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Determination of Drought Tolerance Indices as Selection Criteria of Rice Genotypes under Water Deficit Conditions in Egypt

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The development of rice genotypes with impressive tolerance to abiotic stress is one of the primary objectives of rice breeding programs. The current study was carried out to assess the capability of different indices to identify rice genotypes that are drought-tolerant under Egyptian conditions during the two growing seasons 2018 and 2019. Thirteen drought tolerance indices were calculated using the grain yield of twenty rice genotypes. According to the combined analysis of variance for grain yield, there were highly significant differences between genotypes (G), irrigation regimes (I), and their interactions. All drought tolerance indices, as well as grain yields under non-stress and stress conditions (Yp and Ys), exhibited significant variations among genotypes. For Yp, Ys, and all indices assessed, estimates of broad sense heritability (h^2) and genetic advance as a percentage of mean (GAM%) were high. Using mean performances, drought tolerance indices, and multivariate

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analysis, the genotypes Giza 179, Sakha 104, IET 1444, and GZ 6296-12-1-2-1 were superior genotypes under both stress and non-stress conditions, as were the genotypes Sakha 107, IRAT 170, IR 68552-55-3-2, WAB 56-104, IRGA 318-11-6-2-6, and NERICA -4 under stress conditions. Hence, it was suggested that they can be utilized as parents in hybridization programs that aim to improve the drought tolerance of other rice genotypes in Egypt. Furthermore, mean productivity index (MP), geometric mean productivity (GMP), stress tolerance index (STI), harmonic mean (HM), and yield index (YI) were the tolerance indices that can be classified as better predictors of drought tolerance considering the yield potentials of the genotypes.

Keywords: Genetic parameters; multivariate analysis; drought selection criteria indices; rice.

1. INTRODUCTION

Rice is one of the world's most important stable cereal crops, feeding more than 3.5 billion people [1]. It occupies over one-fifth of the whole land area used to cultivate cereals, according to Chakravarthi and Naravaneni [2].

Drought is one of the most severe abiotic stresses endangering the global food supply. Furthermore, because freshwater supplies are limited worldwide, population expansion is predicted to raise global food consumption, potentially increasing the water required to farm crops [3]. “Rice, as the most diverse monocot, is grown in a broad range of eco-geographical conditions and is subjected to a diverse range of abiotic stresses, such as drought, salinity, cold, and heavy metals, with drought being one of the most destructive stresses at any stage of rice crop production. It is disturbing in many regions around the world, and researchers, farmers, and governmental organizations must pay attention” [4].

Developing rice cultivars with acceptable yields, drought tolerance, and water efficiency has become extremely important for Egypt's food security and water scarcity reduction. Water shortage is a significant obstacle to the widespread use of high-yielding rice varieties in drought-prone rice areas, because farmers cannot afford to be exposed to even short periods of water scarcity [5]. “The relative yield of a genotype in comparison to other genotypes under the same water shortage stress is known as water deficit tolerance” [6]. “Water deficit tolerance is a complex phenomenon that reflects drought tolerance (tissue tolerance, photosystem maintenance, etc.) and drought avoidance (deep root, leaf rolling) characteristics that are controlled by different genes” [1]. “Drought tolerance selection is difficult because of the many interactions between genotypes and the environment, as well as a lack of knowledge about the function and role of tolerance mechanisms” [7]. “Breeding for drought tolerance is therefore often performed by selecting genotypes with high yield under water deficit conditions” [8].

“Drought stress tolerance is a complex characteristic limited by low heritability and the absence of effective selection strategies” [9]. “Recombination breeding can contribute significantly to the accumulation of minor genes for grain yield and other drought-related traits, keeping this in mind. Understanding the genetic diversity of germplasm is crucial before starting a breeding program” [10].

“The amount of genetic variability in germplasm can be determined using genetic parameters such as genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV). In addition, knowledge of heritability is essential for selection since it exposes the degree of a trait's transmission to future generations and the quality of phenotype data in multi-location trials” [11]. “Heritability associated with high genetic advance might be more successful at predicting the significant impact in the selection of the best genotypes for yield and its attributing traits. This helps in assessing how the environment affects the manifestation and reliability of traits” [12]. “Another key selection criterion that breeders use in their breeding programs is genetic advance” [13].

“Several drought indices have been proposed to identify drought-tolerant genotypes; these indices are determined by the mathematical relationship between yield under water deficit and non-stressed conditions. These indices are determined using the drought tolerance or susceptibility of the genotypes reported by Huang” [14]. Fischer and Maurer [15] proposed “the stress susceptibility index (SSI), which detected changes in both prospective and actual yields in variable conditions, as a method of determining yield stability". "A tolerance index (TOL) based on yield differences measured under non-stress (Yp) and stress (Ys) conditions was presented" by Rosielle and Hamblin [16]. "The average of Yp and Ys was used to define the mean productivity index (MP). When the difference between Yp and Ys is large, MP has an upward bias. In both stress and non-stress conditions, the geometric mean productivity (GMP), which is less sensitive to high values, is a better indicator than MP for identifying superior genotypes" [16]. "A stress tolerance index (STI) was presented by Fernandez [17] which can be utilized to select genotypes that produce good yields at both under stress and non-stress conditions". Gavuzzi et al. [18] proposed the yield index (YI), Bouslama and Schapaugh [19] proposed the yield stability index (YSI), Lan [20] proposed the drought tolerance index (DI), Golestani Araghi and Assad [21] presented the yield reduction ratio (YR), Hossain et al. [22] proposed the harmonic mean (HM), and Moradi et al. [23] presented the golden mean (GOL) to determine whether the genotypes are stable under stress and non-stress conditions. Moosavi et al. [24] introduced "abiotic tolerance index (ATI) and stress susceptibility percentage index (SSPI) for screening drought tolerant genotypes in stress and non-stress conditions".

According to Fernandez [17] and Mitra [25], "the best indices are those that have a high correlation with grain yield in both conditions and the capacity to identify potential high-yielding and drought-tolerant genotypes". Plant breeders have used a number of statistical methods, including correlation coefficient, Biplot, and principal component analysis (PCA), to evaluate the efficacy of several drought tolerance indices for genotype screening and identification. Since freshwater supplies are limited in Egypt and the population is increasing rapidly, developing rice cultivars with acceptable yields and drought tolerance has become extremely important for food security and water scarcity reduction. This research, therefore, defined drought tolerance indices that can be used for screening drought-tolerant genotypes. In the meantime, screened for rice genotypes that are characterized by the highest tolerance to drought, recommending some genotypes to be used in future rice hybridization programs in Egypt. Therefore, the present study was conducted to 1) estimate the genetic parameters, 2) evaluate the efficiency of several drought tolerance indices, as well as 3) identify drought-tolerant rice genotypes under Egyptian conditions.

2. MATERIALS AND METHODS

2.1 Genetic Materials and Field Procedures

The experiments were conducted in the Rice Research Department's experimental farm at the Sakha Agriculture Research Station, Kafer El-Sheikh governorate, Egypt, during the two growing seasons of 2018 and 2019. Twenty rice genotypes were used in this investigation; Table 1 presents the names, places of origin, and types of these parental genotypes. The experimental field was located at 30° 57′ 12″ north latitude and 31° 07′ 19″ east longitude. The soil had a pH range of 7.6 to 8.6, and its mechanical components were silt (27.1%), clay (65.2%), and sand (7.4%). Throughout the growing seasons, mean maximum and minimum temperatures of 33.54 °C and 24.65 °C were observed, with a relative humidity of 63.45 %.

The genotypes were planted in two adjacent experiments during the 2018 and 2019 growing seasons. The first experiment was irrigated normally (4-day irrigation intervals), and the second experiment was irrigated under drought stress (10-day irrigation intervals) without any water standing and only when needed based on the permanent wilting point (Table 2). The stress condition became noticeable two weeks after the transplant until it reached maturity.

Moisture content was measured for soil samples collected at intervals of 15 cm to 45 cm in gravity depth. Soil samples were collected, before each irrigation, and 48 hours later. The field capacity was measured in the field. The permanent wilting point and bulk density were measured to a depth of 45 cm using method of Klute [26].

To monitor the soil moisture level during the reproductive stage, periodic soil sample at 15 and 30 cm soil depth after suspension water was used (stress period). The water table was also measured throughout the stress period. In the two experiments, the date of sowing was May 1st, and transplanted one seedling/hill at June 1st. A randomized complete block design (RCBD) with three replicates was used to design each experiment. Each replicate comprised three rows, and each row was five meters long, with a 20 cm x 20 cm space between rows and hills. As usual, all of the recommended cultural practices for growing rice in the area were followed. At the harvesting stage, grain yield data were obtained from 10 plants grown from every genotype in each replication, according to Standard Evaluation System (SES) for Rice published by International Rice Research Institute (IRRI) [27].

2.2 Estimation of Drought Tolerance Indices

Each plot's panicles were all harvested when they reached physiological maturity, dried to a moisture content of approximately 14%, and used to measure drought tolerance indices based on grain yield /plant (g) for non-stress (Yp) and water stress (Ys) conditions for each genotype using the formulas listed in Table 3. To differentiate genotypes based on drought response in terms of grain yield /plant (g). The grain yield per plant (g) was then estimated using 10 weighted individual plant yields from each replication.

2.3 Statistical Analysis

For grain yield, the combined three-way ANOVA was performed considering the effect of years, irrigations regimes and genotypes, and using the PBSTAT-PPB SOFTWARE. For grain yield (Yp and Ys) and drought tolerance indices, the combined two-way ANOVA was performed considering the effects of years and genotypes, and computed according to the method of Gomez and Gomez [28]. “Heritability in broad sense (BSH) was estimated from method” given by Fehr [29]. “The extent of genetic advance to be expected by selecting ten percent of the superior progeny was calculated” according to Robinson et al. [30].

Table 1. List of name, origin and types of the twenty rice genotypes used for assessment of drought tolerance in the current study

No.	Name	Origin	Type
1	Giza 177	Egypt	Japonica
2	Giza 178	Egypt	Indica /Japonica
3	Giza 179	Egypt	Indica /Japonica
4	Sakha 101	Egypt	Japonica
5	Sakha 102	Egypt	Japonica
6	Sakha 104	Egypt	Japonica
7	Sakha 107	Egypt	Japonica
8	Sakha 108	Egypt	Japonica
9	GZ 9730-1-1-1-1	Egypt	Japonica
10	GZ 6296-12-1-2-1	Egypt	Indica /Japonica
11	GZ1368-S-5-4	Egypt	Indica
12	IR 11 L 465	IRRI	Indica
13	WAB 56-104	Africa Rice Center	Indica
14	IRAT170	Côte d'Ivoire	Japonica
15	NERICA -4	Africa Rice Center	*O. Sativa*/*O. Galliberema*
16	IR 65600-127-6-2	IRRI	Tropical-japonica
17	IR 68011-15-1-1	IRRI	Tropical-japonica
18	IR 68552-55-3-2	IRRI	Tropical-japonica
19	IRGA 318-11-6-2-6	Brazil	Indica
20	IET1444	India	Indica

Table 2. Measured soil parameters for each irrigation

Soil depth(cm)	F.C.%	W.P.%	Bulk density g/cm3
0-15 cm	46.25	24.00	1.15
15-30 cm	42.00	22.25	1.20
30-45 cm	38.50	20.50	1.25
Mean	42.25	22.25	1.20

F.C.% = field capacity and W.P.% = permanent wilting

Table 3. Drought tolerance indices used for the evaluation of rice genotypes to water deficit conditions

No.	Drought tolerance indices	Equation	Reference
1	Stress Susceptibility Index (SSI)	[1-(Ys / Yp)]/[1-(Ys¯/ Yp¯)]	Fischer and Maurer [15]
2	Stress tolerance index (TOL)	Yp -Ys	Rosielle and Hamblin [16]
3	Mean Productivity index (MP)	(Yp + Ys)/2	Rosielle and Hamblin [16]
4	Geometric Mean Productivity (GMP)	$(Yp \times Ys)^{1/2}$	Fernandez [17]
5	Stress Tolerance Index (STI)	(Yp X Ys)/(Yp¯)2	Fernandez [17]
6	Yield Index (YI)	Ys / Ys¯	Gavuzzi et al. [18]
7	Yield Stability index (YSI)	Ys / Yp	Bouslama and Schapaugh [19]
8	Drought resistance Index (DI)	[Ys X (Ys / Yp)]/Ys¯	Lan [20]
9	Yield Reduction ratio (YR)	1-(Ys / Yp)	Golestani–Araghi and Assad [21]
10	Abiotic Tolerance Index (ATI)	[(Yp - Ys)/(Yp¯ - Ys¯)]X[√YpXYs]	Moosavi et al. [24]
11	Stress Susceptibility Percentage Index (SSPI)	[(Yp -Ys)/2(Yp¯)] X100	Moosavi et al. [24]
12	Harmonic Mean (HM)	[2(Yp X Ys)] / (Yp + Ys)	Hossain et al. [22]
13	Golden mean (GOL)	(Yp + Ys) / (Yp -Ys)	Moradi et al. [23]

Genotypic (GCV%), phenotypic (PCV%) and error (ECV%) coefficients of variation were calculated according to Burton [31]. Standard error (SE) of BSH was calculated according to Lothrop et al. [32]. Rank sum (RS) = Rank mean ($\bar{R}$) + Standard deviation of rank (SDR) and SDR = $(Si^2)^{0.5}$ [33]. Correlation coefficient, principal component analysis and cluster analysis were performed for better understanding of the relationships among all possible pair-wise comparisons of Yp, Ys and different drought tolerance indices. Correlation coefficient, principal component analysis and cluster analysis were done using a computer software program PAST version 2.17c according to Hammer et al. [34].

3. RESULTS AND DISCUSSION

3.1 Analysis of Variance

Table 4 displays the findings of the combined analysis of variance for grain yield/plant (g). For grain yield, the mean square resulting from genotypes and irrigation regimes were highly significant, as well their interaction (G x I) were significant. The other sources of variance, however, were not significant. Sums of squares (TSS) were largely influenced by irrigation regimes (57.64%), genotypes (37.89%), and G x I interaction (2.67%), in that order. These findings allowed us to screen for drought tolerant genotypes by showing that there were significant variations in genotype responses to non-stress and water stress conditions across seasons for grain yield in rice. Also, highly significant difference between grain yield under non-stress and water deficit conditions indicates existence of genetic variation and possibility of selection for favorable genotypes in both conditions to improve drought tolerance of rice under Egyptian conditions. The result indicates the existence of sufficient variations among the assessed genotypes under consideration that can help breeders in selection of ideal genotypes. This signifies the need for multi-environmental trials of rice at various locations or environments in order to see how the genotypes react in different environments due to the presence of G×E interaction. Such variations in relation to the environment that influenced rice growth performance evaluation studies have extensively been reported previously [35] and [36].

According to combined ANOVA analysis of non-stress (Yp) and stress (Ys) conditions as well as drought tolerance indices (Table 5), grain yield (Yp and Ys) and all drought tolerance indices exhibited highly significant between genotypes (G). El-Hashash and EL-Agoury [37] had previously found similar findings. The findings demonstrated that almost all indices showed a significant genetic variation and could distinguish between genotypes under stress and non-stress conditions. Also, these findings showed that genotypes varied for the genes influencing yield and drought tolerance indices [37]. However, the efficient indices should also be able to select genotypes that combine high yield with drought tolerance [38].

The highest values of genotype variance were recorded for HM index followed by GMP, MP and SSPI indices. There were no significant differences between the years and G x Y interaction for grain yield (Yp and Ys) and tolerance indices except for G x Y interaction for STI. Therefore, those drought tolerance indices were not influenced mainly by year effect. El-Hashash and EL-Agoury [37] reported that a highly significant variation was observed in grain yield and tolerance indices among the studied rice genotypes, while, there were no significant differences between the two study years in terms of grain yield and tolerance indices. Saad et al. [39] mentioned that significant differences were observed between years and genotypes for most studied drought indices. They added that the interaction genotype x year was significant only for SSI and ATI. Thus, those indices ranked differently the genotypes depending on the variation of stress intensity between years.

As presented in Table 5, the values of the CVs varied between 2.12% (STI) and 10.63% (ATI). Based on maximum and minimum values, it was possible to observe the great magnitude between and within the grain yield at non-stresses and stress conditions (Yp and Ys) and drought tolerance indices, which indicates influence of different factors in its measurements [40]. These findings revealed that the environment had a minor influence on all indices, with the exception of the index ATI, which was moderately influenced. The magnitude of CV% indicated that the genotypes had exploitable genetic variability for the studied drought tolerance indices. The other studies showed higher CV% for grain yield in rice by Sangaré et al. [41].

3.2 Genetic Parameters

Table 6 displays the values of genetic parameters and drought tolerance indices for grain yield under non-stressed and stressed conditions (Yp and Ys). The grain yield under non-stress and stress conditions (Yp and Ys) and drought tolerance indices, high values of h^2 ($\geq$ 0.99) were observed, along with high genetic advance as a percent of the mean (GAM%). The highest h^2 values suggested that a greater proportion of the total variance was due to a greater genotypic variance that was influenced less by environmental factors and a lower contribution of experimental error in the overall phenotypic variability, indicating high heritability. Under water stress conditions, genetic variance is mainly due to additive gene action or a few major genes. Therefore, the role of additive variance was higher than that of dominant variance for these drought tolerance indices [33]. The GAM% values for the STI index were the highest, followed by the DI, GOL, SSI, and YR indices. Therefore, it seems that selection for drought tolerance based on most studied indices will be fruitful under water stress conditions. Darvishzadeh et al. [42] mentioned that h^2 estimates were low for SSI and TOL, while, moderate for MP, GMP, HM, STI and YI. On the other hand, the highest values of h^2 and GAM% were recorded for Yp, Ys, TOL, MP, HM, SSI, GMP, STI, YI and YSI by Anwar et al. [43]. Based on the heritability and genetic advance estimates, selection for drought tolerance based on GMP, MP, and STI [38], GMP, STI, HM, and YI, [41] as well as STI [33] will be more fruitful than based on the other studied indices.

Table 4. Combined analysis of variance for grain yield of twenty rice genotypes

SOV	df	SS	MS	Percentage relative to total sum of squares (TSS%)
Years (Y)	1	0.15	0.15ns	0.0010
Irrigation regimes (I)	1	8620.65	8620.65**	57.6473
Y*I	1	1.66	1.66ns	0.0111
Re./Y/I = (Ea)	6	7.81	1.30	0.0523
Genotypes (G)	19	5666.83	298.25**	37.8947
G*Y	19	56.58	2.98ns	0.3783
G*I	19	399.34	21.02*	2.6704
G*Y*I	19	39.92	2.10*	0.2670
Pooled Error = (Eb)	154	161.19	1.05	1.0779
CV	3.03			

** and **: significant at 5% and 1% levels of probability, respectively*

Table 5. Analysis of variance of grain yield under normal (Yp), drought (Ys) conditions and different drought tolerance indices in rice genotypes over the two growing seasons

S.O.V Indices	Year (Y)	Reps within Year	Genotypes (G)	G x Y interaction	Polled error	CV%
D.F.	1	4	19	19	76	
Yp	3.251	0.530	156.653**	1.158^{ns}	1.034	2.54
Ys	3.038	0.523	163.659**	0.821^{ns}	1.282	4.09
SSI	0.079	0.003	0.312**	0.001^{ns}	0.001	3.36
TOL	2.511	1.192	37.103**	0.002^{ns}	0.212	3.52
MP	0.306	1.740	151.082**	0.006^{ns}	0.255	2.49
GMP	4.392	0.819	159.009**	0.027^{ns}	0.289	2.57
STI	0.004	0.003	0.298**	0.001*	0.001	2.12
YI	0.004	0.017	0.212**	0.001^{ns}	0.001	2.74
YSI	0.021	0.001	0.028**	0.004^{ns}	0.001	3.66
DI	0.002	0.002	0.204**	0.001^{ns}	0.002	5.83
YR	0.001	0.004	0.029**	0.001^{ns}	0.001	5.56
ATI	0.001	0.001	0.004**	0.004^{ns}	0.001	10.63
SSPI	1.240	0.497	58.585**	0.009^{ns}	0.564	4.59
HM	6.984	14.820	168.182**	0.167^{ns}	0.503	2.17
GOL	2.094	0.474	11.572**	0.020^{ns}	0.167	6.91

** and **: significant at 5% and 1% levels of probability, respectively. Yp: yield under water non-stress; Ys: yield under water stress; SSI: susceptibility stress index; TOL: tolerance index; MP: mean productivity; GMP: geometric mean productivity; STI: stress tolerance index; YI: yield index; YSI: yield stability index; DI: drought resistance index; YR: yield reduction ratio; ATI: abiotic tolerance index; SSPI: stress susceptibility percentage index; HM: harmonic mean; GOL: golden mean.*

The values of coefficients of phenotypic variation (PCV%) were higher than their corresponding coefficients of genotypic variation (GCV%) for grain yield under non-stress and stress water conditions (Yp and Ys) and drought tolerance indices. Still, the differences between the values were generally low, indicating that the phenotype was close to the genotype, and environmental influence was less for Yp, Ys, and drought tolerance indices. The highest values of the GCV % and PCV% were recorded for STI index followed by DI, GOL, SSI, and YR indices; while, there were moderate values for YI as well as SSPI, TOL, Ys, ATI, HM, and GMP indices, indicating that all these indices are amenable for further improvement. In contrast to that, the lowest values for the GCV% and PCV% were observed for Mp as well as Yp and YSI indices. These findings were supported by [36], who also reported high GCV% for GOL, DI, TOL, SSPI, ATI, YR, and SSI. The values of coefficients of variation (ECV%) varied from 0.74% to10.63% (Table 6).

The ATI index had the highest ECV%, followed by GOL, DI, YR and SSPI indices, while YI index showed the lowest value. In accordance with previously published results, the relative coefficient of variation (RCV=GCV%/ECV%) was greater than unity for grain yield under non-stress and water stress conditions (Yp and Ys) and drought tolerance indices. The highest RCV values (RCV >1) indicate that the environmental variation between genotypes was less than the genetic variation for grain yield under non-stress and water stress conditions (Yp and Ys) and drought tolerance indices. These results suggest that genotypic values may differ from one environment to another, which may have an effect on how genotypes behave in different environments [44].

3.2.1 Drought tolerance indices

Drought tolerance indices of the twenty studied rice genotypes were computed using grain yield under non-stress (Yp) and water stress (Ys) conditions in two consecutive seasons (Table 7). Over two growing seasons, the grain yield (g) of twenty rice genotypes under non-stress conditions increased by approximately 37% compared to yields under water stress conditions. Drought stress in this study might be regarded moderate stress; thus, this result provides a good indicator of genotypic variations under random drought stress [41]. Giza 179, Sakha 104, IET 1444, GZ 6296-12-1-2-1, Giza 178, and GZ 1368-S-5-4 had the highest grain yield under Ys and relatively high grain yield under Yp. The genotypes are Giza 179, Sakha 104, and IET 1444, which had the highest MP, STI, GMP, YI, YSI, DI, HM, and GOL indices and the lowest recorded values for YR, SSI, TOL, ATI, and SSPI indices. Consequently, these genotypes were considered the most drought-tolerant and desirable under Ys. On the other hand, the genotypes Giza 177, Sakha 102, and IR11L465, had the highest recorded values for the YR, SSI, TOL, ATI, and SSPI indices and the lowest recorded values for the MP, STI, GMP, YI, YSI, DI, HM, and GOL indices. Consequently, these genotypes were identified as the most drought-sensitive and undesirable under Ys conditions, as well as drought-sensitive genotypes.

These findings demonstrated that the MP, GMP, and HM indices as well as the STI, YI, YSI, and DI were similarly in their selection of genotypes. In the same text, the results illustrated that the YR, SSI, and ATI were similar in their selection of genotypes. The MP, STI, GMP, and HM indices were useful selection criteria for high-yielding rice genotypes under both non-stress and stress conditions, while the relative decrease in yield indicated that the SSI, TOL, YR, ATI, SSPI, YSI, DI, and GOL values were better to determine drought tolerance levels. These findings are consistent with those found by [45] for the drought indices STI, MP, GMP, and YI, as well as [46] for the drought indices STI and YI, which were superior, indicating that they can be used to select drought-tolerant genotypes as alternatives. Drought indices SSI, TOL, and YSI [45], as well as TOL and SSI [47], can be used to screen for drought tolerance.

3.3 Correlation Analysis

The correlation analysis between grain yield under both non-stress (Yp) and water stress (Ys) conditions and each of the drought indices was done to identify the most acceptable drought tolerance indices (Fig. 1). The correlation coefficients between different tolerance indices are shown in Fig. 1. The correlation coefficient between Yp and Ys was marginally significant, indicating that high yield potential under non-stress growing conditions wasn't associated with superior yield under stress. For example, the genotypes Sakha 101 and IR 65600-127-6-2 produced the highest yield under non-stress conditions but failed to produce high yields under drought conditions. Consequently, indirect selection for stress conditions depending on the performance of the studied genotypes in non-stress conditions is ineffective. The MP, STI, GMP, YI, DI, and HM indices were significantly positively correlated with grain yields (Yp and Ys), showing that these indices were more effective in selecting high-yielding genotypes under both non-stress and stress conditions. Our findings lead us to the conclusion that MP, YI, GMP, STI, DI, and HM were only able to differentiate between specific genotypes under conditions of moderate drought stress. Additionally, there was a highly significant and positive correlation between Ys and the YSI, DI, and GOL indices. These relationships were affected by drought intensity (difference between Ys and Yp) and suggested that genotypes selected based on these indices were distinguished by drought tolerance parameters and might improve yield under stress conditions. The correlation between TOL, ATI, SSPI, YR, SSI, and Ys was either not significant or highly significant and negative. Therefore, these indices are suitable for determining rice genotypes with low yield and drought tolerance, as yield under stress decreased as the indices increased.

However, there was a positive correlation between Yp and MP, STI, GMP, YI, DI, and HM. Therefore, according to Mardeh et al. [48], a negative correlation between YR, SSI, TOL, ATI, and SSPI with Ys implies that selection based on SSI and TOL will increase yield under non-stress conditions (Yp). However, Rizza et al. [49] demonstrated that a selection based on the minimum yield decrease under stress relative to favorable conditions (TOL) was unable to identify the best genotypes.

Positive and highly significant correlation coefficients between SSI, TOL, ATI, YR, and SSPI suggest they are comparable for selecting drought-tolerant genotypes. These findings suggested that SSI, TOL, ATI, YR, and SSPI were all capable of performing stress tolerance. These findings were previously confirmed by Rahimi et al. [50]. All subsets exhibited significant or highly significant correlations between MP, STI, GMP, YI, YSI, DI, and HM, with the exception of YR and SSI, for which the correlation coefficients were negative and highly significant. GOL was highly significant and positively corrected with MP, STI, GMP, YI, YSI, DI and HM. These findings were consistent with those of Rahimi et al. [50] and Baghyalakshmi [30].

3.4 Principle Component Analysis (PCA)

Principal component analysis was used to examine the relationship between rice genotypes and drought tolerance indices on two components (PCA1 and PCA2). The eigenvalues for PC1 and PC2 were 6.72 and 2.91, respectively (Table 8). The PCA1 and PCA2 accounted for 99.61% of the total variance between drought stress indices. These findings are consistent with those of Qamar et al. [51]. According to Amiri et al. [52], selecting genotypes with high PCA1 and low PCA2 is appropriate for both non-stress and stress conditions.

PCA1 contributed 69.49% of the total variation with Yp, Ys, MP, GMP, STI, YI, DI, HM, and GOL, in accordance with the analysis.

Table 6. Genetic parameters of Yp, Ys and different drought tolerance indices in rice

Indices	Genetic parameters						
	h^2	GA	GAM%	GCV%	PCV%	ECV%	RCV
Yp	0.99±0.35	8.93	22.32	12.73	12.78	2.54	5.01
Ys	0.99±0.35	9.15	33.04	18.82	18.87	4.09	4.60
SSI	1.00±0.35	0.45	36.27	20.63	20.75	3.36	6.14
TOL	1.00±0.35	4.38	33.47	19.02	19.09	3.52	5.40
MP	1.00±0.35	8.83	26.06	14.81	14.88	1.49	9.94
GMP	1.00±0.35	9.06	26.51	15.06	15.12	1.57	9.57
STI	0.99±0.35	0.39	53.74	30.54	30.65	1.12	27.29
YI	0.99±0.35	0.33	33.62	19.10	19.32	0.74	25.90
YSI	0.99±0.35	0.12	16.06	9.13	9.23	3.66	2.50
DI	1.00±0.35	0.32	44.08	25.05	25.15	5.83	4.30
YR	0.99±0.35	0.12	35.66	20.33	20.49	5.56	3.66
ATI	1.00±0.35	0.01	29.28	16.63	16.83	10.63	1.56
SSPI	1.00±0.35	5.50	33.61	19.09	19.29	4.59	4.16
HM	0.99±0.35	9.31	28.44	16.17	16.28	2.17	7.46
GOL	1.00±0.35	2.44	41.30	23.49	23.57	6.91	3.40

h^2: broad sense heritability; GA: genetic advance; GAM%: genetic advance as percent of mean; GCV%: genotypic coefficients of variation; PCV%: phenotypic coefficients of variation; ECV%: coefficients of variation; RCV: relative coefficient of variation

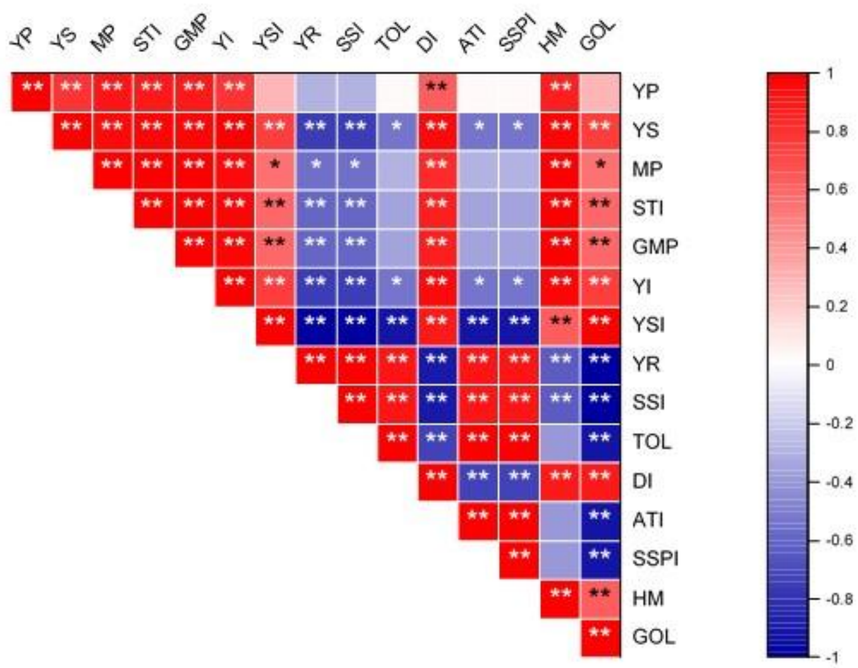

Fig. 1. Corrplot depicting Pearson's correlation between 15 drought tolerance indices with grain yield of 20 rice genotypes under normal (Yp) and drought condition (Ys)

Red squares indicate a positive correlation; blue squares indicate a negative correlation; and white squares indicate no correlation. The asterisks indicate significant correlations using a two-tailed t-test (and ** p < 0.05; and *** p < 0.01)*

Table 7. Comparison of different drought tolerance indices for rice genotypes based on grain yield under non-stress (Yp) and water stress (Ys) conditions (averaged over two growing seasons)

Genotype	Drought tolerance indices														
	Yp	**Ys**	**MP**	**STI**	**GMP**	**YI**	**YSI**	**YR**	**SSI**	**TOL**	**DI**	**ATI**	**SSPI**	**HM**	**GOL**
G.177	35.00	14.70	26.85	0.413	25.58	0.673	0.534	0.466	1.55	16.30	0.359	0.041	20.48	24.38	3.29
G.178	41.68	27.67	37.18	0.853	36.76	1.139	0.742	0.258	0.86	11.02	0.845	0.028	13.84	36.36	6.75
G.179	45.50	32.84	41.67	1.082	41.39	1.325	0.792	0.208	0.69	9.66	1.050	0.024	12.13	41.11	8.63
SK.101	41.73	23.90	34.82	0.735	34.12	1.004	0.669	0.331	1.10	13.83	0.671	0.035	17.38	33.44	5.03
SK.102	36.20	16.70	28.45	0.473	27.37	0.745	0.572	0.428	1.43	15.50	0.426	0.039	19.47	26.34	3.67
SK.104	43.67	30.50	40.58	1.023	40.26	1.277	0.777	0.223	0.74	10.17	0.993	0.025	12.77	39.95	7.98
SK.107	37.19	23.47	32.33	0.645	31.96	0.988	0.739	0.261	0.87	9.72	0.730	0.024	12.21	31.60	6.65
SK.108	42.30	26.63	37.97	0.876	37.25	1.102	0.676	0.324	1.08	14.67	0.745	0.037	18.43	36.55	5.18
GZ9730	37.00	23.33	29.17	0.516	28.58	0.839	0.667	0.333	1.11	11.67	0.560	0.029	14.66	28.00	5.00
GZ6296	43.83	31.17	40.50	1.010	40.00	1.229	0.730	0.270	0.90	12.67	0.897	0.032	15.91	39.51	6.39
GZ1368	45.90	30.90	38.40	0.895	37.66	1.112	0.673	0.327	1.09	15.00	0.748	0.038	18.84	36.94	5.12
IR11L465	40.67	19.40	27.53	0.446	26.59	0.734	0.588	0.412	1.37	14.27	0.432	0.036	17.92	25.69	3.86
WAB56	37.80	26.45	32.63	0.655	32.21	0.987	0.726	0.274	0.91	10.35	0.717	0.026	13.00	31.80	6.30
IRAT170	33.25	23.67	28.46	0.497	28.05	0.851	0.712	0.288	0.96	9.58	0.606	0.024	12.04	27.65	5.94
NERICA4	39.70	27.15	31.93	0.629	31.57	0.977	0.740	0.260	0.87	9.55	0.722	0.024	12.00	31.21	6.69
IR65600	42.04	25.00	37.52	0.843	36.54	1.043	0.630	0.370	1.23	17.04	0.657	0.043	21.41	35.59	4.40
IR68011	36.33	22.83	29.08	0.509	28.40	0.821	0.646	0.354	1.18	12.50	0.531	0.031	15.70	27.74	4.65
IR68552	41.27	25.98	30.63	0.579	30.27	0.935	0.737	0.263	0.88	9.29	0.689	0.023	11.67	29.92	6.60
IRGA318	36.17	25.07	30.62	0.572	30.11	0.902	0.693	0.307	1.02	11.10	0.625	0.028	13.94	29.61	5.52
IET1444	43.67	29.26	40.46	1.009	39.99	1.252	0.734	0.266	0.89	12.40	0.905	0.031	15.58	39.51	6.52
Max.	45.90	32.84	41.67	1.08	41.39	1.325	0.792	0.466	1.55	17.04	1.050	0.043	21.41	41.11	8.63
Min.	33.25	18.70	26.85	0.41	25.58	0.673	0.534	0.208	0.69	9.29	0.359	0.024	11.67	24.38	3.29
Mean	40.15	25.33	33.84	0.71	33.23	0.997	0.689	0.311	1.04	12.31	0.695	0.031	15.47	32.64	5.71

PCA2 accounted for 30.12% of the total variability with SSI, SSPI, YR, and TOL. Consequently, the PCA2 can be referred to as a drought-sensitive dimension with a high yield under non-stress conditions and a low yield under stress conditions. The first two components, as reported by Baghyalakshmi [30] and El-Hashash, EL-Agoury [37], represented 81.01% and 70.66%, along with 13.23% and 28.48% of the total variation, respectively.

According to Fernandez's classification, the studied genotypes were divided into four categories based on their performance in non-stress and stress conditions using biplot analysis (Fig. 2). The genotypes namely: Giza 179, IET 1444, GZ 6296-12-1-2-1, GZ 1368-S-5-4, and Sakha 108, using STI, MP, GMP, and HM, presented high yields under both stress and non-stress (group A). The genotypes Sakha 104, Giza 178, Sakha 107, IRAT 170, WAB 56-104, IRGA 318-11-6-2-6, NERICA -4, and IR 68552-55-3-2, using YSI, DI, and GOL, produced high yields under stress conditions and were included in Group B. Genotypes, namely: IR11L465, Giza 177, Sakha 102, and IR 68011-15-1-1, based on the most studied indices, had low grain yield performance in stress conditions meanwhile had relatively high yield under non-stress conditions and using SSI, YR, SSPI and TOL (Group C).Group D consisted of the genotypes IR68011, GZ9730 and IRAT170, which have a low yield response in stress conditions and relatively low yield under non-stress conditions comparing to the other studied genotypes. The result obtained from principal component analyses using biplos provides valuable information from the data analysis and confirms the correlation analysis. These findings were similar to the results of El-Hashash, EL-Agoury [37].

3.5 Cluster Analysis

On the basis of the Yp, Ys, and drought tolerance indices, cluster analysis with the Paired group/chord method was used to divide the genotypes into four groups (Fig. 3A).

The first cluster (I) consisted of the genotypes Giza 177, Sakha 102, and IR11L465 that had the highest recorded values for YR, SSI, TOL, ATI, and SSPI indices and the lowest values for MP, STI, GMP, YI, YSI, DI, HM, and GOL indices. Thus, these genotypes were recognized as the most drought-sensitive and undesirable under non-stress conditions (Ys) and identified as sensitive genotypes to drought.

The second cluster (II) consisted of the genotypes, namely: GZ 1368-S-5-4, Sakha 108, Sakha 101, IR 65600-127-6-2, GZ 9730-1-1-1-1, and IR 68011-15-1-1. Regarding the genotypes GZ 1368-S-5-4 and Sakha 108, they had relatively high values of the indices MP, STI, GMP, YI, YSI, and HM, and grain yield under Yp and Ys, as well as relatively low values of YR and ATI. Thus, these genotypes are considered moderately tolerant to drought. Meanwhile, the genotypes, namely, Sakha 101 and IR 65600-127-6-2, had moderate values of MP, YI, and YSI and high grain yield under non-stress conditions, so it's considered desirable to grow only under Yp conditions. The cluster III consisted of two genotypes, namely: Giza 179 and Sakha 104, which had the lowest recorded values for YR, SSI, TOL, ATI, and SSPI indices and the highest values for MP, STI, GMP, YI, YSI, DI, HM, and GOL indices. Thus, these genotypes were recognized as the most drought-tolerant and desirable under Ys. It seems that these indices have succeeded in selecting genotypes with high yields under both Yp and Ys conditions. Cluster IV is comprised of nine genotypes, namely: IET 1444, GZ 6296-12-1-2-1, Giza 178, Sakha 107, IRAT 170, WAB 56-104, IRGA 318-11-6-2-6, NERICA -4, and IR 68552-55-3-2. For the three genotypes, IET 1444, GZ 6296-12-1-2-1, and Giza 178 had relatively high values of MP, STI, GMP, YI, YSI, GOL, and HM indices and grain yield under Yp and Ys, as well as relatively low values of YR, SSI, and ATI. Thus, these genotypes are considered moderate to highly drought-tolerant. Thus, under stress conditions, the selection should be based on high rates of YI.

Regarding the genotypes Sakha 107, IRAT 170, IR 68552-55-3-2, WAB 56-104, IRGA 318-11-6-2-6, and NERICA -4, they had relatively the lowest values of YR, SSI, TOL, ATI, and SSPI indices among the studied genotypes, but unfortunately they couldn't have succeeded in having high MP, STI, GMP, and YI indices. So these genotypes are considered desirable only under Ys conditions. In Fig. 3, the cluster analysis for grain yields (Yp and Ys) based on the indices values tended to group into three clusters (I, II, and III). The cluster I consisted of the YR, SSI, TOL, SSPI, and ATI indices. Cluster II is comprised of Yp, Ys, MP, GMP, YSI, YI, and HM indices. While, the cluster III is comprised of STI, DI, and GOL. The tree diagram detected the minimum distance or dissimilarity between the indices inside each group. While the highest distance was found among the indices of the two groups, these results indicated that each cluster contained drought tolerance indices that were highly similar. These findings were consistent with the results of Iqbal et al. [53].

3.6 Ranking Method

The ranks of genotypes for YSI, YR, SSI, and GOL; for TOL, ATI, SSPI; STI, GMP, and HM, Ys, MP, YI, DI, and Yp were identical (Table 9). These results were consistent with the findings of Baghyalakshmi [30] and Amiri et al. [52].

Giza 179, followed by Sakha 104, IET 1444, GZ 6296-12-1-2-1 and Giza178, showed the best rank mean with an almost low standard deviation and sum of rank. Thus, these genotypes were identified as the most drought tolerant genotypes. On the contrary, the genotypes Giza 177, Sakha 102, and IR11L465 were the most sensitive under drought stress conditions. The other genotypes were identified as semi-tolerant or semi-sensitive to drought stress.

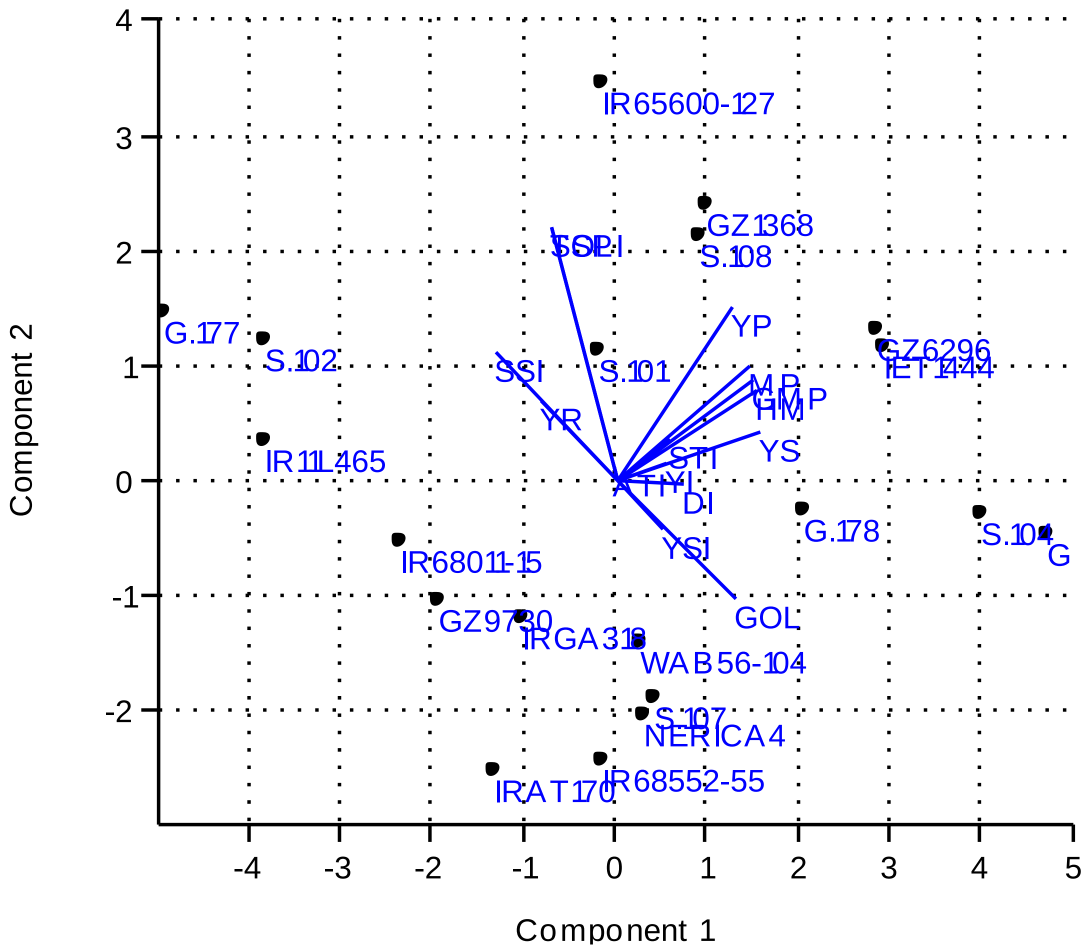

Fig. 2. Biplot diagram based on first two principal component axes of twenty rice genotypes according to mean measured of drought tolerance indices under non-stress and stress conditions

Table 8. Principal Component Analysis (PCA) for grain yield of rice genotypes based on non-stress and stress conditions and drought tolerance indices

Principal component analysis (PCA)	Eigen value	Percentage of variance	Cumulative variance
PCA1	6.72343	69.493	69.493
PCA2	2.91389	30.118	99.611

Table 9. Rank, rank mean (R), Standard Deviation of Ranks (SDR) and Rank Sum (RS) of drought tolerance indices

Genotype	Drought tolerance indices															Rank method		
	YP	YS	MP	STI	GMP	YI	YSI	YR	SSI	TOL	DI	ATI	SSPI	HM	GOL	R	SDR	RS
G.177	18	20	20	20	20	20	20	20	20	19	20	19	19	20	20	19.67	0.62	20.28
G.178	8	5	8	7	7	5	3	3	3	8	5	8	8	7	3	5.87	2.10	7.97
G.179	3	1	1	1	1	1	1	1	1	4	1	4	4	1	1	1.73	1.28	3.01
SK.101	9	9	9	9	9	9	14	14	14	14	12	14	14	9	14	11.53	2.50	14.04
SK.102	13	18	18	18	18	18	19	19	19	18	19	18	18	18	19	18.00	1.46	19.46
SK.104	6	2	2	2	2	2	2	2	2	6	2	6	6	2	2	3.07	1.83	4.90
SK.107	11	10	11	11	11	10	5	5	5	5	8	5	5	11	5	7.87	2.88	10.74
SK.108	7	7	6	6	6	7	12	12	12	16	7	16	16	6	12	9.87	4.00	13.86
GZ9730	17	16	15	15	15	16	15	15	15	10	16	10	10	15	15	14.33	2.32	16.65
GZ6296	1	4	3	3	3	4	8	8	8	13	4	13	13	3	8	6.40	4.08	10.48
GZ1368	5	6	5	5	5	6	13	13	13	17	6	17	17	5	13	9.73	5.04	14.77
IR11L465	19	19	19	19	19	19	18	18	18	15	18	15	15	19	18	17.87	1.55	19.42
WAB56	10	11	10	10	10	11	9	9	9	7	10	7	7	10	9	9.27	1.33	10.60
IRAT170	20	15	17	17	17	15	10	10	10	3	15	3	3	17	10	12.13	5.67	17.80
NERICA4	12	12	12	12	12	12	4	4	4	2	9	2	2	12	4	7.67	4.50	12.17
IR65600	4	8	7	8	8	8	17	17	17	20	13	20	20	8	17	12.80	5.68	18.48
IR68011	16	17	16	16	16	17	16	16	16	12	17	12	12	16	16	15.40	1.80	17.20
IR68552	15	13	13	13	13	13	6	6	6	1	11	1	1	13	6	8.73	5.09	13.82
IRGA318	14	14	14	14	14	14	11	11	11	9	14	9	9	14	11	12.20	2.11	14.31
IET1444	2	3	4	4	4	3	7	7	7	11	3	11	11	4	7	5.87	3.14	9.00

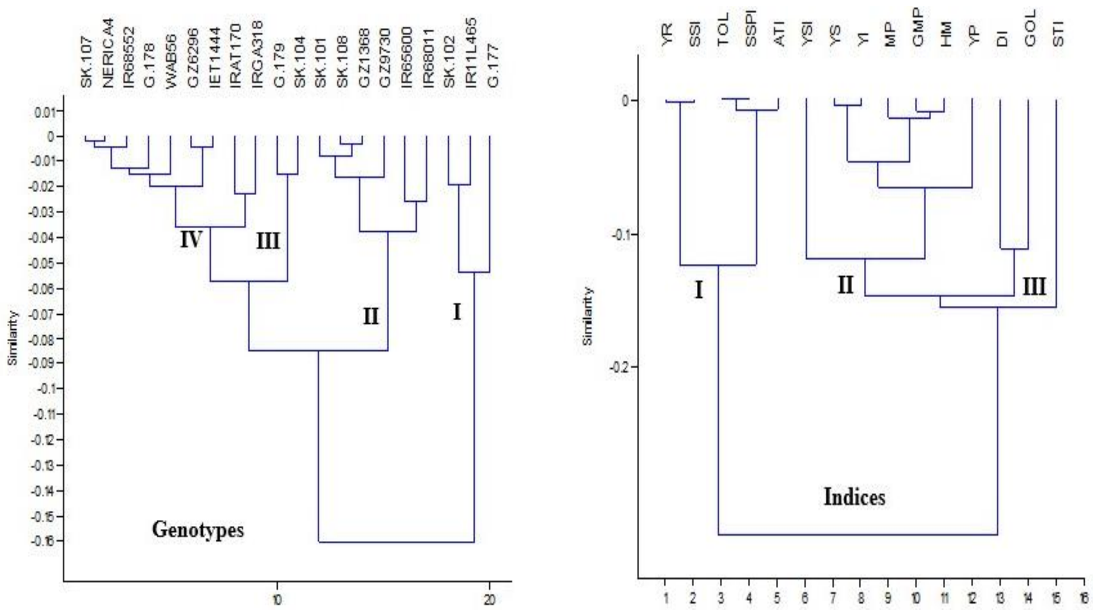

Fig. 3. Dendrogram between groups showing classification of genotypes (A) and drought tolerance indices (B) using paired group/chord

4. CONCLUSIONS

There were significant differences among genotypes for all indices, indicating that genes controlling yield and drought tolerance differed across genotypes. The grain yields (Yp and Ys) and all drought tolerance indices were highly h^2 and GAM% and are usually able to select high-yielding genotypes under drought conditions. In general, the results of this study based on correlation coefficients, multivariate analysis, and a ranking method showed that among all drought tolerance indices, MP, GMP, STI, HM, and YI can be used as the most suitable indicators for screening drought-tolerant genotypes, and the genotypes Giza 179, followed by Sakha 104, Giza178, IET 1444, and GZ 6296-12-1-2-1, were characterized by the highest tolerance to drought under the climate conditions of Egypt. Accordingly, they are considered parents for enhancing the drought tolerance of rice in Egypt's hybridization programs.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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