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Evaluation of Drought Tolerance Ability in Wheat Genotypes Through Comprehensive Stress Indices

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ABSTRACT

The objective was to assess a range of stress indices to discern wheat genotypes resilient to drought stress, so forty-nine genotypes underwent scrutiny in both drought stress in rainfed conditions and non-stress settings (with supplementary irrigation), employing a 7 × 7 lattice layout with two replicates across years 2019 and 2020. The evaluation incorporated twenty stress indices anchored in yield under water stress (YS) and potential (YP) circumstances. Primary analysis indicated that eight indices (RDI, YSI, YI, K_2STI, MRP, REI, RR and SSPI) did not give any new information, so they were eliminated in further analysis. Genotypes G33 (4234 kg ha^{-1}) and G9 (2227 kg ha^{-1}) were the best genotypes based on YP in 2019 and 2020, respectively. A positive association was observed between ATI and YP and between YS with DI and K1STI in the year 2019, while in the second year, such positive associations were not seen. We found some wheat genotypes G6, G9, G10 and G11 demonstrated high performance in both potential and rainfed conditions across two years, showing yield higher than 1,800 and 2,700 kg ha^{-1} for YS and YP, respectively, across both years. These genotypes were detected as the most tolerant genotypes by mean-based indices (TOL, HM, GMP, and MP) as well as SSI and ATI indices, so it can be concluded that these indices are more useful than other indices for identifying the most tolerant as well as the high yielding genotypes.

1. Introduction

Bread wheat is a crucial winter cereal crop globally, serving as a staple source for a significant portion of the human population. The evaluation of yield performance in wheat entails a nuanced consideration of various yield component traits, each assuming varying degrees of importance depending on the timing and severity of environmental stresses and their time progression. However, wheat production faces numerous challenges, with climate change posing a substantial threat. Drought stress, characterized by inadequate water availability for plant growth and development, is an important abiotic stress factor influencing the production of wheat (Ahmad *et al.* 2018). In Mediterranean regions, where the majority of rainfall occurs during autumn and winter, a subsequent water deficit in spring imposes moderate drought stress on rainfed wheat during crucial stages such as anthesis and seed filling stages (Yang *et al.* 2020). This stress, notably intensified during the anthesis stage, significantly jeopardizes yield by diminishing the spikes and spikelets and reducing the fertilization of spikelets. The consequential loss in yield poses a formidable challenge for breeders, who prioritize the crop's performance under water stress. The complexity of tolerance breeding is compounded by the absence of reliable selection tools and the difficulty in establishing consistently replicable water drought conditions, hindering the efficient evaluation of large populations (Mwadzingeni *et al.* 2016). The severity of deficit, particularly during anthesis, emerges as a

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pivotal factor influencing the fertility of spikelets, underscoring the imperative for robust and innovative strategies within a breeding process to address the multifaceted challenges imposed by drought stress on wheat. Drought stress negatively impacts various physiological and biochemical processes in wheat plants, including photosynthesis, nutrient uptake, and overall metabolism. So, wheat yields are significantly reduced under drought conditions, leading to economic losses and food security concerns (Ahmad *et al.* 2018). Given the unpredictable nature of climate patterns, understanding and enhancing drought tolerance in wheat varieties is imperative for sustainable agriculture (Mohammadi 2018).

In recent years, researchers and plant breeders have been employing advanced techniques to screen wheat for tolerance to water stress. In the pursuit of identifying and characterizing tolerant lines, various stress indices have been devised, centering on the intricate interplay between potential and rainfed circumstances. One approach involves the use of stress tolerance indices, which serve as valuable tools, offering a quantitative measure of the impact of drought by focusing on the yield decrease under water stress compared to potential circumstances. These indices provide valuable insights into the performance of different wheat genotypes under water stress, aiding in the detection and selection of breeding lines that exhibit resilience to water scarcity. The stress susceptibility index (SSI) of Fischer and Maurer (1978) assesses the extent to which a genotype is susceptible to stress, considering both yield reduction and yield variability under water stress circumstances. In other words, the stress tolerance index (STI) of Rosielle and Hamblin's (1981) evaluates a genotype's ability to maintain a desirable level of performance in terms of yield and stability under stress relative to non-stress conditions. These indices, along with others like the mean productivity (MP) and yield index (YI), offer comprehensive tools for evaluating and comparing wheat genotypes in the context of drought stress.

By employing stress tolerance indices, researchers can gain valuable insights into the adaptive mechanisms of different wheat genotypes and identify those with superior drought tolerance. This knowledge is instrumental in the development of new, climate-resilient wheat varieties through targeted breeding programs, ultimately contributing to global food security in the face of changing environmental circumstances. Bouslama and Schapaugh (1984) introduced the yield stability index, and Lin and Binns (1988) presented the superiority index, both aiming to estimate genotype adaptability across diverse regions. The superiority index, specifically, is calculated as the variance of the distance between each yield data and the maximum record yield under potential or rainfed circumstances. Fernandez (1992) contributed to this field by suggesting the STI, GMP (geometric mean products), and HM (harmonic mean) as additional criteria for the selection of promising lines under water stress. Gavuzzi *et al.* (1997) and Sadiki (2006) suggested the YI (yield index) and RR (relative reduction), respectively, as innovative approaches to screening for drought-tolerant genotypes. These indices collectively provide a nuanced and comprehensive framework for evaluating and selecting genotypes with heightened adaptability and resilience to the challenges posed by drought stress across a spectrum of environmental conditions.

The pursuit of an ideal selection index delves into the nuanced challenge of differentiating genotypes that consistently exhibit favorability in both potential and rainfed circumstances from those excelling in only one setting. Among the array of various stress indices, the strategic use of the SSI and STI criteria emerges as a preference, particularly for favoring individuals with a lower yield potential under potential circumstances but demonstrating higher yield under water stress circumstances. This intentional selection methodology aims to pinpoint genotypes not only with enhanced stress tolerance but also the potential for superior yields when faced with challenging stress conditions. In the study conducted by Ayed *et al.* (2021), the utilization of SSI and STI to evaluate water stress tolerance in wheat revealed a noteworthy yearly variability in SSI and STI indices for different individuals, influencing their ranking patterns while the other mean-based indices like harmonic or geometric means, essentially statistical derivation of the original data, could serve as a combined foundation for selection. This suggests that integrating both indices into the selection process might offer a more comprehensive index for genetic improvement of water stress tolerance in wheat.

Against this backdrop, the current investigation sought to achieve three objectives: (i) identification of tolerant wheat genotypes under water stress, (ii) evaluation of the stress indices in categorizing individuals as tolerant or nontolerant, and (iii) exploration of association among the stress indices. These objectives represent a thorough exploration of the ability of stress tolerance of wheat genotypes and the intricate dynamics of screening methods in facilitating the selection process, aiming for a deeper understanding of the underlying complexities in identifying resilient genotypes under challenging environmental conditions.

2. Materials and Methods

2.1. Trials

In this study, 49 bread wheat genotypes were studied in a 7 × 7 lattice design with two replicates. All of these genotypes were newly improved lines sourced from Iran's National Wheat Breeding Program and International Center for Agricultural Research in the Dry Areas (ICARDA), and check cultivar Tak-Ab (from Iran) was included as a check. The trials were conducted under dry-land conditions at the Maragheh Research Experimental Station during the two growing seasons of 2019 and 2020 from October to July. Detailed information regarding the pedigree and origin of each genotype is provided in Table 1. The field plots were meticulously designed, each measuring 6 m in length with six rows spaced 17.5 cm apart (width 6 × 0.175 = 1.05 m), resulting in a total plot area of 6.3 m^2. The study encompassed two humidity conditions: potential or non-stress (involving two supplementary irrigations, 50 ml after sowing and 30 ml on stem elongation) and water stress (rainfed conditions with rainfall controlling with shelter. In 2019 and 2020, rainfall amounted to 495 and 327 mm, while the monthly rainfall and average temperature are illustrated in Figure 1. To optimize growth, fertilization was applied at a rate of 80 kg ha^{-1} urea and triple superphosphate at a rate of 30 kg ha^{-1}. Noteworthy was the absence of significant diseases, and weed control was meticulously executed. Upon reaching physiological maturity, the plots underwent careful harvesting. To ensure consistency and comparability, the yield was meticulously adjusted to a standardized moisture content of 12.5%. In other words, when the wheat reached full maturity based on the physiological stage, after removing half a meter from both sides of the plot, the plants of each plot were harvested by an experimental combine machine, and the yield was weighed.

2.2. Stress Indices

Several stress tolerance indices were used as the modified form of drought response index (DRI), which is suggested by Bidinger *et al.* (1987):

$$DRI = |[E(Ys) - Ys] / [SE]|$$

Where: E(Ys) is the expected yield of stressful condition estimate by linear regression model (Ys = a + bYp, a = intercept and b = line slope); Ys is the expected yield of stressful condition estimate by the linear regression model; and SE is the residual effect of the linear regression model estimation.

Fischer and Maurer (1978) introduced SSI (stress susceptibility index) as:

$$SSI = [1 - (Ys / Yp)] / [1 - (\bar{Y}s / \bar{Y}p)]$$

Where: Yp is the yield of potential condition; $\bar{Y}s$ is the mean value of Ys and $\bar{Y}p$ is the mean value of Yp. Fischer and Wood (1979) suggested RDI (relative drought index) as:

$$RDI = (Ys / Yp) / (\bar{Y}s / \bar{Y}p)$$

The superiority index (PI) of Lin and Binns (1988) was computed as:

$$Pi = \sum_{j=1}^{n} \frac{(X_{ij} - M_j)^2}{2n}$$

Where n is the number of environments, X_{ij} is the yield of ith genotype in the jth environment, and M_j is the maximum performance of environment j. Rosielle and Hamblin (1981) proposed MP (mean productivity) and TOL (tolerance) as:

$$MP = (Ys + Yp) / 2$$

$$TOL = (Yp - Ys)$$

Bouslama and Schapaugh (1984) suggested YSI (yield stability index):

$$YSI = Ys / Yp$$

Fernandez (1992) proposed STI (stress tolerance index), GMP (geometric mean productivity) and HM (harmonic mean) as:

$$STI = (Yp \times Ys) / Yp^2$$

$$GMP = \sqrt{(YsYp)}$$

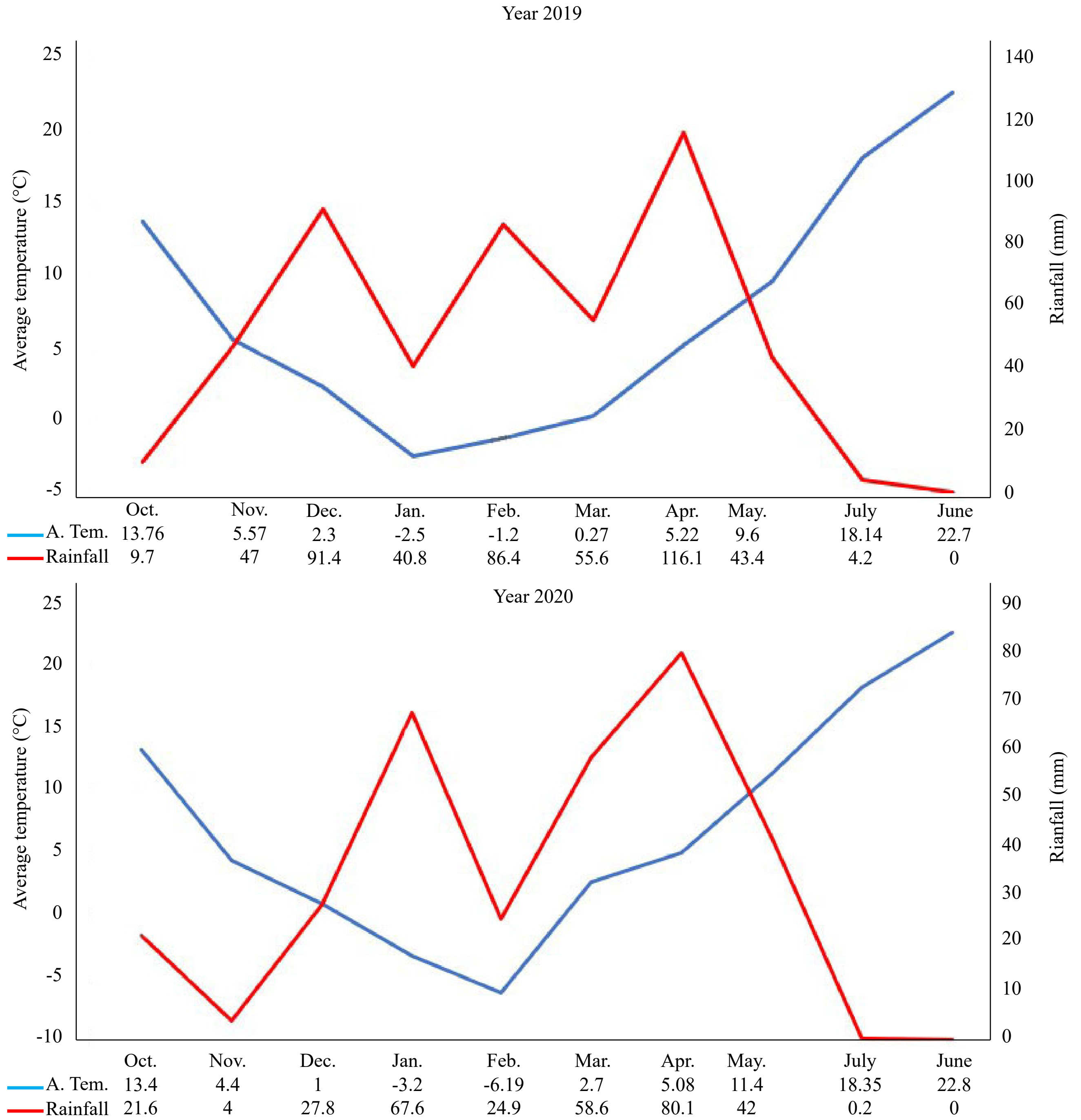
$$HM = [2 (Yp \times Ys)] / (Yp + Ys)$$

The yield index (YI) was obtained based on (Gavuzzi *et al.* 1997):

$$YI = Ys / \bar{Y}s$$

Table 1. Name and pedigree of studied wheat genotypes

Pedigree
Tak-Ab
Arvand//78Zhong291/Azar2 IRW2009-10-058-0MA-0MA-0MA-0MA-0MA-4MA
HGO94.9.1.37/2*NAVJ07
ATTILA/2*PASTOR//YUMAI 29
KARL/NIOBRARA//TAM200/KAUZ/3/TAM200/KAUZ
Mahooti/6/Vee"s"/Pvn"s"/4/Cc//Cal/Sr/3/Kal/Bb/5/Sabalan IRW2009-10-115-0MA-0MA-0MA-0MA-0MA
Systani/Sar-101IRW2009-10-131-0MA-0MA-0MA-0MA-0MA
Bocro-4/Shahi (Ir64…Ste//Weebill1 IRW2009-10-142-0MA-0MA-0MA-0MA-0MA
Systani/3/KS82W409/SPN//TAM106/TX78V3630 IRW2009-10-143-0MA-0MA-0MA-0MA-0MA
Azar-2/14- Gen Bank IRW2009-10-171-0MA-0MA-0MA-0MA-0MA
Manning/Sdv1//Dogu88/3/GB1- 254IRW2009-10-184-0MA-0MA-0MA-0MA-0MA
F130-L-1-12//PONY/OPATA/3/Kharchia IRW2009-10-217-0MA-0MA-0MA-0MA-0MA
F130-L-1-12//PONY/OPATA/3/Kharchia IRW2009-10-217-0MA-0MA-0MA-0MA-0MA
Shahi/Prl"S"//Fenkang15/Sefid/3/316 Collection IRW2009-10-230-0MA-0MA-0MA-0MA-0MA
Koohdasht/RasadIRW2009-10-249-0MA-0MA-0MA-0MA-0MA
Koohdasht/Wang shui baiIRW2009-10-251-0MA-0MA-0MA-0MA-0MA
Int F5 2014-44-0MA-1MA
Int F5 2014-54-0MA-1MA
Int F5 2014-70-0MA-3MA
Int F5 2014-78-0MA-1MA
MK 3744/BWKLDN-95 (23FAWWON)
ID2619/5/GRTPL 6121/6/ID3910066/7/SHARK/F4105W2.1 (23FAWWON)
TX71A983.4/TX69D4812//PYN/3/VPM/MOS83.11.4.8//PEW/4/NS-55-25 (23FAWWON)
DAGDAS/APCB-40 (23FAWWON)
Mahooti/6/Vee"s"/Pvn"s"/4/Cc//Cal/Sr/3/Kal/Bb/5/Sabalan IRW2009-10-115-0MA-0MA-0MA-0MA-0MA
Maroon/GaharIRW2009-10-006-0MAR-00SAR-0SAR-0SAR-0SAR-1SAR
Systani/Sar-101IRW2009-10-131--0MAR-00SAR-0SAR-0SAR-0SAR-2SAR
Bocro-4/Shahi (Ir64…Ste//Weebill1IRW2009-10-142-0Mar- -0MAR-00SAR-0SAR-0SAR-0SAR-2SAR
SN64//SKE/2*ANE/3/SX/4/BEZ/5/SERI/6/VORONA/HD2402/7/F10S-1/8/Rsk/Nac/Sardari/5/Lr64/Iz1813//093-4413/No57/4/Sul66/6/Cno67/Mfd//Mon"s"/3/Seri/4/Shahi /7/Desconciod-7IRW2009-10-204--0MAR-00SAR-0SAR-0SAR-0SAR-2SAR
SN64//SKE/2*ANE/3/SX/4/BEZ/5/SERI/6/VORONA/HD2402/7/F10S-1/8/Rsk/Nac/Sardari/5/Lr64/Iz1813//093-4413/No57/4/Sul66/6/Cno67/Mfd//Mon"s"/3/Seri/4/Shahi /7/Desconciod-7IRW2009-10-204-0Mar-0SAR-0SAR
SN64//SKE/2*ANE/3/SX/4/BEZ/5/SERI/6/VORONA/HD2402/7/F10S-1/8/Rsk/Nac/Sardari/5/Lr64/Iz1813//093-4413/No57/4/Sul66/6/Cno67/Mfd//Mon"s"/3/Seri/4/Shahi /7/Desconciod-7IRW2009-10-204--0MAR-00SAR-0SAR-0SAR-0SAR-6SAR
SARDARI-HD83//LINFEN875072/KAUZ/4/92 ZHONG 257//CNO79/PRL/3/ OK82282/ /BOW/NKTT IRW2009-10-214--0MAR-00SAR-0SAR-0SAR-0SAR-1SAR
SARDARI-HD83//LINFEN875072/KAUZ/4/92 ZHONG 257//CNO79/PRL/3/ OK82282/ /BOW/NKTT IRW2009-10-214--0MAR-00SAR-0SAR-0SAR-0SAR-1SAR
BITOP/MUFITBEY
ZUSTRICH/SELYANKA
KROSHKA/4/VORONA//MILAN/SHA7/3/MV17
JI5418/MARAS/4/1D13.1/MLT/3/LFN/SDY//PVN/5/GALLYA-ARAL1
BONITO-37//PYN/2*BAU
CITARI-9/MV18-2000//STARSHINA
FULLER/OVERLEY//KS980554-12-~9
KS020446TM~2/KS020469TM~1//KAJAGGER
CO050337-2/BYRD
DARI-14 (22 th ERWYT-C) -22
55.1744/7C//SU/RDL/3/CROW/4/VS73.600/MRL/3/BOW//YR/TRF/5/BLOYKA /6/ZARGANA-3
QUAIU//MILLENNIUM/NE93613
KUPAVA/7/AU/3/MINN//HK/38MA/4/YMH/ERA/5/PMF//CNO/GLL/6/KAUZ//ALTAR 84/AOS/8/DEMIR
ZCL/3/PGFN//CNO67/SN64/4/SERI/5/UA.2837/6/ATTILA/3*BCN/7/ZARGANA-6
BONITO-37/MV10-2000/3/SHI#4414/CROWS"//GKSAGVARI/CA8055
Manning/Sdv1//Dogu88-0YC-0YC-0YC-12YC-0YC



	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	July	June
A. Tem.	13.76	5.57	2.3	-2.5	-1.2	0.27	5.22	9.6	18.14	22.7
Rainfall	9.7	47	91.4	40.8	86.4	55.6	116.1	43.4	4.2	0

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	July	June
A. Tem.	13.4	4.4	1	-3.2	-6.19	2.7	5.08	11.4	18.35	22.8
Rainfall	21.6	4	27.8	67.6	24.9	58.6	80.1	42	0.2	0

Figure 1. Monthly average temperate (A. Temp.) and rainfall across growing season of 49 wheat genotypes at (A, above) the first year, 2019 and (B, blow) the second year, 2020

The drought resistance index of Lan (1998) was calculated as:

$$DI = Ys\,(Ys / Yp) / \bar{Y}s$$

The K_1STI and K_2STI (two forms of STI corrections) were computed as (Naderi *et al.* 1999):

$$K_1STI = [(Yp)^2 / (\bar{Y}_p)^2]\ STI$$

$$K_2STI = [(Ys)^2 / (\bar{Y}s)^2]\ STI$$

Also, the simplified forms of mean relative performance (MRP) and relative efficiency index (REI) of Hossain *et al.* (1999) were computed as follows:

$$MRP = (Ys / \bar{Y}p) + (Ys / \bar{Y}s)$$

$$REI = (Yp / \bar{Y}p)\ (Ys / \bar{Y}s)$$

The relative reduction (RR) was obtained according to the suggestion of Sadiki (2006):

$$RR = (Yp - Ys) / Yp$$

The abiotic tolerance index (ATI), stress susceptibility percentage index (SSPI) and stress non-stress production index (SNPI) were computed according to Moosavi *et al.* (2008) suggestions:

$$ATI = [(Yp - Ys) / [(\bar{Y}p / \bar{Y}s)]\ [\sqrt{(YpYs)}]$$

$$SSPI = [(Yp - Ys) / (2\bar{Y}p)]100$$

$$SNPI = [\sqrt[3]{(Yp + Ys) / (Yp - Ys)}][\sqrt[3]{(YpYsYs)}]$$

Principal component (PC) analysis was employed to estimate the general divergence among individuals based on the correlation matrix, which helps define patterns of variation according to stress indices. According to the results of PC analysis, the most similar stress indices, which represent the same information as well as non-responsive indices, were identified and removed for genotype by index (G×I) biplot analysis. The standardized values of the index's averages were computed to create the biplots through Model-2 of the GGEbiplot application (Yan 2001), which served as the foundation for the biplot analyses; that is, the data was stress indices-centered, within-stress indices square root of standardized variance, and not transformed. The vector view, which is good for visual analysis of the interrelationships among stress indices and genotypes, was used to decompose stress index-based singular values. In contrast, the polygon tool was used according to the singular value decomposition of genotype-focused values. Plotting the symmetric scaled values of the stress indices and genotypes results in G×I biplot images, where a marker represents each stress indices as a tester and genotype as an entry in the image.

3. Results

Analysis of variance indicated significant differences among wheat genotypes for yield in potential condition (Yp) and rainfed condition (Ys) across two years, so indicating substantial variability in their performance under different conditions (Table 2). Additionally, such significant differences were observed for most stress indices, highlighting diverse responses among the genotypes. A total of 91% (52 and 39% for the first two PCs, respectively) of the variability in the standardized data of the year 2019 was explained by the PC analysis (Figure 2A). According to this graph, some stress indices were completely correlated with each other and reflected the same information, so only one of them was used for the next G×I biplot analysis. In 2019, MRP, K$_2$STI, GMP, and REI indices were completely associated, and only GMP, the first introduced index, was selected. Also, regarding similar moods for STI, YSI, and RDI, only STI was chosen as the primary suggested index. Considering RR and SSI indices, Ys and YI indices, and SSPI and TOL indices, the most famous parameters (SSI, TOL and Ys) were selected for the next G×I biplot analysis. In the year 2020, 90% (47 and 43 for the PC1 and PC2, respectively) of the data variation was described by the PC analysis (Figure 2B). Based on the graph, K$_2$STI, GMP and REI indices were completely associated, and GMP was selected. Similar to the past year, regarding STI, YSI and RDI indices; RR and SSI indices; Ys and YI indices; MRP and HM; and SSPI and TOL indices, the most famous parameters (STI, SSI, TOL, HM and Ys) were selected for the next G×I biplot analysis in 2020 (Figure 2B). The correlations of DRI of SNPI indices with the yield in potential and rainfed circumstances, as well as the other stress indices, were not high due to the short length of related vectors, so they were also eliminated for the G×I biplot analysis.

Table 2. Analysis of variance for yield of potential and water stress conditions as well as stress tolerance indices

SOV	DF	YS	YP	DRI	SSI	RDI	PI	MP	TOL	YSI	STI	GMP
Y	1	3347968**	26069984**	18301386**	2.8504**	1.4380**	7.19E+11**	6012581**	5366207**	2.4581**	2.4581**	10192997**
R/Y	2	1093369	241740	1703306	0.8539	0.4308	1.72E+11	583905	334679	0.1473	0.1473	664321
G	48	591073**	1748421**	31138562**	0.9588**	0.4837**	7.24E+11**	718999**	1803684**	0.1654**	0.1654**	656886**
G×Y	48	162151**	491205**	10807760**	0.3510**	0.1771**	1.83E+11**	159912**	667091**	0.0605**	0.0605**	136165**
E	96	46869	40665	5096725	0.0574	0.0289	2.14E+10	30509	53017	0.0099	0.0099	33523

SOV	DF	HM	YI	DI	K$_1$STI	K$_2$STI	MRP	REI	RR	ATI	SSPI	SNPI
Y	1	8608585**	4.5926**	0.3500**	2.0740**	0.7028**	6.3609**	2.0559**	2.4581**	1.46E+12**	1258.3**	83540746**
R/Y	2	746419	0.3000	0.0478	0.6626	0.0633	0.4831	0.1852	0.1473	1.06E+11	78.5	53824138
G	48	637447**	0.1622**	0.2914**	0.5127**	0.1039**	0.4122**	0.3040**	0.1654**	4.03E+12**	423.0	606607930**
G×Y	48	130749**	0.0445**	0.1112**	0.1995**	0.0267**	0.0884**	0.0780**	0.0605**	1.49E+12**	156.4	253725358**
E	96	37636	0.0129	0.0207	0.0330	0.0036	0.0222	0.0105	0.0099	6.58E+10	12.4	59691960

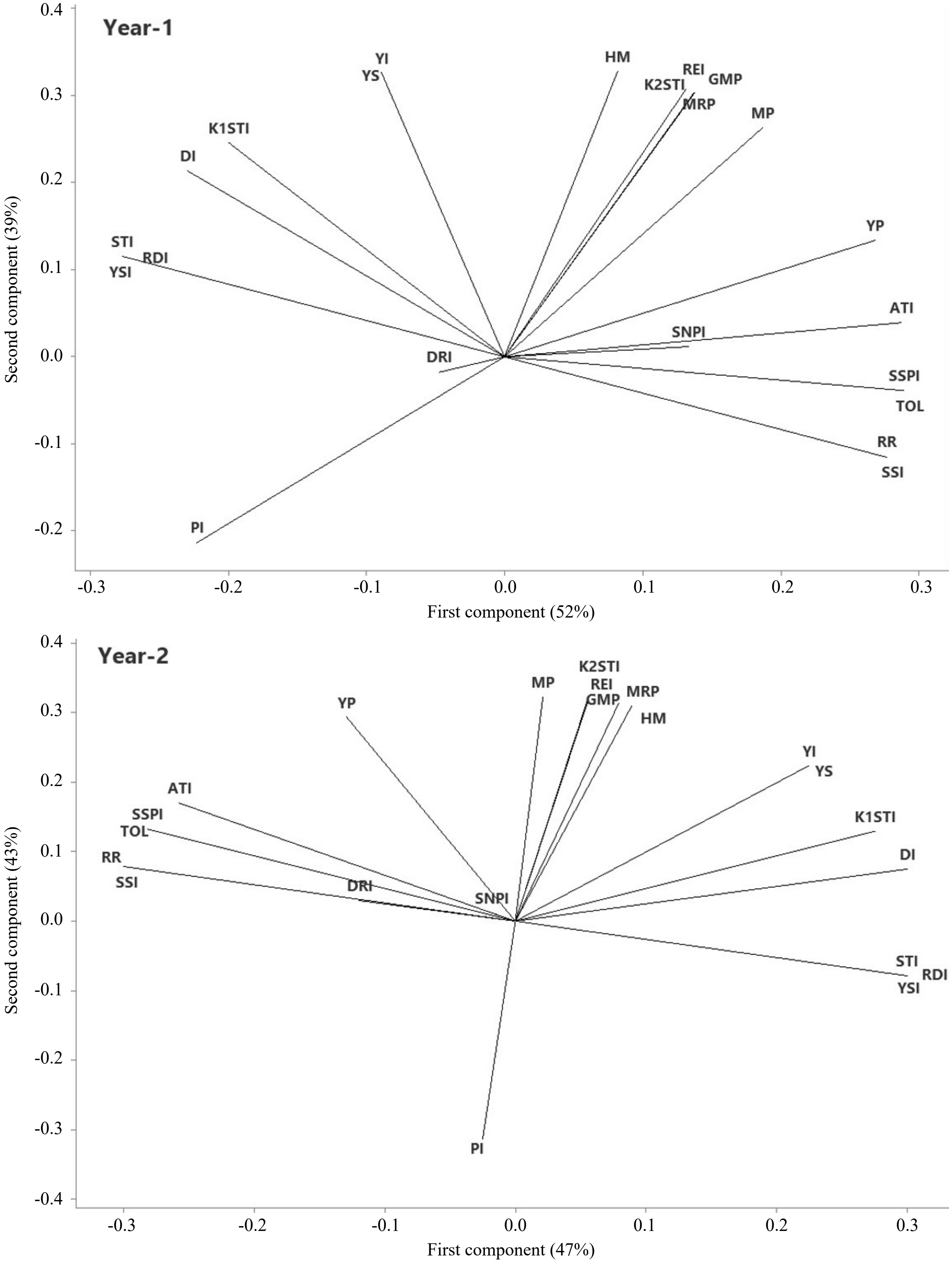


Figure 2. Principal components analysis of 20 stress indices which computed on 49 wheat genotypes at (A, above) the first year, 2019 and (B, blow) the second year, 2020

The G×I biplot analysis explained almost all the total data variability (99%, 58% and 41% due to PC1 and PC2, respectively) in the first year (Figure 3A). In the polygon-view graph, the wheat genotypes present within the section were defined via the lines that reach the center's origin, and the genotypes of each head were the best. In terms of yield performance in potential conditions (Yp), G33 (4,234 kg ha^{-1}) was the best genotype, suggesting that it can be used as the cultivar for obtaining high yield under non-stress conditions in 2019. Also, genotype G33 was identified as the best stress-tolerant genotype based on the MP stress index due to falling to the same section as Yp (Figure 3A). However, the head genotype, G4 (2,263 kg ha^{-1}), was the best one regarding yield performance in rainfed conditions (Ys). Also, genotype G4 was detected as the best stress-tolerant genotype based on STI, K_1STI and DI stress indices in 2019. Genotype G10 (2,425 and 3,533 kg ha^{-1}, in YS and Yp, respectively) was the best based on GMP and HM indices, and its section was located between sections of Yp and Ys, suggesting the function of these indices is the average of two conditions due to nature of their calculation. Genotype G25 was the best genotype based on SSI, TOL and ATI indices, while genotype G30 was the best genotype based on PI stress index in 2019. In addition, G40 was the vertex genotype; however, no stress index or yield performance was detected in either sector, suggesting that it is not exceptional for any of the indices or yield performances (Figure 3A).

In the second year (Figure 3B), the G×I biplot model described almost all the data variation (98%, 49% and 49% due to PC1 and PC2, respectively). In the polygon-view graph, six head genotypes, G7, G9, G15, G28, G40 and G49, were identified, whereas G9 (2,227 kg ha^{-1}) was the most favorable genotype in terms of Yp, while G15 (1,662 kg ha^{-1}) was the most favorable genotype in term of Ys. Also, genotype G15 was detected as the best stress-tolerant genotype based on HM, GMP and MP stress indices in 2020. Also, the head genotype, G49, was the best one, regarding K_1STI and DI indices, while genotype G28 was the best based on STI (Figure 3B). Genotype G7 was the best genotype based on SSI, TOL and ATI indices, while genotype G40 was the best genotype based on PI in 2020. The best genotypes of each year and the related section of the head genotypes varied year by year, suggesting the exitance of G×E (genotype × environment) interaction in performances of potential condition (Yp) and rainfed condition (Ys) across two years.

To make the relationships between and among the stress indices easier to see, some vectors are produced from the center of the graph to signs of the stress indices. In contrast, their length indicates how much of an impact on the other stress indices that are being measured. Thus, two stress indices have a positive correlation if there is a sharp angle and a negative correlation if there is an obtuse angle. Figure 4A illustrates the positive association among HM, GMP and MP, between DI and K_1STI, between SSI and TOL, between ATI and TOL, between ATI and YP, and between YS with DI and K_1STI in year 2019. These correlations imply that a single index like ATI may be able to detect the most favorable genotypes in potential conditions, and a single index like K_1STI may be able to identify the high-yielding genotypes in rainfed conditions. Also, YS with PI, SSI with PI, YS with ATI, SSI with HM, GMP and MP stress indices were not correlated due to the perpendicular angle of their vectors (Figure 4A). Also, regarding obtuse angle, SSI was correlated negatively with STI, while PI was correlated negatively with YP in the year 2019 (Figure 4A). In the second year (Figure 4B), positive associations were observed among HM, GMP and MP, among SSI, TOL and ATI, and between K_1STI and STI. Unlike the first year, a high correlation was not obtained for YP or YS with the stress indices in the year 2020.

Regarding perpendicular angle between vectors in the year 2020, there was not any significant correlation between PI with STI, between PI with SSI, TOL and ATI, between STI with HM, GMP and MP, among SSI, TOL and ATI with HM, GMP and MP (Figure 4B). Also, YS with PI, SSI with PI, YS with ATI, SSI with HM, GMP and MP stress indices were not correlated due to the perpendicular angle of their vectors (Figure 4A). Also, regarding obtuse angle, STI was correlated negatively with SSI, TOL and ATI, while PI was correlated negatively with HM, GMP and MP in the year 2020 (Figure 4B). Finally, due to the perpendicular angle between vectors of YP and YS in both years, there were not any meaningful correlations between performances in potential and rainfed conditions.

Examining the Performance of/at the Tester tool of the biplot model for YP in the year 2019 indicated that G32 (4,176 kg ha^{-1}) and G33 (4,234 kg ha^{-1}) were the best genotypes for obtaining high yield in potential conditions (Figure 5A). These genotypes were followed by G26, G25, G27, G22, and G39 genotypes, while the performance of the genotypes G4, G5 and G30 were the worst in the year 2019 (Figure 5A). Also, the

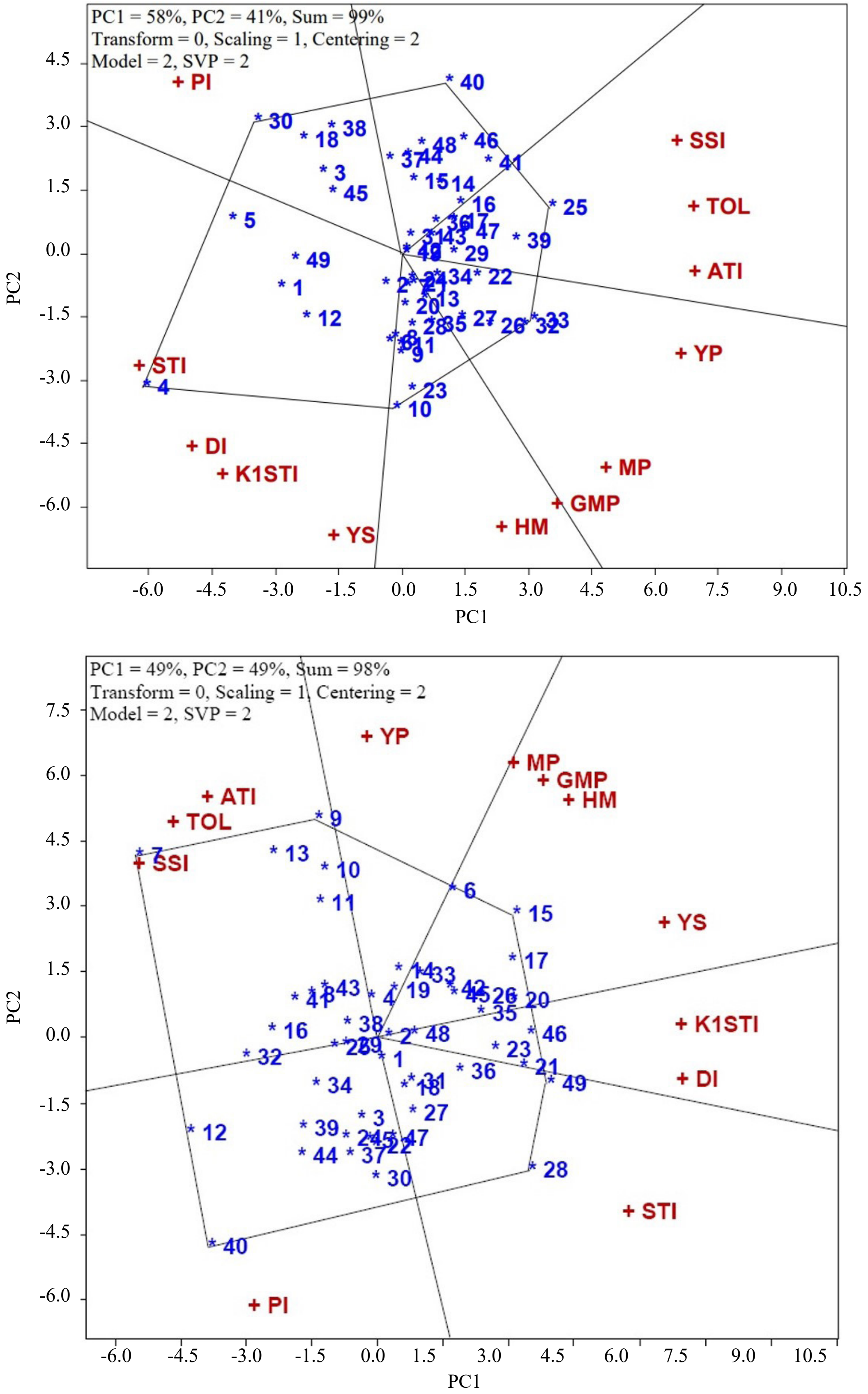


Figure 3. Polygon tool of the G×I biplot for 10 stress indices which computed on 49 wheat genotypes at (A, above) the first year, 2019 and (B, blow) the second year, 2020

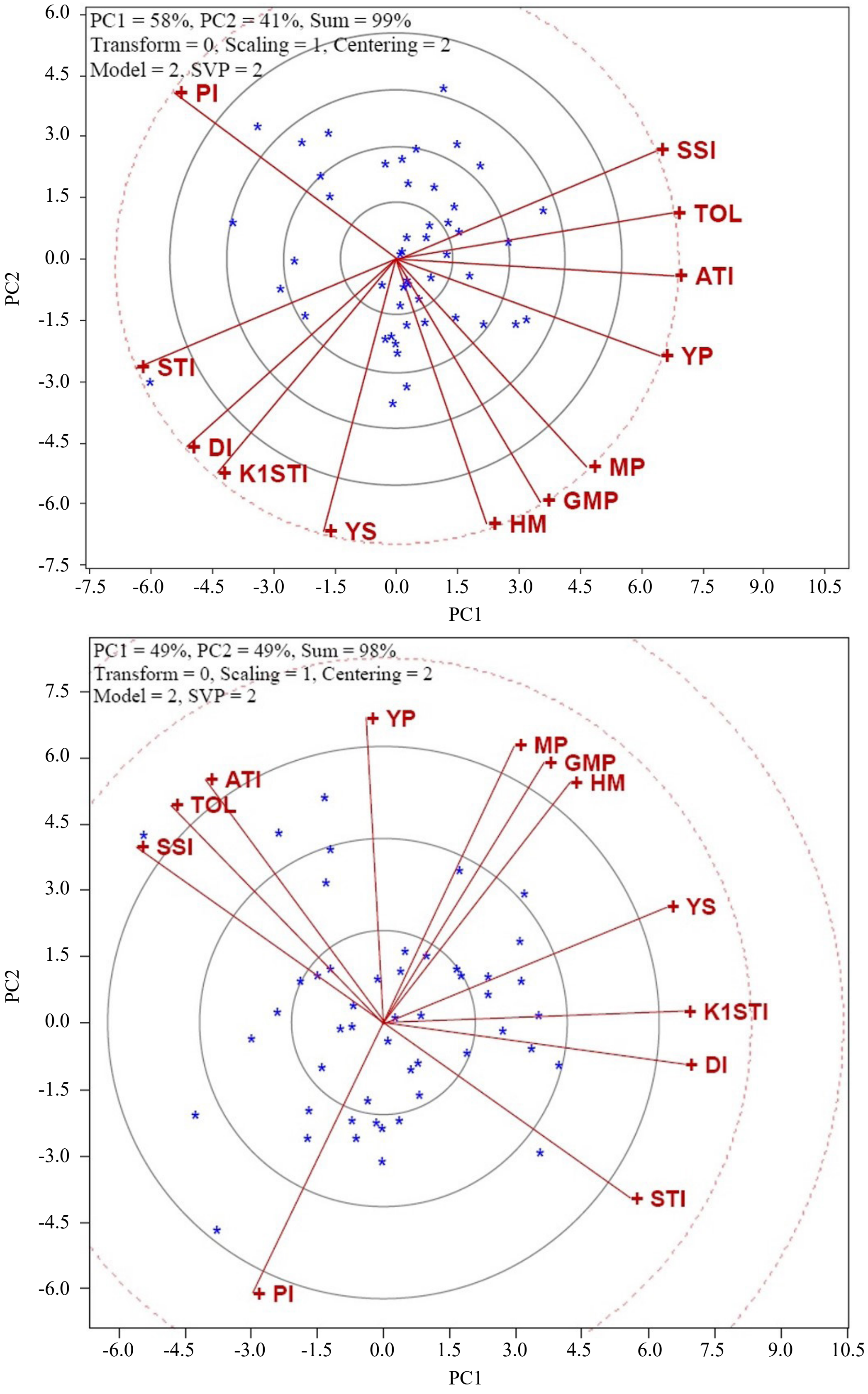


Figure 4. Vector tool of the G×I biplot for 10 stress indices which computed on 49 wheat genotypes at (A, above) the first year, 2019 and (B, blow) the second year, 2020

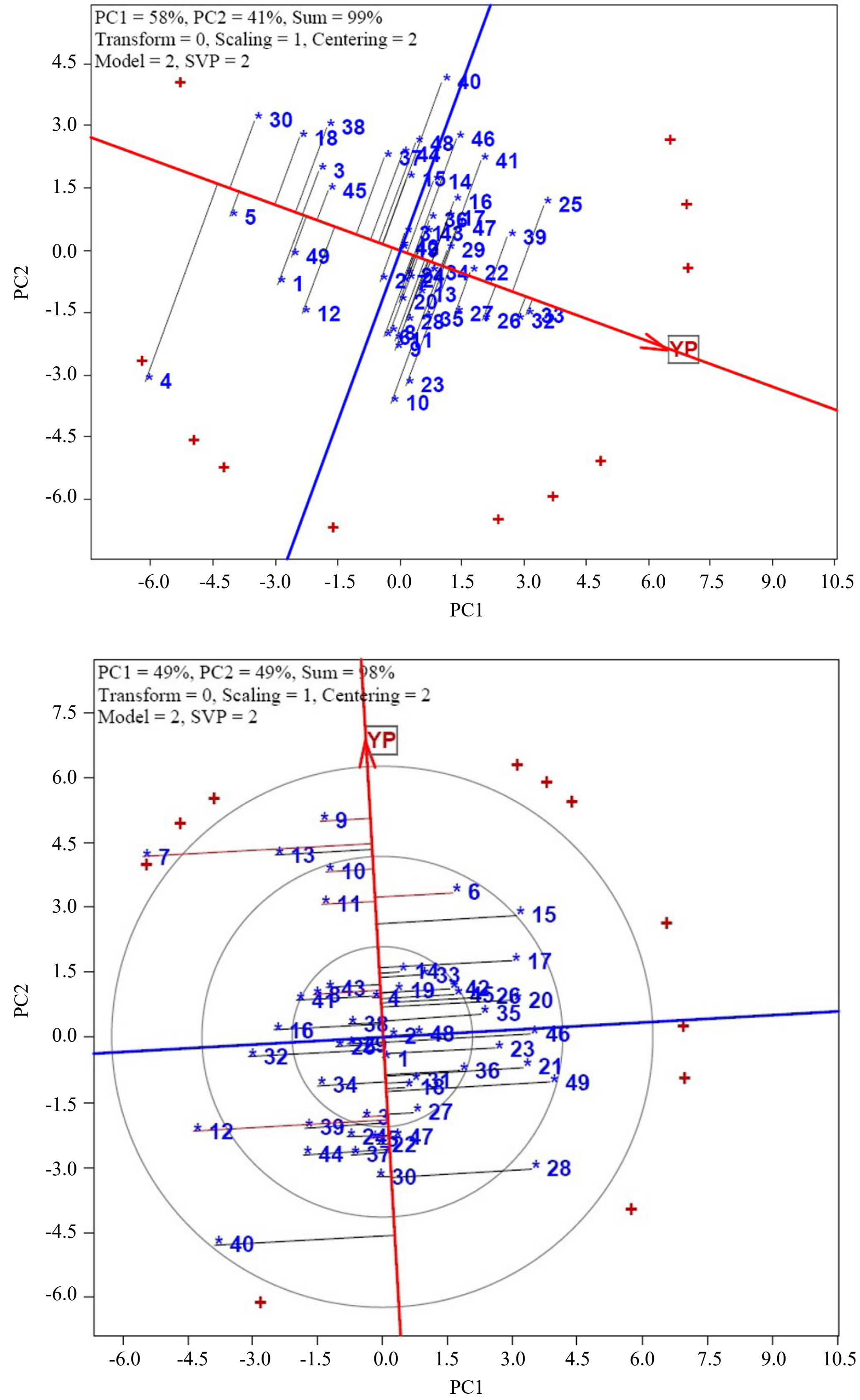


Figure 5. Examine of yield performance on potential condition (YP) through the G×I biplot across 49 wheat genotypes at (A, above) the first year, 2019 and (B, blow) the second year, 2020

performance of the genotypes, which were located in the above position of the blue line, was higher than the average of YP. In contrast, the genotypes in the blow position of the blue line were lower than the average of YP. In the year 2020, genotype G9 (2,227 kg ha^{-1}) was the best genotype for obtaining high yield in potential conditions, which was followed by G7, G13, G10, G11, G6 and G15 genotypes (Figure 5B). Also, the performance of the genotypes G40, G28, and G30 was the worst in 2020. A comparison of two years indicated that some genotypes such as G8, G14, G16, G17, G20, G35, G41 and G42 were located in the above position of the blue line and did not show GE interaction, so could be advised for wheat production in potential condition.

Similar to YP, the Examining of Performance of/at Tester tool of the biplot model was used for YS in the year 2019 and demonstrated that G4 (1,722 kg ha^{-1}) was the best genotype for obtaining high yield in rainfed conditions (Figure 6A). This genotype was followed by the G10, G23 and G9 genotypes, while the performance of the genotypes G40 and G46 were the worst in the year 2019 (Figure 6A). In the year 2020, genotype G15 (1,662 kg ha^{-1}) was the best genotype for obtaining high yield in rainfed conditions, followed by G17, G20, G46, and G49 genotypes (Figure 6A). Also, the performance of the genotypes G40, G12, and G7 was the worst in 2020. A comparison of two years indicated that some genotypes such as G4, G6, G9, G10, G11, G23, G26 and G33 were located in the above position of the blue line and did not show GE interaction, so could be advised for wheat production in rainfed condition.

4. Discussion

Drought stress decreases the crops' productivity, and breeding drought-tolerant cultivars is an important way to address the water shortage problem. Bread wheat, as a native crop to semi-arid environments, is suitable for production in such regions, so the genetic improvement of multi-purpose cultivars (high yielding, drought tolerant and quality) is a novel aspect in new breeding programs of wheat (Yahaya and Shimelis 2022). Several stress indices showed highly significant differences among genotypes, emphasizing the varied drought responses within the wheat population. Some studied indices, especially most of the newly introduced indices, including RDI (Fischer and Wood 1979), YSI (Bouslama and Schapaugh 1984), YI (Gavuzzi *et al.* 1997), K_2STI (Naderi *et al.* 1999), MRP and REI (Hossain *et al.* 1999), RR (Sadiki 2006), and SSPI Moosavi *et al.* (2008), did not give any new information regarding the previous indices, thus using of these indices are not devised. It can be verified via comparison of their statistical formulas due to their similar nature to the past methods. Afrooz *et al.* (2021) reported similar results for YI and RR indices in durum wheat and suggested K_2STI for the evaluation of drought-tolerant genotypes. Also, the DRI method of Bidinger *et al.* (1978) was not suitable for our dataset because the linear regression model was not fitted adequately, so it can be concluded that the DRI method may be useful where the dataset is fitted in a regression model. Such behavior was observed in the SNPI method, where the mathematical third root is the base of the formula, so this method was not good in the present dataset. We found some wheat genotypes [G6 (1,892 and 2,661 kg ha^{-1}), G9 (1,816 and 2,825 kg ha^{-1}), G10 (1,880 and 2,828 kg ha^{-1}) and G11 (1,772 and 2,693 kg ha^{-1}), for YS and YP across both years, respectively], demonstrated high performance in both potential and rainfed conditions across two years, without statistically significant differences from the best genotypes in each condition. It is noteworthy that achieving high performance in both rainfed and potential conditions is relatively uncommon but interesting (Sedri *et al.* 2019). The notable performances of specific genotypes in diverse humidity conditions underscore their potential resilience across a range of environmental stressors. The results highlighted the complex nature of water stress tolerance in wheat genotypes and emphasized the importance of considering multiple indices to evaluate their performance comprehensively under varying conditions. The discussion could delve further into the implications of these findings for wheat genetic improvement programs and the potential identification of genotypes with broad adaptability to different environmental conditions (Jan *et al.* 2023).

The polygon view of the biplot demonstrated that the yield in the potential condition (Yp) and yield in the rainfed condition (Ys) formed distinct sectors and were not positively correlated with each other across both years. Thus, breeding for new wheat cultivars must be performed separately in target environments. The vector view of the biplot indicated that mean-based indices (HM, GMP and MP) and DI with K_1STI were highly associated, and it can be proposed using one of them (for example, GMP and

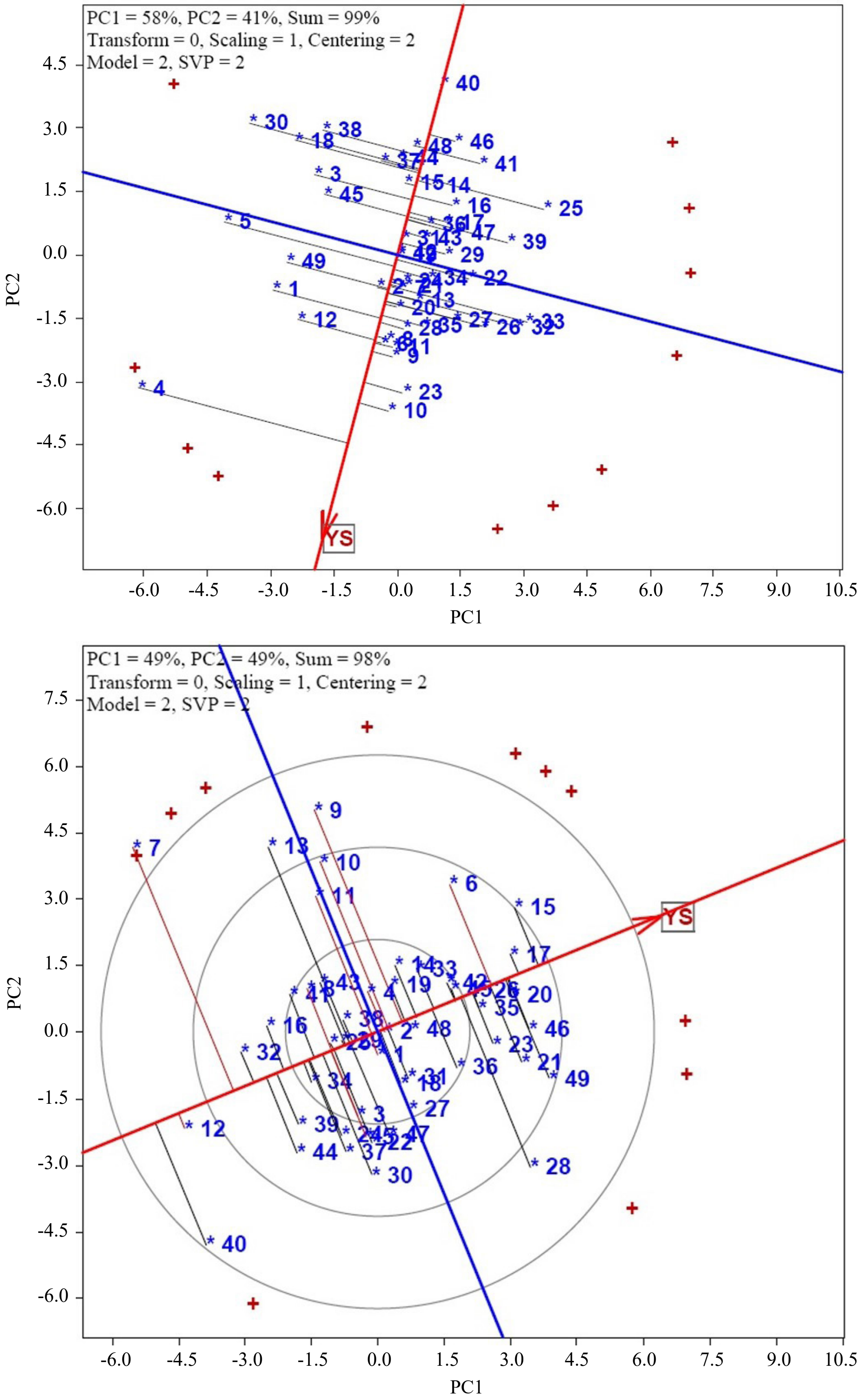


Figure 6. Examine of yield performance on water stress condition (YS) through the G×I biplot across 49 wheat genotypes at (A, above) the first year, 2019 and (B, blow) the second year, 2020

DI) could be sufficient in the screening of genotypes. The results of the Examining the Performance of/at Tester showed that some wheat genotypes can be selected for each potential or rainfed condition, ignoring G×E interaction effects like G7 and G8 for potential condition and G4 and G23 for rainfed condition. Also, we found that some wheat genotypes had above-average performances at both potential or rainfed circumstances across two experimental years, so ignoring the highest performance, they can be used at each humidity condition without concerns of G×E interaction.

The most favorable genotypes (G6, G9, G10 and G11) can be detected by mean-based indices (TOL, HM, GMP and MP) as well as SSI and ATI indices, so it can be concluded that these indices are more useful than other indices for identifying the most tolerant as well as the high yielding genotypes. Yehia (2020) mentioned MP, GMP and HM are the better prediction indices of yield performance in stressful and non-stressful environments than the other stress indices, whereas screening drought-tolerant genotypes using such indices detects the most tolerant and high-yielding genotypes so that they can be recommended for breeding of tolerance to water shortage. Similarly, Rabieyan *et al.* (2023) found that tolerant genotype selection acceding to MP, GMP, and HM can cause high-yielding genotypes to be obtained in water-stress environments. This investigation provided valuable insights into the interrelationships among different stress indices and underscored the importance of considering multiple parameters when assessing drought tolerance in wheat genotypes. The results contribute to the understanding of how various indices interplay and complement each other in evaluating the complex trait of drought tolerance. This research underscores the complex nature of drought tolerance assessment in wheat genotypes, highlighting the need for careful consideration of multiple indices and their interrelationships for comprehensive evaluation. These revelations furnish pivotal insights for plant breeding initiatives striving to cultivate wheat varieties fortified with heightened drought tolerance, thereby contributing to the pursuit of sustainable agriculture (Li *et al.* 2021). Suppose the strategy is to increase yield performance under stressful conditions. In that case, it may be possible to describe local adaptability to obtain acceptable gains from selecting, so selection should be according to the stress tolerance indices computed from the performance under potential and drought circumstances when the plant breeder is exploring the genotypes adapted for a stressful condition.

In conclusion, some studied indices, including RDI, YSI, YI, K2STI, MRP, REI, RR, and SSPI, indicated similar information regarding the previous indices, so using these indices is not devised. The identified wheat genotypes, particularly G6, G9, G10 and G11, emerge as promising lines for widespread commercial recommendation to farmers navigating diverse environmental terrains. The meticulous evaluation leveraging an array of drought tolerance indices (TOL, HM, GMP, MP, SSI and ATI) augments confidence in pinpointing genotypes endowed with expansive adaptability and resilience in the face of varying drought stress levels.

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