59 ± 0.01	0.31 ± 0.01	0.45 ± 0.01	0.63 ± 0.02	0.31 ± 0.02	0.47 ± 0.02	0.61 ± 0.03	0.31 ± 0.02	0.46 ± 0.02
Gemmeza 09	0.61 ± 0.01	0.56 ± 0.01	0.59 ± 0.01	0.65 ± 0.02	0.6 ± 0.02	0.62 ± 0.02	0.63 ± 0.03	0.58 ± 0.02	0.61 ± 0.03
Gemmeza 10	0.61 ± 0.01	0.22 ± 0.01	0.42 ± 0.01	0.65 ± 0.02	0.22 ± 0.03	0.44 ± 0.03	0.63 ± 0.03	0.22 ± 0.02	0.43 ± 0.02
Gemmeza 11	0.82 ± 0.03	0.69 ± 0.02	0.75 ± 0.02	0.88 ± 0.03	0.74 ± 0.03	0.81 ± 0.03	0.85 ± 0.04	0.71 ± 0.03	0.78 ± 0.04
Gemmeza 12	0.72 ± 0.02	0.5 ± 0.01	0.61 ± 0.01	0.77 ± 0.03	0.52 ± 0.02	0.65 ± 0.02	0.74 ± 0.04	0.51 ± 0.02	0.63 ± 0.03
Giza 160	0.84 ± 0.03	0.83 ± 0.03	0.83 ± 0.03	0.91 ± 0.04	0.89 ± 0.03	0.9 ± 0.04	0.88 ± 0.05	0.86 ± 0.04	0.87 ± 0.05
Giza 164	0.52 ± 0.01	0.46 ± 0.01	0.49 ± 0.01	0.55 ± 0.02	0.48 ± 0.02	0.52 ± 0.02	0.54 ± 0.02	0.47 ± 0.02	0.5 ± 0.02
Giza 165	0.58 ± 0.01	0.41 ± 0.01	0.5 ± 0.01	0.62 ± 0.02	0.43 ± 0.02	0.52 ± 0.02	0.6 ± 0.03	0.42 ± 0.02	0.51 ± 0.02
Giza 171	0.28 ± 0.01	0.27 ± 0.01	0.28 ± 0.01	0.29 ± 0.02	0.26 ± 0.01	0.27 ± 0.02	0.29 ± 0.02	0.27 ± 0.01	0.28 ± 0.02
Masr 01	0.85 ± 0.03	0.33 ± 0.01	0.59 ± 0.02	0.91 ± 0.04	0.34 ± 0.02	0.62 ± 0.03	0.88 ± 0.05	0.33 ± 0.02	0.6 ± 0.03
Masr 03	0.41 ± 0	0.14 ± 0.02	0.27 ± 0.01	0.43 ± 0.02	0.13 ± 0.03	0.28 ± 0.03	0.42 ± 0.02	0.13 ± 0.02	0.27 ± 0.02
Sahel 01	0.79 ± 0.02	0.6 ± 0.01	0.69 ± 0.02	0.84 ± 0.03	0.64 ± 0.02	0.74 ± 0.03	0.82 ± 0.04	0.62 ± 0.03	0.72 ± 0.03
Sakha 69	0.68 ± 0.02	0.35 ± 0	0.52 ± 0.01	0.73 ± 0.03	0.36 ± 0.02	0.54 ± 0.02	0.7 ± 0.03	0.36 ± 0.02	0.53 ± 0.02
Sakha 92	0.66 ± 0.02	0.15 ± 0.02	0.41 ± 0.02	0.71 ± 0.03	0.14 ± 0.03	0.42 ± 0.03	0.68 ± 0.03	0.15 ± 0.02	0.42 ± 0.03
Sakha 93	0.75 ± 0.02	0.54 ± 0.01	0.65 ± 0.02	0.8 ± 0.03	0.57 ± 0.02	0.69 ± 0.03	0.78 ± 0.04	0.56 ± 0.02	0.67 ± 0.03
Sakha 94	0.72 ± 0.02	0.68 ± 0.02	0.7 ± 0.02	0.78 ± 0.03	0.73 ± 0.03	0.75 ± 0.03	0.75 ± 0.04	0.7 ± 0.03	0.73 ± 0.03
Sakha 95	0.77 ± 0.02	0.47 ± 0.01	0.62 ± 0.01	0.83 ± 0.03	0.49 ± 0.02	0.66 ± 0.03	0.8 ± 0.04	0.48 ± 0.02	0.64 ± 0.03
Sakha 98	0.73 ± 0.02	0.63 ± 0.01	0.68 ± 0.02	0.78 ± 0.03	0.67 ± 0.02	0.72 ± 0.03	0.75 ± 0.04	0.65 ± 0.03	0.7 ± 0.03
Shandaweel 01	0.94 ± 0.03	0.06 ± 0.01	0.5 ± 0.02	1.02 ± 0.04	0.1 ± 0.01	0.56 ± 0.03	0.98 ± 0.05	0.08 ± 0.03	0.53 ± 0.04
Sids 01	0.53 ± 0.01	0.49 ± 0.01	0.51 ± 0.01	0.56 ± 0.02	0.52 ± 0.02	0.54 ± 0.02	0.55 ± 0.02	0.5 ± 0.02	0.53 ± 0.02
Sids 04	0.63 ± 0.07	0.58 ± 0.01	0.6 ± 0.04	0.71 ± 0.09	0.56 ± 0.19	0.64 ± 0.14	0.67 ± 0.09	0.57 ± 0.12	0.62 ± 0.1
Sids 12	0.73 ± 0.02	0.58 ± 0.01	0.65 ± 0.02	0.79 ± 0.03	0.61 ± 0.02	0.7 ± 0.03	0.76 ± 0.04	0.59 ± 0.03	0.68 ± 0.03
Sids 14	0.65 ± 0.02	0.28 ± 0.01	0.47 ± 0.01	0.69 ± 0.03	0.28 ± 0.02	0.49 ± 0.02	0.67 ± 0.03	0.28 ± 0.02	0.48 ± 0.02
Mean	0.67 ± 0.02	0.44 ± 0.01	0.55 ± 0.02	0.72 ± 0.03	0.46 ± 0.04	0.59 ± 0.02	0.69 ± 0.01	0.45 ± 0.02	0.57 ± 0.01
F Test (S)					**LSD′ (T × C)**		0.03		
F Test (T)					**LSD′ (S × C)**		0.05		
LSD′ (C)					**LSD′ (S × C × T)**		NS		
LSD′ (S × T)									

3.2.8. Tolerance and Susceptibility Indices

Ten tolerance and susceptibility indices were estimated for the overall mean of the two growing seasons for grain yield and the data shown in Table 6. From the obtained results, some cultivars showed high tolerance to drought stress in this study. Depending on the estimated indices, the cultivars Giza 160 and Sakha 94, were superior. They marked a high record in all evaluated indices and were to be found among the highest 20% cultivars of each parameter. In the second grade, the cultivars Gemmeza 09, Giza 164, and Sids 01 were among the highest 20% cultivars regarding five of the ten tested parameters. The cultivars Shandaweel 01, Masr 03, and Sakha92 were among the lowest 20% cultivars regarding nine of the ten tested parameters.

3.2.9. Cluster Analysis

The cluster analysis of the genotypes based on investigated combined grain yield under normal, drought, and stress susceptibility index (SSI) is presented in Figures 10–12, respectively. All cultivars were classified due to their performance under normal and drought conditions in four distinguished groups as follows:

1. Super cultivars, which had an average yield more than 25% higher than the mean of all cultivars;
2. High-yielding cultivars have yields equal to or not higher than 25% of the mean of all cultivars;
3. Low yielding cultivars, whose yield is not lower than 25% of the mean of all cultivars;

4. Weak cultivars, which had an average yield lower than 25% of the mean of all cultivars.

Table 6. Tolerance and susceptibility indices calculated based on a combined average of grain yield.

Cultivar	SSI	RSI	TI	MP	YSI	HM	YRR	GMP	STI	YI
Gemmeza 07	1.39	0.79	0.30	0.46	0.51	0.41	0.49	0.43	0.39	0.69
Gemmeza 09	0.22	1.42	0.05	0.61	0.92	0.61	0.08	0.61	0.76	1.29
Gemmeza 10	1.83	0.54	0.41	0.43	0.35	0.33	0.65	0.38	0.29	0.50
Gemmeza 11	0.46	1.30	0.14	0.78	0.84	0.77	0.16	0.78	1.25	1.59
Gemmeza 12	0.89	1.06	0.23	0.63	0.69	0.60	0.31	0.62	0.78	1.13
Giza 160	0.06	1.52	0.02	0.87	0.98	0.87	0.02	0.87	1.56	1.91
Giza 164	0.36	1.35	0.07	0.50	0.87	0.50	0.13	0.50	0.52	1.04
Giza 165	0.84	1.09	0.18	0.51	0.70	0.49	0.30	0.50	0.52	0.94
Giza 171	0.19	1.44	0.02	0.28	0.93	0.28	0.07	0.28	0.16	0.59
Masr 01	1.76	0.58	0.55	0.60	0.38	0.48	0.62	0.54	0.60	0.74
Masr 03	1.94	0.49	0.29	0.27	0.32	0.20	0.68	0.23	0.11	0.29
Sahel 01	0.69	1.17	0.20	0.72	0.76	0.70	0.24	0.71	1.04	1.38
Sakha 69	1.39	0.78	0.35	0.53	0.51	0.47	0.49	0.50	0.52	0.79
Sakha 92	2.22	0.33	0.54	0.42	0.22	0.24	0.78	0.32	0.21	0.33
Sakha 93	0.79	1.11	0.22	0.67	0.72	0.65	0.28	0.66	0.90	1.25
Sakha 94	0.18	1.45	0.05	0.73	0.94	0.73	0.06	0.73	1.09	1.57
Sakha 95	1.14	0.92	0.32	0.64	0.60	0.60	0.40	0.62	0.79	1.06
Sakha 98	0.39	1.33	0.10	0.70	0.86	0.70	0.14	0.70	1.01	1.44
Shandaweel 01	2.60	0.12	0.90	0.53	0.08	0.15	0.92	0.28	0.16	0.17
Sids 01	0.24	1.41	0.05	0.53	0.91	0.52	0.09	0.53	0.57	1.12
Sids 04	0.52	1.26	0.12	0.61	0.82	0.60	0.18	0.61	0.76	1.22
Sids 12	0.61	1.21	0.16	0.68	0.78	0.67	0.22	0.67	0.93	1.32
Sids 14	1.64	0.65	0.39	0.48	0.42	0.40	0.58	0.44	0.39	0.63
Selection pattern	Min	Max	Min	Max	Max	Max	Min	Max	Max	Max

Max = Maximum; Min = Minimum.

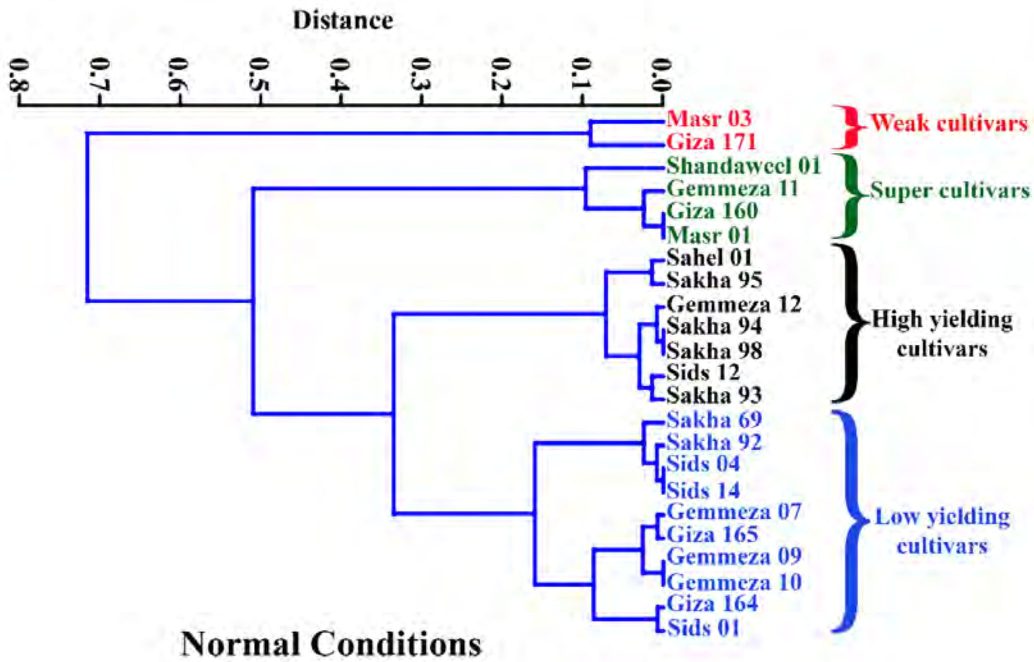

Figure 10. Dendrogram using Ward's method among groups showing the classification of genotypes based on the combined grain yield per m^2 under normal conditions.

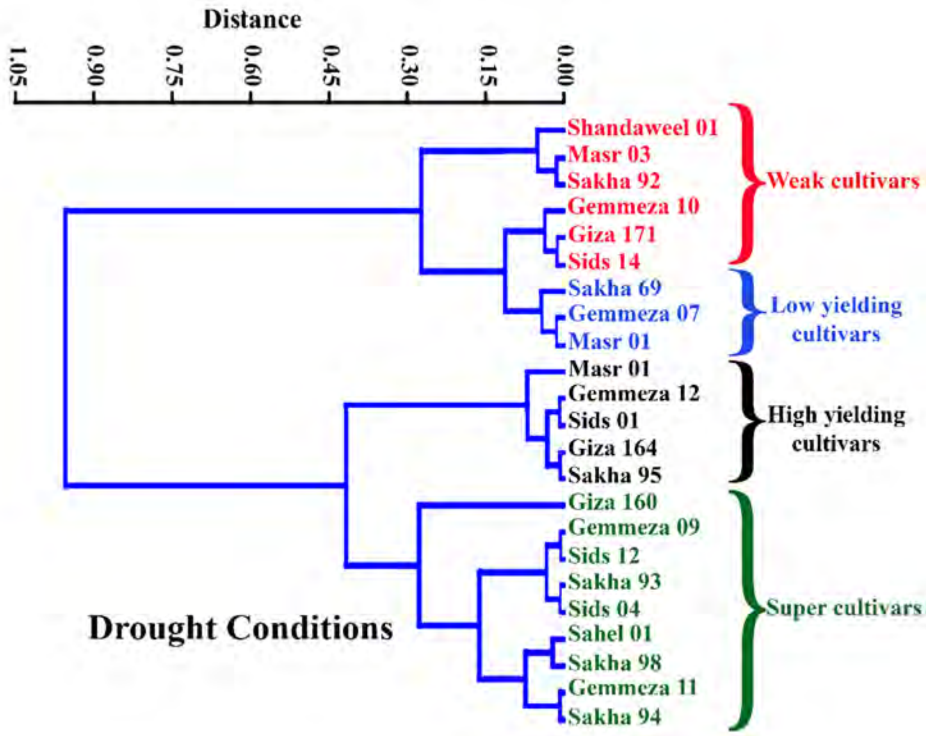

Figure 11. Dendrogram using Ward's method among groups showing the classification of genotypes based on the combined grain yield per m^2 under stress conditions.

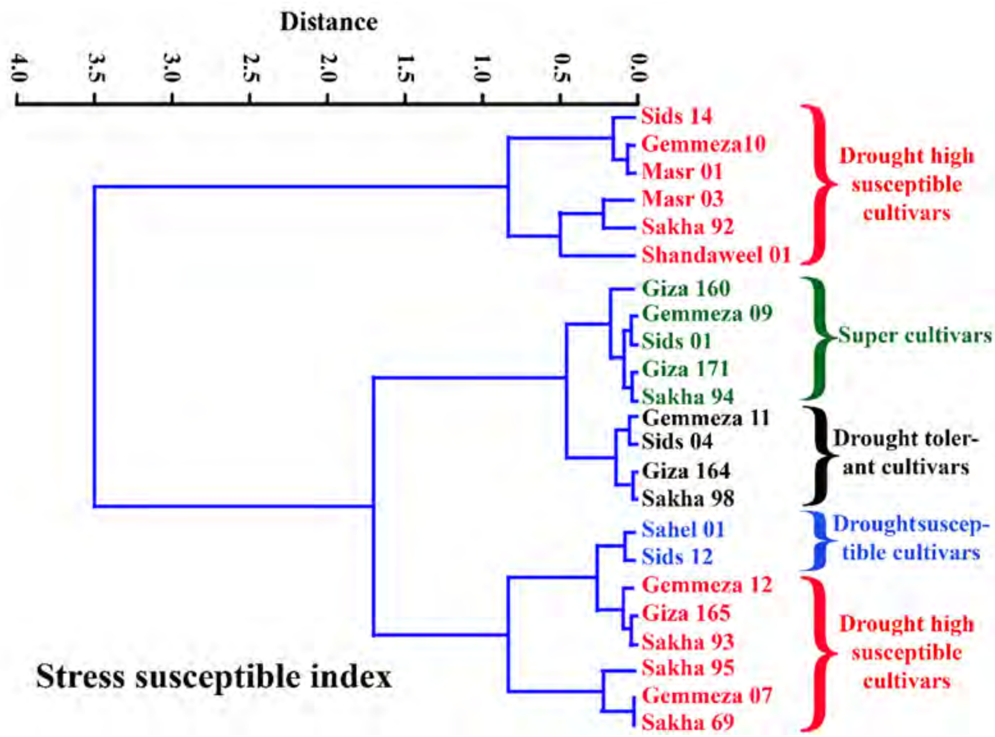

Figure 12. Dendrogram using Ward's method among groups showing the classification of genotypes based on the stress susceptibility index.

Under normal conditions, 4 major groups of genotypes were obtained by cluster analysis containing 2, 4, 7, and 10 genotypes, respectively. Each cluster contained genotypes that were highly similar (Figure 10). In the same way, under stress conditions, 4 major groups of genotypes were obtained by cluster analysis containing 6, 3, 5, and 9 genotypes, respectively. Each cluster contained genotypes that were highly similar (Figure 11). According to Figure 12, they were also classified according to their record in stress susceptibility index into four different groups as follows:

1. Super cultivars (with SSI lower than 0.25) in a group of 9 genotypes;
2. Drought tolerant cultivars (0.25 ≥ SSI ≤ 0.50) in a group of 4 genotypes;
3. Drought susceptible cultivars (0. 50 ≥ SSI ≤ 0.75);
4. Drought high susceptible cultivars (SSI ≥ 0.75).

As genotypes had low SSI values, thus they can be characterized as the most desirable genotypes.

4. Discussion

Globally, climate change affects the spatial and temporal distribution of crop yields, which can critically impair food security [29]. However, the identification of high-yielding drought-tolerant genotypes remains a proficient approach to cope with climate challenges [30]. In the current study, we aimed at redistributing the most common local bread wheat cultivars according to their drought tolerance to zones that were classified based on climate analysis. The climate analysis revealed that there is an increase in rainfall and temperature in the future in the 21st century with an average of 16.83% and 12.7%, respectively. However, rainfall and temperature will vary from region to region in Egypt. According to this, some regions will have both increases in rainfall and temperature, which is important to grow drought and high-temperature tolerant varieties. Liu et al. [29] indicated that over 60% of harvested areas could experience significant changes in interannual yield variability under a high-emission scenario by the end of the 21st century (2066–2095). The results from several studies, such as [29,31,32], have indicated substantial changes in interannual yield variability as a result of climate change, and that the sign and magnitude of change varied by production region. Zhu et al. [33] analyzed subnational wheat yield shocks across Europe during the last four decades and found that the attribution analysis revealed that 32% of the wheat yield shocks were mainly driven by water limitation, making it the leading climate driver. Our results are partially in accordance with those obtained by Bento et al. [34], who pointed to different regional responses of wheat and barley to the climate changes expected in the future in Spain, and stated that, in the southernmost regions, the results indicated that the main yield driver is the spring maximum temperature, while in the north area, there is a larger dependence on the spring precipitation and early winter maximum temperature.

We screened fourteen bread wheat cultivars under normal and drought stress conditions in the Assiut region as a central region in Egypt to offer a methodology for the evaluation of the drought-tolerant wheat cultivars based on the morphological traits. The results revealed that drought stress drastically reduced all studied traits.

At the time of maturity, stress conditions and genotypes significantly affect all studied traits. Moreover, the interaction between genotypes and the irrigation treatment was a highly significant source of variation [35]. On the other hand, the performance of the genotypes was almost the same within the two seasons, except for GW and SI, which means that these traits may be affected by environmental factors more than the other studied traits [36].

Plant height is an indicator for wheat growth [37], and drought conditions reduce plant height in this study, especially with long cultivars. Nine of the tested cultivars show high performance under drought conditions compared with regular irrigation (Sids 12, Gemmeza 11, Gemmeza 09, Sids 01, Sakha 95, Sakha 94, Giza 164, Masr 03, and Sahel 01) with a reduction of less than 5% as a mean reduction of the two growing seasons. On the other hand, two cultivars show a reduction exceeding 20% as a mean reduction of the two growing seasons (Sakha 93 and Shandaweel 01). The drop in plant height may be due to the effect of water deficit on coleoptile elongation, which led to a reduction in plant growth [38].

Spikes are the part that carries the spikelets and flowers, which contain embryos that will be seed and grains. So perhaps the spike shape and length play an essential role in grain yield [39]. The reduction effect of drought stress on spike length was higher than what appears in plant height. Only three cultivars recorded a decrease in spike length of less than 5% (Giza164, Sakha 94, and Gemmeza 11) as a mean reduction of the two growing seasons compared with normal irrigation. On the other hand, three cultivars recorded more than a 20% reduction due to a water deficit treatment (Masr 03, Shandaweel 01, and Gemmeza 07).

Drought stress also affected the number of grains per spike as the reduction ranged from 1.50% to 52.48% as the mean reduction of the two seasons. This reduction may be due to the effect of water stress on the fertility of the florets [40]. Moreover, water stress affected grain weight per spike and caused a loss ranging from 9.58 to 63.42% as a mean reduction of the two growing seasons compared to regular irrigation. We noticed that cultivars with the minimum decrease in the number of grains per spike are not necessary the same with a minimum reduction in grain weight per spike, which means that drought stress did not affect the two traits in the same way [41].

Seed index is an indicator for the grain filling period, and the most sensitive stage in wheat growth and environmental conditions have a significant impact during this stage [42]. Moreover, the seed index plays a crucial role in the final quantitative and qualitative yield. Drought stress adversely affected the seed index and caused a reduction of up to 38.48% as a mean reduction of the two growing seasons compared to regular irrigation. During the grain filling stage, water deficit usually leads to abnormal grain maturity, and grains did not have enough time for optimum ripening, reducing seed weight and producing an irregular shape [43].

Biological yield is the total dry matter of the plant, and it reflects the performance of the genotype during its life cycle. The genotype that can withstand severe conditions and does not lose a remarkable biological yield could be tolerant, and this depends on its adaptive mechanisms [35]. Drought stress affected biological yield and caused a reduction varied between cultivars. Seven cultivars recorded a decrease of less than 10% in biological yield (Sakha 94, Sahel 01, Gemmeza 11, Gemmeza 09 Sids 04, Giza 165 and Sids 12) as a mean reduction of the two growing seasons compared to regular irrigation, which means that they can withstand stress conditions. Furthermore, five cultivars lost more than 50% of their biological yield due to water stress (Sids 14, Giza 171, Masr 01, Sakha 95, and Shandaweel 01) as a mean reduction of the two growing seasons compared to regular irrigation.

Grain yield is the most economical product in wheat plants, and as a complex trait, many factors affect it. Drought stress has a high impact on grain yield in this study, and the reduction rate exceeded 90% as a mean reduction of the two growing seasons compared to regular irrigation. Among the tested cultivars, the cultivar Giza 160 was the strongest one as it appeared on the superior group in both normal and drought conditions in addition to stress susceptibility index as confirmed by cluster analysis. Moreover, it was between the superior genotypes in biological yield, which means there is a correlation between the two traits [44]. Cultivars Sakha 94, Gemmeza 11, and Sakha 98 were promising genotypes as they appeared on the high yielding groups in addition to low records of SSI as confirmed by cluster analysis. On the contrary, cultivar Masr 03 was the weakest one as it was between the lowest yield cultivars in both normal and drought conditions in addition to the stress susceptibility index as confirmed by cluster analysis. This may be due to its reduction in seed index and weight of grains per spike [45]. Sayed et al. [46] evaluated fourteen wheat cultivars at six sowing dates under Assiut conditions and found that Gemiza 11, Gemiza 9, and Sakha 94 ranked in the first order as high-yielding cultivars and had greater stability level over all sowing dates. Recently, Sayed et al. [47] evaluated CIMMYT wheat lines across multiple environments in Egypt, and detected several genotypes adapted to the north (as moderate weather) and southern area (as hot weather).

Susceptibility indices are a good tool for discovering the superior genotypes under unfavorable conditions with various calculation methods [48]. In this study, ten different susceptibility indices were estimated for the mean of the two growing seasons for grain yield. Some cultivars showed high performance in many indices from the obtained results, whereas some other cultivars were not. Interestingly, some cultivars with high performance were among the superior cultivars on more than one of the tested traits in this study. For example, if we consider a 10% reduction, our limit for each studied trait, cultivars Giza 160 and Sakha 94 were superior in all tested traits except the number of grains per spike and weight of grains per.

From the previous discussion, we can notice that the tested cultivars could be classified into three groups depending on their performance on the SSI scale. The first group contains the superior genotypes in yield and susceptibility indices (Giza 160 and Sakha 94), which could be grown under severe conditions without a noticeable reduction in their yield. The second group contains superior genotypes in grain yield without precise performance undesired conditions (Gemmeza 11, Sahel 01, Sakha 98, Sids 12, and Sakha 93) as there were among the heist 20% of high yielding cultivars as the average of the two seasons. Still, they did not have a good record in half of the calculated susceptibility indices. The second group is suitable for growing in locations with favorable growth conditions. The last group contains the rest of the cultivars that did not have a noticeable trend even in grain yield or tolerance indices.

From the previous findings, we can appoint some cultivars for each zone as a pre-selection step (Table 7).

Table 7. Average rainfall and high temperature from March to May 2021 and the most appropriate cultivar(s) to each zone.

Zone Name	Average Rainfall (mm)	Average High-Temperature °C	Overall Conditions	Appropriate Cultivar
Alti Plano Egypt	12.00	24.77	Good	Gemmeza 11, Gemmeza 12, Giza 160 Masr 01, Sahel 01, Sakha 93 Sakha 94, Sakha 95, Sakha 98 Shandaweel 01, Sids 12
Delta and Cairo	3.80	21.00	Good	
Mediterranean Sea Coast	11.00	22.60	Good	
Red Sea Coast	0.30	23.00	Good	
Eastern Desert	5.60	28.63	Moderate	Gemmeza 09, Gemmeza 11 Giza 160, Giza 164, Sahel 01, Sakha 94 Sakha 98, Sids 01, Sids 04, Sids 12
Northern Upper Egypt	2.00	29.83	Moderate	
Southern Egypt	0.10	33.87	Severe	Gemmeza 09, Gemmeza 11 Giza 160, Giza 164, Giza 171 Sakha 94, Sakha 98, Sids 01, Sids 04
Southern Upper Egypt	0.20	30.57	Severe	
Western Desert	0.00	33.83	Severe	

The average rainfall and temperature data were obtained from https://www.weather-atlas.com (accessed on 24 December 2021) [49].

Finally, if we want to make a combination between the climatic data and the experimental data, we can say that group one (Giza 160 and Sakha 94) remained more prone to adverse effects of harsh environments, such as eastern desert and southern Egypt. In such areas, climate changes seem to increase spring maximum temperature from March to May, while group two (Gemmeza 11, Sahel 01, Sakha 98, Sids 12, and Sakha 93) is suitable to be grown in zones with good growing environments, such as Delta and northern Egypt. The results offer a warning regarding the need to implement sustainable agriculture policies, and on the necessity of regional adaptation strategies. Chowdhury et al. [30] recommended the genotype BAW 1169 for general adoption and utilization in future wheat breeding programs aimed at developing potent drought-tolerant wheat genotypes to ensure food security on a sustainable basis.

5. Conclusions

There is no doubt that the world faces global warming and climate changes, and that we should modify our agricultural system to meet these challenges. Breeding programs for heat stress tolerance in wheat are strongly needed under Egyptian conditions as the predicted data highlighted that there is an increase in temperature over all locations.

Furthermore, the redistribution of cultivars is one of the modifications that could prevent yield reduction. Cultivars differ from each other in their ability to tolerate severe conditions. Thus, we should cultivate the appropriate genotype in its best conditions to maximize its yield or have the lower reduction due to continuous climate change. In the future, more experiments in each zone are required to have a clearer image of the performance of the selected genotypes to put our hand on the best one or two genotypes for each zone.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12010113/s1, Supplementary Table S1: Means and standard deviations for all studied traits under normal and drought conditions for the two growing seasons.

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