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Study of grain yield stability of four cereal crops grown under semi-arid environments

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Abstract

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In agriculture, stability is assessed by examining the variance across different environments to analyze genotype-by-environment interactions (GEI). To evaluate the grain yield stability of four cereal crops (durum wheat, bread wheat, barley, and oats) and identify high-yielding and consistent crops, a field experiment was conducted in the semi-arid zone of eastern Algeria over a period of ten cropping seasons (2010–2020). Parametric and nonparametric indices, calculated using the STABILITY-SOFT program, were utilized for this purpose. According to the regression coefficient (bi),Tichedrette and Waha genotypes exhibited high stability and adaptability with significant mean grain yield. Wifak and HD1220 bread wheat genotypes demonstrated stability across crop seasons based on various stability indices such as Wricke's ecovalence (Wi^2), Shukla's stability variance ($\sigma^2 i$) and GE variance component ($\theta_{(i)}$). Boussalem genotype showed exceptional stability across all stability parameters according to non-parametric indices. The relationships between the different stability statistics consistently separated two distinct categories and the principal component analysis placed Boussalem and Waha genotypes in the dynamic stability group with the highest grain yield. In conclusion, the Boussalem durum wheat genotype emerged as the most stable and well-adapted under semi-arid conditions, combining high grain yield and stability indices.

Keywords: Algeria; cereal; non-parametric; parametric; stability

Introduction

Climate change poses significant challenges to agricultural production, particularly crop production, due to its sensitivity to environmental factors. Fluctuating precipitation patterns, temperature changes, and extreme weather events create uncertainty in crop yields, making it difficult to maintain stable food production (Molnár & Molnárné, 2015). In Algeria, cereal cultivation dominates the agricultural sector, covering approximately 3.6 million hectares annually. Cereal production is estimated at around 3.5 million tons, with durum wheat accounting for 45%, barley for 28%, and bread wheat for 24% (Benbelkacem, 2013). Plant breeders commonly use the term «stability» to describe genotypes that exhibit consistent yields across different environments. This concept aligns with the idea of homeostasis in quantitative genetics and can be viewed as a static notion of stability (Becker & Leon, 1988).

However, a genotype that consistently performs in all environments may not necessarily exhibit increased yield under improved growing conditions. Assessing yield stability across multiple environments through multi-environment trials (MET) plays a crucial role in selecting the best cultivars and agronomic practices for future use (Mohammadi et al., 2010). Statistical analysis offers two main groups for interpreting genotype-environment interactions (GEI). The first group consists of parametric indices, such as regression coefficient (bi), variance of deviations from regression (S^2di), Wricke's ecovalence stability index (Wi^2), Shukla's stability variance (σi^2), environmental coefficient of variance (CVi), and yield stability index (YSi). These indices rely on assumptions about the distribution of genotypic, environmental, and GxE effects. The second group involves non-parametric or analytical clustering approaches that consider biotic and abiotic environmental factors without specific modeling assumptions. Examples include Nassar & Huhn's statistics ($S^{(1)}$ and $S^{(2)}$), Huhn's equation ($S^{(3)}$ and $S^{(6)}$), and Thennarasu's statistics (NP(i)). This study aims to compare the yield stability of four cereal crops (durum wheat, bread wheat, barley, and oats) using both parametric and non-parametric indices and identify high-yielding and stable crops under semi-arid conditions in Eastern Algeria.

Materials and Methods

Plant material and field conditions

The experiment took place at the LARBI ABASSI pilot farm in the eastern region of Algeria, specifically in the province of BORDJ BOU ARRERIDJ. The farm is situated at coordinates 4°76′E, 36°06′N, and an elevation of 930 meters above mean sea level. This area experiences a variable climate, characterized by cold springs and a drought towards the end of the plant's growth cycle, accompanied by hot winds known as siroco (Chourghal, 2016). The farm has moderately deep clayey sandy loamy soils with low organic matter content and a high limestone content, resulting in alkaline pH levels. The study involved four cereal species: three durum wheat genotypes (TD1-TD3), two bread wheat genotypes (TE1-TE2), one barley genotype (HV1), and one oat genotype (AS1). The genotypes tested in the respective crops are, on one hand, introduced into production and used by the farmers in the region, and on the other hand, their productivity potentials are distinct. The experiments were conducted over ten agricultural campaigns from 2010 to 2020 under rainfed conditions (Table 1 provides further details on genotypes and experimental conditions). A randomized complete design with three replicates was used, and the plot size was 7.2 m² (6 rows with a spacing of 20 cm and a row length of 6 m). Grain yield was evaluated in all environments following the appropriate technical practices for each crop.

Statistical Procedures

Statistical procedures were employed to assess the stability of the genotypes in this study. For the parametric indices, two stability parameters, namely the regression coefficient (bi) and the variance in regression deviations (S^2di), were calculated based on Eberhart & Russell (1966) concept of stability. A bi value greater than 1 indicated adaptability to favorable conditions, while a bi value less than 1 indicated adaptability to unfavorable conditions. A bi value of 1 indicated average adaptation to all environments. A stable genotype would have an S^2di value of 0, whereas a higher S^2di value indicated lower stability across all environments. Therefore, genotypes with lower S^2di values were considered more desirable. The ecovalence index (Wi^2), proposed by Wricke (1962), was used as a measure of stability, representing a genotype's contribution to the interaction sum of squares. A lower Wi^2 value indicated higher relative stability. Stability was also evaluated by combining the coefficient of variation (CV) and mean yield, where genotypes with low CV and high yield were considered preferable (Francis & Kannenberg, 1978).

The variance component of genotype-environment interactions (θi) was proposed by Plaisted & Peterson (1959)

Table 1. Genotype code, specie's name and origine, environmental code, cropping season and precipitation

Genotype				Environment		
Code	Specie	Name	Origine	Code	Cropping season	Rainfall
TD1	*Triticum turgidum* var. *durum*	Boussalem	CIMMYT-ICARDA	E1	2010–2011	474.98
TD2	*Triticum turgidum* var. *durum*	MBB	INRA Algeria	E2	2011–2012	302.77
TD3	*Triticum turgidum* var. *durum*	Waha	CIMMYT	E3	2012–2013	392.93
TE1	*Triticum aestivum* L.	HD1220	ITGC Sétif	E4	2013–2014	286.51
TE2	*Triticum aestivum* L.	Wifak	Cimmyt	E5	2014–2015	318.05
HV1	*Hordeum vulgare* L.	Tichedrette	ITGC Sétif	E6	2015–2016	237.74
AS1	*Avena sativa*	Avon	Australia	E7	2016–2017	341.35
				E8	2017–2018	339.08
				E9	2018–2019	280.07
				E10	2019–2020	243.97

as a stability measure. A lower value of θi indicated greater stability. Similarly, the GE variance component $\theta_{(i)}$ was calculated by removing the ith genotype from the dataset and evaluating the GEI variance of the remaining subset. Genotypes with higher values of $\theta_{(i)}$ were considered more stable. Shukla's stability variance (σ^2i) (1972) quantified the variance of genotype i across environments after removing the main effects of environmental means. Genotypes with the minimum values of σ^2i were considered more stable. Non-parametric methods were also employed to assess genotype stability based on the classification order of genotypes by environment. Huhn (1990) and Nassar & Huhn (1987) proposed four non-parametric statistics: $S^{(1)}$ represented the mean of the absolute rank differences of a genotype across all tested environments, $S^{(2)}$ measured the variance among ranks across environments, $S^{(3)}$ calculated the sum of absolute deviations for each genotype relative to the mean of ranks, and $S^{(6)}$ evaluated the sum of squares of ranks for each genotype relative to the mean of ranks. Lower values of these statistics indicated higher stability for a genotype. Thennarasu (1995) introduced four alternative non-parametric stability statistics (NP1-NP4) based on the ranks of adjusted means in each environment. Low values of these statistics indicated high stability. Kang's rank-sum (Kang, 1988) combined yield and σ^2i as selection criteria, assigning equal weight to both. The genotype with the highest yield and lowest σ^2i was ranked first, and the ranks of yield and stability variance were summed for each genotype. Genotypes with the lowest rank-sum were considered the most desirable.The data were analyzed using the online software STABILITYSOFT, developed by Pour-Aboughadareh et al. (2019).

Results and Discussion

Mean yield and stability performance

Parametric measures

The genotypic mean yield data and stability measures (Table 2) were utilized to analyze the stability of the four cereal crops. The regression coefficient (bi) values ranged from 1.21 for genotype TD1 to 0.87 for genotype AS1, indicating that each species responded differently to environmental changes. The interpretation of this parameter suggests that genotypes with low values (bi < 1) exhibit greater resistance to environmental fluctuations and are better suited to low-yielding environments, as observed for the oat genotype AS1. Conversely, genotypes with high values (bi > 1) display a greater specificity of adaptability to high-yielding environments, as seen in the case of the durum wheat genotype TD1. The graphical distribution (Figure 1) between the regression coefficient and the average grain yield of the studied species further confirmed that genotypes HV1 and TD3 are the most stable and adaptable, exhibiting high grain yield under these conditions.

On the other hand, genotype AS1 displayed a high CVi value and was classified as an unstable genotype with the lowest mean grain yield (0.97). This analysis revealed that the adapted and stable genotypes with high mean grain yield under these conditions are TD3, TD1, and HV1. Among them, TD3 had the lowest CVi value (43.58), with a bi value close to unity (0.97), a low S^2di value (8.30), and a mean grain yield of 1.58 (compared to the general mean of 1.32). Hence, TD3 can be considered the most stable genotype according to the criteria set by Finlay & Wilkinson (1963)

Table 2. Mean grain yield ($t.ha^{-1}$) and Parametric stability index for the four cereal tested under semi-arid conditions

Genotype	Y	b_i	s^2d_i	σ^2_i	W_i^2	CVi	$\theta_{(i)}$	θ_i
Durum wheat								
TD1	1.65	1.21	5.60	7.44	57.34	50.16	7.39	8.15
TD2	1.28	0.98	15.73	15.68	110.33	57.30	6.01	11.59
TD3	1.58	0.97	8.30	7.61	58.40	43.68	7.36	8.22
Bread wheat								
TE1	1.13	0.92	6.24	5.70	46.16	57.25	7.68	7.43
TE2	1.20	1.02	2.19	0.94	15.56	57.53	8.47	5.44
Barley								
HV1	1.39	1.03	9.24	8.63	65.00	52.48	7.19	8.65
Oat								
AS1	0.97	0.87	5.61	5.75	46.45	62.64	7.67	7.45
Mean	1.32	1.00	7.56	7.39	57.03	54.44	7.39	8.13
Standard deviation	0.24	0.11	4.24	4.42	28.45	6.20	0.74	1.84

Y: Mean Grain Yield ($t.ha^{-1}$), bi: Regression coefficient, S^2di: Deviation from regression, σ^2_i: Shukla's stability variance,Wi²: Wricke's ecovalence index, CVi: Environmental coefficient of variance, $\theta_{(i)}$: GE variance component, θi: Mean variance component.

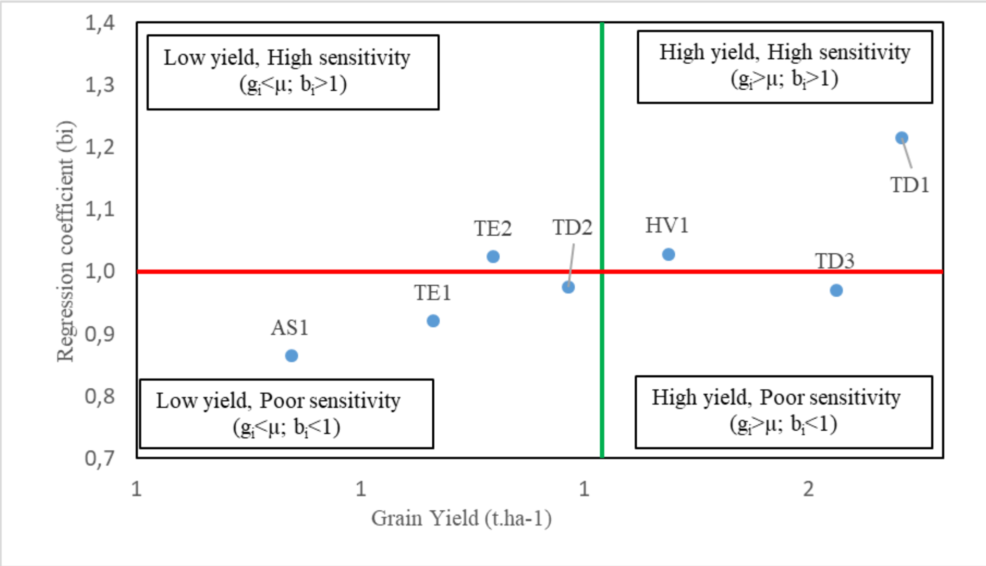

Fig. 1. The relationship between the regression coefficients and mean grain yield (t.ha^{-1}) for tested genotypes

and Eberhart & Russell (1966), who define stable genotypes as those with a high average yield, a regression coefficient equal to unity (bi = 1), and small deviations from the regression (S^2di = 0). The values of deviation from regression (S^2di) classified genotype TE2 as the most desirable, despite its lower mean grain yield (1.20) compared to the overall average. Furthermore, the selection of adapted and stable genotypes based on Wricke's ecovalence stability index (Wi^2), Shukla's stability variance (σ^2i), GE variance component ($\theta_{(i)}$), and mean variance component (θi) revealed that the bread wheat genotypes TE2 and TE1 had smaller deviations from the mean across cropping seasons and exhibited higher stability (Table 2). In contrast, genotypes HV1 and TD1 displayed high values and were categorized as unstable genotypes under these conditions. Several studies have validated the effectiveness of utilizing these parametric indices to select adapted and stable barley genotypes (Ramla et al., 2016; Verma et al., 2019) as well as stable durum wheat genotypes (Guendouz & Hafsi, 2017).

The non-parametric measures Si$^{(1)}$, Si$^{(2)}$, Si$^{(3)}$, and Si$^{(6)}$ developed by Nassar & Huhn (1987) were used to assess the stability of the genotypes based on their ranks across environments. According to these measures, the TD1 genotype (Boussalam) was identified as the most stable genotype, displaying the lowest Si values among all the cultivars and the highest grain yield of 1.65 t.ha^{-1}. On the other hand, the TD2

Table 3. Mean grain yield (t.ha^{-1}) and Non-parametric stability index for the four cereal tested under semi-arid conditions

Genotype	Y	S$^{(1)}$	S$^{(2)}$	S$^{(3)}$	S$^{(6)}$	NP$^{(1)}$	NP$^{(2)}$	NP$^{(3)}$	NP$^{(4)}$	*K*R
Durum wheat										
TD1	1.65	0.89	0.62	0.90	1.03	1.60	0.45	0.32	0.14	5.00
TD2	1.28	2.36	4.49	8.78	3.65	1.90	0.29	0.51	0.51	11.00
TD3	1.58	1.64	2.04	3.29	2.14	1.70	0.40	0.35	0.29	7.00
Bread wheat										
TE1	1.13	1.22	1.12	3.74	3.33	1.70	1.12	0.72	0.45	8.00
TE2	1.20	1.38	1.56	4.67	2.67	0.80	0.40	0.37	0.46	6.00
Barley										
HV1	1.39	2.02	2.99	6.90	3.44	1.80	0.43	0.55	0.52	9.00
Oat										
AS1	0.97	0.91	0.68	3.59	4.12	1.90	1.20	1.25	0.54	10.00
Mean	1.32	1.49	1.93	4.55	2.91	1.63	0.61	0.58	0.42	8.00
Sd	0.24	0.55	1.40	2.58	1.05	0.38	0.38	0.33	0.15	2.16

Y: Mean Grain Yield (t.ha^{-1}), S$^{(1)}$ and S$^{(6)}$: Nassar and Huhn's non-parametric statistics, NP$^{(1)}$ and NP$^{(4)}$: Thennarasu's non-parametric statistics, *K*R: Kang's rank-sum

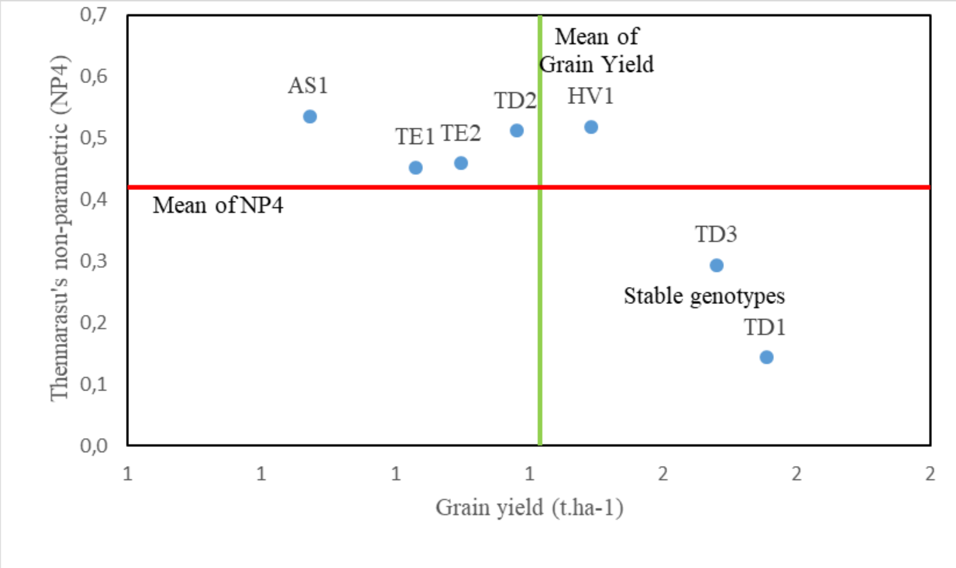

Fig. 2. The relationship between the Thennarasu's non-parametric index (NP4) and mean grain yield ($Q.ha^{-1}$) for tested genotypes

and HV1 genotypes had the highest Si values for all four indices, indicating their instability (Table 3). According to the non-parametric index developed by Thennarasu (1995), the TD1 and TD3 genotypes of durum wheat were identified as the most stable among all the tested genotypes, exhibiting low values for the $NP^{(1)}$, $NP^{(3)}$, and $NP^{(4)}$ indices, along with the highest mean grain yield (Table 3). Conversely, the AS1 oat genotype displayed the highest values for all four non-parametric indices, indicating its lower stability. These results are also evident in the graphical classification based on the distribution between the non-parametric Thennarasu index and the average grain yield of the tested genotypes in Figure 2. The values of Kang's rank-sum (*K*R), which consider both yield and stability statistics, ranged from 1 for TD1 to 6 and 7 for the genotypes AS1 and TD2, respectively (Table 3). Based on the *K*R values, the TD1 genotype is considered the most stable with the highest mean yield.

Stability indices and genotype ranking

The analysis of stability parameters revealed differences in genotype rankings, indicating that different stability parameters have varying abilities to discriminate between genotypes. Among the parametric indices (Wi^2, $\sigma^2 i$, $\theta_{(i)}$, and θi), as well as the non-parametric indices ($S^{(1)}$ and $S^{(2)}$), similar genotype rankings were observed. The top two and bottom two genotype rankings based on each stability index for each crop species are presented in Table 4. The TD1 genotype, corresponding to the Boussalem variety of durum wheat, consistently ranked among the top two genotypes for the majority of stability parameters (11 out of 16) as well as for average yield, indicating its high stability performance. The TE2 genotype also ranked among the top two for seven out of the sixteen stability parameters. On the other hand, the TD2 genotype was considered the least stable according to eleven stability indices, followed by the AS1 genotype with eight out of the sixteen parameters studied (Table 4).

Interrelationships among stability measures

Figure 3 illustrates the Spearman rank correlation coefficients between the sixteen stability methods and the average yield. Strong correlations were observed among several important relationships, including b_i, CVi, $S^{(6)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, and average grain yield, which constitute group 1. Previous studies have also reported a significant correlation between $S^{(6)}$ and $NP^{(2)}$ as well as $NP^{(4)}$ (Pour-Aboughadareh et al., 2019). Another group, designated as group 2, consists of W_i^2, σ^2_i, s^2d_i, $S^{(1)}$, $S^{(2)}$, $S^{(3)}$, $\theta_{(i)}$, and θ_i (Figure 3). Our findings align with those of Bouchareb & Guendouz (2021), who discovered significant negative correlations between wheat grain yield and $S^{(6)}$, $NP^{(2)}$, and $NP^{(4)}$, suggesting that selection based on these stability parameters may be less valuable when the primary breeding objective is yield. In our study, *K*R demonstrated significant correlations with all the indices used (Figure 3). However, $NP^{(1)}$ correlated with the parametric indices W_i^2, σ^2_i, s^2d_i, $\theta_{(i)}$, and θ_i, but not with yield or the non-parametric indices. According to Kilic (2012), this suggests that these parameters play similar roles in classifying genotype stability. The indices in group 1 are closely correlated with average yield and are associated with the dynamic concept of stability, while the indices in group 2 are not linked to average yield and can be defined in terms of homeostasis. There was also no correlation observed be-

Table 4. Comparison of stability indices in the discrimination of best and worst ranked genotypes within and between the crop species

Parameter	Genotype ranking				Non-Parametric index	Genotype ranking			
	1st	2nd	6th	7th		1st	2nd	6th	7th
Y	TD1	TD3	TE1	AS1	$S^{(1)}$	TD1	AS1	HV1	TD2
Parametric index					$S^{(2)}$	TD1	AS1	HV1	TD2
bi	TD1	HV1	TE1	AS1	$S^{(3)}$	TD1	TD3	HV1	TD2
W_i^2	TE2	TE1	HV1	TD2	$S^{(6)}$	TD1	TD3	TD2	AS1
σ^2_i	TE2	TE1	HV1	TD2	$NP^{(1)}$	TE2	TD1	TD2	AS1
s^2d_i	TE2	TD1	HV1	TD2	$NP^{(2)}$	TD2	TD3	TE1	AS1
CVi	TD3	TD1	TE2	AS1	$NP^{(3)}$	TD1	TD3	TE1	AS1
$\theta_{(i)}$	TE2	TE1	HV1	TD2	$NP^{(4)}$	TD1	TD3	HV1	AS1
θ_i	TE2	TE1	HV1	TD2	*K*R	TD1	TE2	AS1	TD2

Y: Mean Grain Yield ($t.ha^{-1}$), Wi^2: Wricke's ecovalence index, σ^2_i: Shukla's stability variance, bi: Regression coefficient, S^2di: Deviation from regression, CVi: Environmental coefficient of variance, $\theta_{(i)}$: GE variance component θi: Mean variance component, $S^{(1)}$ and $S^{(6)}$: Nassar and Huhn's non-parametric statistics, $NP^{(1)}$ and $NP^{(4)}$: Thennarasu's non-parametric statistics, *K*R: Kang's rank-sum.

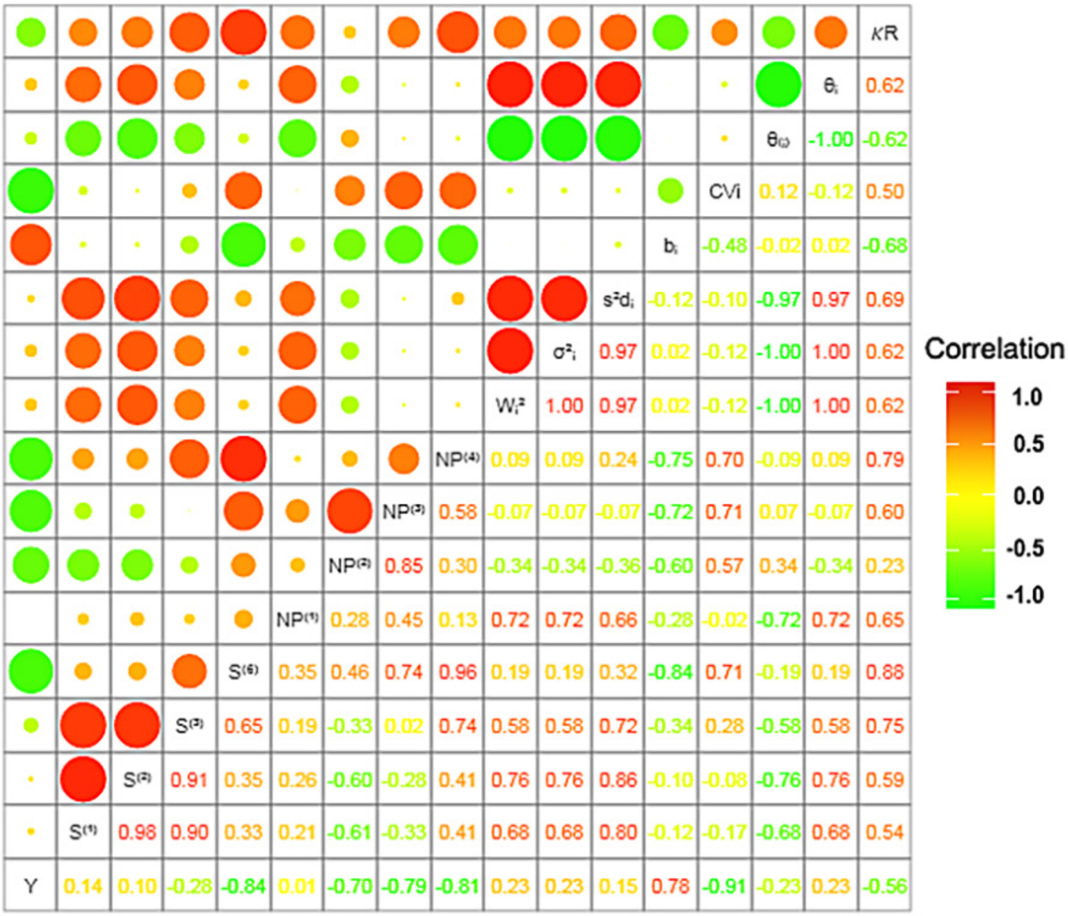

Fig. 3. Spearman's coefficients of rank correlation between mean yield and the sixteen stability measures tested during this study

tween the methods in groups 1 and 2. Our results are consistent with those of Mohammadi et al. (2010), who conducted a study in Iran involving three crops (durum wheat, bread wheat, and barley), and found no association between the group comprising Pi, GAI, and grain yield, and the group comprising ASV, S^2di, and Wi^2.

Principal component analysis of the rank correlations

To examine the relationships between parametric and nonparametric stability parameters, we employed principal component analysis (PCA) based on the rank correlation matrix (Figure 4). The results of this analysis revealed that the first and second principal components accounted for 48.34% and 34.35% of the variance, respectively, totaling 82.59% of the original variance among the stability parameters. Our findings align with similar studies conducted by Guendouz & Bendada (2022) on barley and Kilic et al. (2010) on durum wheat. Becker & Leon (1988) proposed categorizing measures of yield stability into static and dynamic approaches to describe how genotypes respond differently to varying environments. In the principal component analysis, genotypes TD1 and TD3 were classified into the dynamic stability group due to their high grain yield and bi parametric index values. Conversely, the least productive genotypes, AS1 and TE1, characterized by their high values of CVi, $NP^{(2)}$, $NP^{(3)}$, and $S^{(6)}$, formed a group with lower performance. The genotypes HV1 and TD2, with acceptable grain yield, were placed in the static stability group, determined by the indices W_i^2, σ^2_i, s^2d_i, $S^{(1)}$, $S^{(2)}$, $S^{(3)}$, and θi. Static genotypic stability refers to a stable genotype that consistently performs well under various environmental conditions. However, farmers may not prefer this type of stability as it implies a genotype would not respond to different levels of inputs such as fertilizer, temperature, and humidity (Becker & Leon, 1988).

Conclusion

Stability analysis of four cereal crops was conducted using data on mean grain yield and stability measures. The durum wheat genotypes, TD1 and TD3, exhibited the highest yielding abilities, and selection of stable and adapted genotypes based on parametric and non-parametric indices consistently ranked TD1 as the most stable genotype. The relationships between different stability statistics revealed the existence of two distinct groups: one comprising b_i, CVi, $S^{(6)}$, $NP^{(2)}$, and average yield, and the other including Wi^2, σ^2_i, s^2d_i, $S^{(1)}$, $S^{(2)}$, $S^{(3)}$, $\theta_{(i)}$, and θ_i. Principal component analysis further placed TD1 and TD2 genotypes in the dynamic

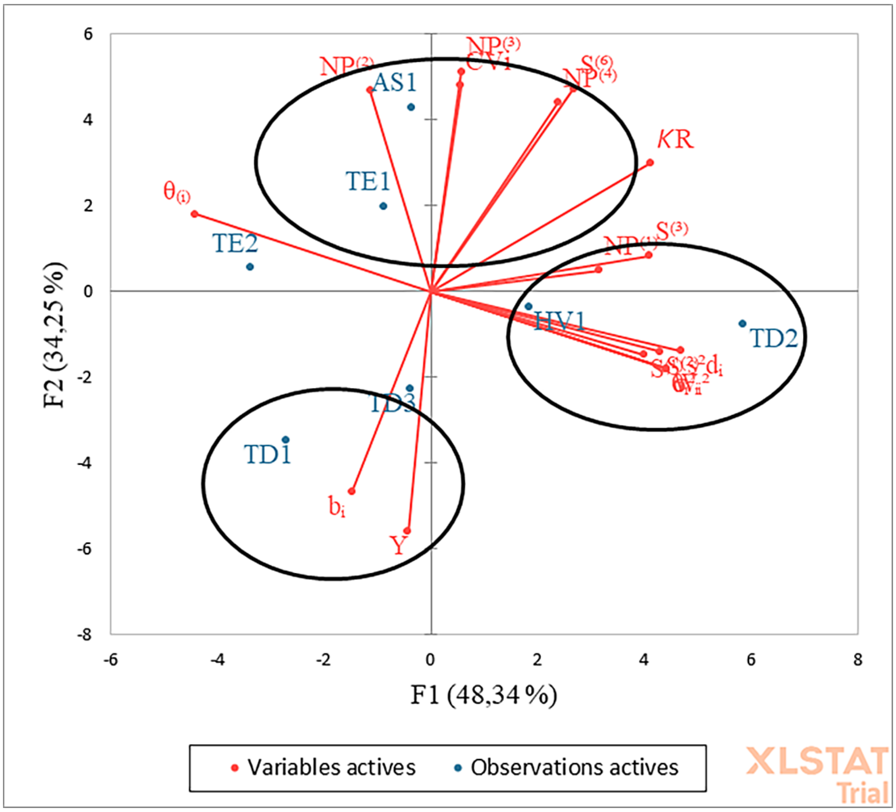

Fig. 4. Biplot of IPC1 (F1) and IPC2 (F2) of the rank correlation matrix of the stability parameters with grain yield and genotypes tested

stability group with the highest grain yield, while HV1 and TD2 genotypes were categorized in the static stability group. The findings of this study indicate that both parametric and non-parametric methods were effective in identifying stable genotypes across various environmental conditions.

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