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Stability analysis and genotype×environment interaction study for grain yield of some barley genotypes

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Abstract

Analysis of the genotype×environment (GE) interaction of barley (*Hordeum vulgare* L.) can aid in detecting genotype performance better under diverse and harsh environments. Sixteen advanced breeding lines and two cultivars were tested across five locations at Gachsaran, Gonbad, Ilam, Lorestan and Mughan districts during three years of 2017 to 2019. Stability analysis was determined using 19 different variance and regression methods with 26 univariate statistics because each method explores stability from different aspects and all of them can reflect a comprehensive stability characteristic of genotypes. The result showed that environment, genotype and GE contributed 92, 2 and 8% of the total variation and there is no strongest genetic control. According to the GE sum squares-based parameters, genotypes G13, G12 and G15 were more stable. The coefficient of line slope and residual variance of common and adjusted linear regression, manifested G1, G2, G12 and G18 as the most stable and responsive genotypes. The selective value of genotype (SVG) identified G6, G10 and G11 as the most stable genotypes while G2, G5 and G13 were the most stable genotypes based on superiority measure (SM). According to H parameter, genotypes G2, G13 and G18 were identified as the most stable genotypes while the dynamic CV and dynamic regression introduced G3 and G15 as the most stable genotypes. The relative superiority (RS), proposed G1, G2 and G5 as the most stable genotypes. Finally, H statistic, RS and SM could be recommended for stability analysis in future breeding programs for the simultaneous selection of yield and stability.

***Key words*: Multi-environmental trials, Regression models, Stable genotype, Univariate statistics.**

INTRODUCTION

Barley (*Hordeum vulgare* L.) is used for brewing and is also considered as food in some regions, which makes it one of the most important cereals in the world. It was grown on over 48 million ha worldwide in 2018 (FAOSTAT, 2018). Global barley production is approximately 141 million tons and the main producers are Russian Federation, 12%; Germany, 8%; France, 7% and Australia 7% (FAOSTAT, 2018). Iranian barley breeders improved grain yield as well as other important traits such as drought tolerance which has led to the release of the most favorable improved varieties and has made barley attractive to local farmers and led to its broader extension. Barley production was about 1290 kg ha^{-1} average yield under rain-fed conditions in Iran, while its average yield under irrigation conditions was 3788 kg ha^{-1} (Paknejad *et al.,* 2017).

The genotype×environment (GE) interaction is the response of each genotype to environmental variations and it has been one of the important issues in genetic improvement, permitting the invention of different procedures for the selection and recommendation of the most stable genotypes (Sabaghnia *et al*., 2011; Maniruzzaman *et al.,* 2019). Also, understanding the GE interaction aids plant breeders to explore specific adaptations especially in complex characters like yield which has led to the development of various statistical models for stability analysis. These statistical models have their own benefits and disadvantages which have been reviewed previously (Lin *et al*., 1986; Florest *et al*., 1998; Sabaghnia, 2010). Lin *et al*. (1986) evaluated environmental variance, environmental coefficient of variation (by Francis and Kannenberg, 1978), method of Plaisted and Peterson (1959), the parameter of Plaisted (1960), ecovalance of Wricke (1962), stability variance of Shukla (1972), regression models of Finlay and Wilkinson (1963), Eberhart and Russell (1966), and Perkins and Jinks (1968). Hanson (1970) developed genotypic stability based on the concept of a genotypic stability space and Tai (1971) suggested partitioning the GE interaction effect into stability statistics as α and λ, according to the principles of structural relationship analysis. An independent regression model with an independent environmental index was developed by Freeman and Perkins (1971) while Pinthus (1973) improved linear regression model by using another regression parameter as the coefficient of determination. Another selection value of genotype-based was developed by Kilchevskii (1985) on both genotypic and the GE effects.

Lin and Binns (1988) developed a superiority measure based on superiority measure and MS of GE interaction and Martynov (1990) developed H statistic according to weighted sum of standardized deviations from the mean in each environment. Muir *et al*. (1992) partitioned the GE interaction effect into heterogeneity variance and the incomplete correlation and suggested using incomplete correlation for stability analysis and Lidansky *et al*. (1997) calculated mean, variance and coefficient of variation via their dynamic method and suggested stability analysis using dynamic coefficient of variation. Lidansky *et al*. (1998) developed another regression model as dynamic regression and used its line slope and residual MS for detection of the most stable genotypes while Kamidi (2001) proposed a relative superiority index based on genotypic correlation and line slope of linear regression for stability analysis.

Sabaghnia *et al.* (2013) investigated the stability of 16 barley genotypes and introduced G4 and G12 with yield of 3.4 t ha^{-1} as the most stable genotypes based on environmental variance, environmental coefficient of variation and regression model of Eberhart and Russell (1966). Although, each procedure gave a mark of stability, most breeders preferred to use more than one procedure for precise evaluation and there is no meeting among breeders as to which procedure is the best (Sabaghnia *et al*., 2013). In the other study, Ramla *et al.* (2016) examined the yield stability of barley double haploid lines across multi-environments through univariate statistical analysis and revealed the significant correlations within the two groups of parameters of static stability concept and reliability of univariate analysis.

The major objective of this research was to grasp the adaptation of barley genotypes across rainfed conditions of Iran with a Mediterranean type climate. This research employs various univariate stability parameters based on variance components as well as regression models to evaluate the significance of the GE interactions on grain yield, determine the best genotype, and discuss the concept of the GE interactions to barley breeding, because each method explores the stability from different aspects and all together can reflect a comprehensive stability characteristics of genotypes.

MATERIALS AND METHODS

Plant materials consisted of two barley check cultivars “Mahour” and “Khorram” and 16 inbred lines (Table 1) developed by self-pollination of selected individuals from different gene pools in Dryland Agricultural Research Institute of Iran. The study was carried out during three growing seasons (2017-2019) at the experimental fields of the DARI in the Gachsaran, Gonbad, Ilam, Lorestan and Mughan stations with variable climatic and geographic conditions (Table 2). The field trials in all environments (year-location) were arranged in a randomized complete block design with four replicates. Seeds were sown by hand in six rows,

Table 1. Code and pedigree of studied barley genotypes.

Code	Pedigree
G1	Mahour (check cultivar)
G2	Khorram (check cultivar)
G3	Arbayan-01//As46/Aths/3/Barjouj ICB02-0406-0AP-8AP-0AP
G4	Avt/Attiki//MAtt733371/3/Aths/Lignee686/4/Kabaa ICB98-0796-0AP-15AP-0AP-14AP-0AP-8AP-0AP
G5	Lignee527/NK1272/4/Avt/Attiki//Aths/3/Giza121/Pue ICB95-0279-0AP-8AP-0AP-14AP-0AP
G6	Rhn03/3/Mr2584/Att//Mari/Aths*302/4/Rhn03/Lignee527 ICB05-0272-3AP-0AP
G7	Rhn03/3/Mr2584/Att//Mari/Aths*302/4/Ssn/Badia//Arar/3/Gloria'S'/Copal'S' ICB05-0292-7AP-0AP
G8	Aths/Lignee686//Mari/Aths*2/3/Lignee527/NK1272//Alanda/6/JLB7001/5/DeirAlla106//DL70/Pyo/3/RM 1508/4/Arizona5908/Aths//Avt/Attiki/3/Ager ICB05-0238-0AP-5AP-0AP
G9	AwBlack/Aths//Arar/3/9Cr27907/Roho/4/CompCr229//As46/Pro/3/DeirAlla106//DL71/Strain205 ICB97-0605-0AP-10AP-0AP-5AP-0AP-1AP-0AP
G10	E. ACACIA/DEFRA//PENCO/CHEVRON-BAR CBSS02Y00319S-0M-0M-5Y-1M-0Y
G11	SHENMAI NO.3/MSEL//CANELA CBSS04Y00367T-I-2Y-2M-0Y-0M-0Y
G12	SHENMAI NO.3/MSEL//CANELA CBSS04Y00367T-D-3Y-1M-0Y-0M-0Y
G13	ATAH92/2*M81//TOCTE/3/PENCO/CHEVRON-BAR CBSS01M00733T-0TOPY-7M-2M-2Y-1M-0Y
G14	DEFRA/CL128//PFC 88209 CBSS02Y00326S-0M-0M-4Y-1M-0Y
G15	FRESA/LEGACYCBSS05Y00125S-7Y-0M-0Y-0M-1AP
G16	MoB1337/Wi2291//Mooroco9-75/3/Hml
G17	TRADITION/6/P.STO/3/LBIRAN/UNA80//LIGNEE640/4/BLLU/5/PETUNIA1/7/LEGACY//PENCO/CHEVRON-BARCBSS04M00295T-2M-0Y-0M-0Y-1M-0AP
G18	LIMON/BICHY2000//NE167/CLE176 CBSS05Y00064S-29Y-0M-0Y-0M-3AP

Table 2. Some characteristics of rainfed test locations.

Location	Gachsaran	Gonbad	Ilam	Lorestan	Mugan
Longitude	30°18′N	37°16′N	39°39′N	33°39′N	33°44′N
Latitude	50°59′E	55°12′E	47°88′E	48°28′E	46°36′E
Altitude (m)	668	45	100	1125	975
Rainfall (mm), Mean of 30 Years	443	466	312	520	550

7 m long, with the between-row spacing of 17.5 cm and thinning provided the within-row spacing of 5 cm, thus the sowing rate was about 200 seeds m^{-2} and the field plots were measured about 7.4 m^2. Fertilizers were applied at planting time with rates 50 kg ha^{-1} N and 75 kg ha^{-1} P_2O_5, weeds were chemically controlled by 2,4-D at 11–18 (leaves 1–8 unfolded) stage, and the field plots were harvested using farm machinery. The grain yield per plot (kg) was measured in 4.2 m^2 of the four center rows of each experimental unit.

Analysis of variance was performed for each environment separately to plot residuals and identify outlier data. Bartlett's homogeneity test was used to test homogeneity of error variance. Here, the effect of the environment (E) was assumed to be random but the genotype (G) effect was assumed to be fixed in the combined analysis of variance. Nineteen stability methods including 36 univariate statistical parameters were computed with a comprehensive SAS-based program which calculates the most parametric stability statistics (Hussein *et al.,* 2000). Emebiri *et al.* (2004) developed a GenStat-based computer program that computes the sum squares of heterogeneous variances (HV) and sum squares imperfect correlations (IC) parameters of Muir *et al.* (1992). Both programs were used to calculate univariate parametric stability statistics. Principal component analysis (PCA) based on the rank correlation matrix was performed to obtain an understanding of the relationship among stability methods via SPSS version 13.0 (SPSS Inc., 2004) software.

RESULTS AND DISCUSSION

The significant differences among genotypes as well as environments ($P<0.01$) was detected regarding to combined analysis of variance (Table 3) for grain yield. Hence, tested environments had possessed a wide range of agro-climatic conditions to assess the yield performance and the stability issue. The significant GE interaction showed the differential response of each barley genotypes to environmental conditions and need for stability analysis. The combined ANOVA also showed that grain yield was significantly affected by E, which explained about 92% of the total (G+E+GE) variation, whereas G and GE interaction accounted for 2% and 8%, respectively (Table 3). In this study, genotypes seed yield ranged from 1742.5 kg ha^{-1} for G10 to 2159.4 kg ha^{-1} for G2 with a mean of 1947.8 kg ha^{-1} (Table 4). Tukey's one degree of freedom for the non-additivity test was applied and the examination of non-additive GE interaction and its significance (P<0.01) showed a complex crossover on GE interaction for barley multi-environmental trials. The genetic expression of grain yield as a complex trait is the result of G, E and GE interaction and the presence of the crossover interaction. The relatively high contribution of GE interaction for barley grain yield found in this study is similar to those found in other investigations (Mohammadi *et al*., 2013; Faramoushi *et al*., 2018; Kobus-Cisowska *et al.,* 2020) which causes difficulties to identify the most favorable genotypes in the crop improvement programs. Therefore, the GE interaction was further analyzed through 19 different univariate parametric stability methods, in order to interpret the stability of 18 barley genotypes.

Table 3. Combined analysis of variance for 18 barley genotypes in 15 rainfed environments.

Sources of Variation	DF†	MS‡	% of G+E+GE
Environment (E)	14	40602381.6**	90
Replicates within E	45	354778.8	
Genotype (G)	17	568591.2**	2
GE interaction	238	211314.1**	8
Error	765	83909.8	

†DF: Degrees of Freedom, ‡MS: Mean of Square.
**: Significant F test at the 0.01 level.

According to the environmental variance (EV) stability parameters, genotypes G6, G10 and G17 were more stable, but their yield performance was near or lower than average yield while based on θ_i, $\theta_{(i)}$ and W^2 parameters, genotypes G13, G12 and G15 were more stable (Table 4) which is based on the contribution of each genotype to the GE interaction sum of squares. All of the mentioned stability parameters represent Type I stability concept and usually identify low yielding genotypes as the stable genotypes and this type is useful for stability analysis in a marginal region to a selection of genotypes for specific adaptation (Lin *et al*., 1986; Sabaghnia *et al*., 2012b). According to the coefficient of linear regression slope (Finlay and Wilkinson, 1963)

Table 4. Grain yield performance and stability parameters from 1917 to 1968.

Code	GY	EV	θ_i	$\theta_{(i)}$	W^2	b	δ^2	β	δ^2
G1	1976.18	700927	41959	54187	411080	1.095	26090	0.095	26090
G2	2159.43	897213	64991	51308	1020146	1.231	46093	0.231	46094
G3	1890.77	535876	37066	54799	281684	0.957	20560	-0.043	20560
G4	1939.30	609801	49978	53185	623138	1.001	47933	0.001	47933
G5	1997.77	746547	64611	51356	1010103	1.098	71873	0.098	71873
G6	1843.95	393512	48010	53431	571094	0.813	22634	-0.187	22634
G7	1948.98	641513	62540	51615	955336	1.008	73446	0.008	73446
G8	1877.53	629071	44601	53857	480929	1.027	36542	0.027	36542
G9	1970.42	696856	55633	52478	772684	1.069	56552	0.069	56552
G10	1742.50	438237	55573	52485	771097	0.840	43715	-0.160	43715
G11	1866.73	621501	47696	53470	562776	1.015	43146	0.015	43146
G12	1946.02	622454	38746	54589	326100	1.031	24491	0.031	24492
G13	2114.13	664674	54474	52623	742014	1.042	55990	0.042	55989
G14	1965.57	572800	74157	50162	1262542	0.928	93963	-0.072	93963
G15	1897.27	542504	39035	54553	333741	0.960	24695	-0.040	24695
G16	1945.15	560017	54026	52679	730175	0.950	54667	-0.050	54667
G17	1916.38	514084	74084	50172	1260587	0.876	87627	-0.124	87627
G18	2062.69	661092	43732	53966	457961	1.057	33244	0.057	33244

GY: Grain yield (kg he^{-1}), EV: Environmental variance (Romer, 1917; in Becker, 1981), θ_i: Mean variance component (Plaisted and Peterson, 1959), $\theta_{(i)}$: GE variance component (Plaisted, 1960), W^2: Ecovalance (Wricke, 1962), b: Slop of linear regression (Finlay and Wilkinson, 1963), δ^2: Residual MS of joint linear regression (Eberhart and Russell, 1966), β: Slop of adjusted regression (Perkin and Jinks, 1968), and δ^2: Residual MS of adjusted regression (Perkin and Jinks, 1968).

and regarding, residual MS of joint linear regression (Eberhart and Russell, 1966), genotypes G1, G2, G12 and G18 were the most stable and responsive genotypes with moderate or relatively high mean yield performances (Table 4). The results of the adjusted regression model (Perkin and Jinks, 1968) were similar to above linear regression model and considering line slope and residual MS helps to obtain the same results (Table 4), whereas the residual MS as a measure of nonlinear sensitivity to the environmental changes were considered as a stability parameter with line slope as a measure of linear sensitivity. Deviation from the linear regression model is the index of Type III stability, and stable genotypes based on this concept are acceptable over a wide range of environmental conditions (Allard and Bradshaw, 1964).

The genotypic stability (GS) as the common formulation of EV, W^2 and the residual MS of regression parameters, introduced genotypes G3, G6 and G15 as the most stable genotypes (Table 5), while based on three parameters (line slope, residual MS and CDI) of independent linear regression model of Freeman and Perkins (1971), genotypes G1, G8 and G12 were the most stable and responsive ones. Lin *et al*. (1986) categorized the regression slopes as Type II stability, which, the yield response of a stable genotype is parallel to the mean response of the tested one. According to the α and λ parameters of Tai's (1971) method, genotypes G1, G2, G12 and G18 were the most stable and the results of stability variance (SV) parameter of Shukla (1972) were found to be similar to θ_i, $\theta_{(i)}$ and W^2 parameters and detected the same stable genotypes (Table 5). Pinthus (1973) proposed the coefficient of determination (CD) as the third parameter after line slope and regression residual MS for stability analysis, so considering these three parameters, indicated that genotypes G1, G2, G3, G12 and G18 were the most stable genotypes and the genotype response to environments is linear because most of the genotypes showed high CD values (Table 5). The existence of GE interaction is of a great concern and various tasks have been made to interpret stability, and not a single method perfectly fits the GE interaction, most breeders use some forms of stability aspects in their selection strategies (Pinthus, 1973). The CV parameter similar to EV, showed that genotypes G6, G10 and G17 have a low value and were the most stable but their yield was low (Table 5). Lin *et al*. (1986) grouped CV as Type I stability which is related to poor yield performance in environments but it is statistically valuable from stability aspects while most agronomists do not prefer it as they like to have genotypes with high yield potential (Flores *et al*., 1998).

Kilchevskii (1985) partitioned the observed values

Table 5. Univariate stability parameters for barley from 1970 to 1978.

Code	GS	b	$δ^2$	CDI	α	λ	SVS	CD	CV
G1	970132	1.153	40699	0.95	0.096	1.22	29731	0.96	42.4
G2	1979739	1.273	60774	0.93	0.233	2.15	78674	0.95	43.9
G3	432259	0.966	20472	0.96	-0.043	0.96	19334	0.96	38.7
G4	903577	1.035	85480	0.87	0.001	2.25	46772	0.92	40.3
G5	1576581	1.153	63987	0.92	0.099	3.37	77867	0.90	43.2
G6	294243	0.820	54166	0.87	-0.189	1.05	42590	0.94	34.0
G7	1256706	1.084	79218	0.89	0.008	3.44	73466	0.89	41.1
G8	838519	1.081	42018	0.94	0.028	1.71	35344	0.94	42.2
G9	1253348	1.118	52330	0.93	0.070	2.65	58789	0.92	42.4
G10	574047	0.911	90403	0.83	-0.162	2.04	58661	0.90	38.0
G11	885192	1.066	59252	0.91	0.016	2.02	41921	0.93	42.2
G12	695335	1.070	40671	0.94	0.032	1.15	22903	0.96	40.5
G13	1144051	1.089	123078	0.83	0.043	2.62	56324	0.92	38.6
G14	1326242	0.999	81192	0.86	-0.073	4.40	98153	0.84	38.5
G15	491944	0.999	45115	0.92	-0.040	1.16	23517	0.95	38.8
G16	860054	1.037	97754	0.85	-0.050	2.56	55373	0.90	38.5
G17	1170719	0.895	97403	0.81	-0.125	4.10	97995	0.83	37.4
G18	903800	1.134	49745	0.93	0.058	1.56	33499	0.95	39.4

GS: Genotypic stability (Hanson, 1970), b: Independent regression's slop, $δ^2$: Independent regression's residual MS, and CDI: Independent regression's determination coefficient of Freeman and Perkins (1971), α: Regression like coefficient, and λ: Regression residual MS like parameter of Tai (1971), SV: Stability variance (Shukla, 1972), CD: Coefficient of determination for liner regression (Pinthus, 1973), CV: Coefficient of variation (Francis and Kannenberg, 1978).

into general adaptive abilities (GAA) as induction of G effect and specific adaptive ability (SAA) as induction of E+GE effect and proposed a statistic as selective value of genotype (SVG) for stability analysis, and based on the SVG, genotypes G6, G10 and G11 were the most stable genotypes with high breeding value because the SVG assesses the ecological stability and adaptability (Table 6). Regarding both PI and MSGE parameters of Lin and Binns (1988), as superiority measure (SM), genotypes G2, G5 and G13 were the most stable genotypes (Table 6). According to HI parameter (Table 6), genotypes G2, G13 and G18 had high values and were identified as the most stable genotypes because HI has the ability to combine yield with stability unfavorable conditions (Martynov 1990), whereas the stable genotypes had high yields. Thus, it seems that the procedure of HI was successful in the detection of the most favorable genotypes. Muir *et al*. (1992) portioned the GE interaction into heterogeneous variances and imperfect correlations (IC) which is based on heterogeneity among genotypes in the scaling of differences among environments (Table 6). The IC is more useful in evaluating fixed genotypes for sensitivity to random environments and genotypes G3, G6 and G15 were the most stable genotypes although their yield performances were low.

The dynamic procedure of Lidansky *et al*. (1997), proposed dynamic coefficient of variation (DCV) parameter for yield stability analysis which is different from the conventional static versus dynamic concepts and benefits from dynamic differentiation to variation mean and genetic characteristics.

However, based on the DCV, genotypes G2, G3 and G15 were the most stable genotypes, but only yield performance of G2 was higher than average performance and could be recommended as the most favorable genotype based on yield and DCV (Table 6). Lidansky *et al*. (1998) developed the dynamic regression (DR) model which does not include any GE interaction and according to DR model, and regarding MS deviations, genotypes G3, G8 and G15 were identified as the most stable genotypes but their yield performances were lower than average yield, thus this method could not introduce high yielding genotypes as the most stable ones (Table 6). Developing genotypes with high yield performance and good stability is one of the main targets and according to Kamidi (2001), it can be assessed by relative superiority (RS) parameter. The RS parameter is produced by multiplying the yield measure by an index the variability and according to this parameter, genotypes G1, G2 and G5 were identified as the most stable genotypes and their yield performance was high (Table 6). Finally, regarding most of the stability statistics as well as mean yield

Table 6. Univariate stability parameters for barley from 1985 to 2001.

Code	SVG	PI	MSGE	HM	IC	DCV	b	δ^2	RS
G1	2.008	84301	21768	-0.32	165513	82.0	0.128	0.389	0.094
G2	1.849	24992	10474	44.87	209533	72.2	0.145	0.397	0.224
G3	2.089	124281	27892	-19.56	146109	71.0	0.132	0.220	-0.042
G4	2.041	125921	49664	-2.34	208434	80.2	0.107	0.411	0.001
G5	1.989	76781	21648	6.02	256540	79.6	0.134	0.395	0.093
G6	2.133	167368	49329	-16.01	145202	80.2	0.097	0.241	-0.182
G7	2.033	127283	54761	0.10	262799	96.8	0.107	0.446	0.008
G8	2.109	133322	31036	-28.81	184344	74.6	0.133	0.323	0.026
G9	2.014	86235	21646	3.33	226414	84.1	0.118	0.446	0.066
G10	2.260	236043	63565	-52.86	200482	75.6	0.121	0.215	-0.152
G11	2.121	140181	32951	-25.39	198221	73.3	0.125	0.357	0.015
G12	2.035	111396	37739	-3.06	158751	77.6	0.128	0.319	0.031
G13	1.875	42829	19565	48.96	225380	72.6	0.116	0.372	0.040
G14	2.012	153457	87114	11.77	313727	93.8	0.109	0.354	-0.066
G15	2.082	125234	31679	-19.81	155753	71.2	0.130	0.240	-0.039
G16	2.032	117825	43836	4.21	223904	75.2	0.116	0.313	-0.047
G17	2.060	151119	65650	11.33	305350	78.6	0.093	0.375	-0.113
G18	1.922	76831	41149	37.56	178387	76.2	0.123	0.346	0.056

SVG: Selection value of genotype (Kilchevskii, 1985), PI: Superiority measure, and MS(GE): MS of GE interaction of Lin and Binns (1988), HM: H statistic of Martynov (1990), IC: Imperfect correlation SS (Muir *et al.*,1992), DCV: Dynamic coefficient of variation of Lidansky *et al*. (1997), b: Slop of dynamic regression, and δ^2: Residual of dynamic regression) of Lidansky *et al*. (1998), and RS: Relative superiority of Kamidi (2001).

performances, it can be concluded that genotype G1 (Mahour) or check cultivar and G18 were the most favorable genotypes. The behavior of Mahour as the check cultivar in rainfed conditions was predictable due to its nature and longtime adaptability to local conditions. However, the yield performance of G8 had not any significant difference with this cultivar and can be recommended for cultivation.

For understanding the relationships among the univariate stability methods (for similar θ_i, $\theta_{(i)}$, W^2 and SV parameters, only SV was used and from linear regression (LR) and adjusted regression, only LR was used) (Table 7), a PC analysis based on the rank correlation matrix was carried out, and the two first PCAs explained 81% (47 and 34% by PC1 and PC2, respectively) of the variance of the original variables and the loadings of the first two PCs were used for graphic display of the relationships among them (Figure 1). In this plot, the PC1 axis mainly distinguishes the yield purely from stability parameters such as EV and CV while the PC2 axis distinguishes the dynamic concept stability from static concept stability. Overall, three main groups can be identified as: Class-A (up-left) including EV, CV, GS and SVG parameters, Class-B (up-right) including IC, SV, DCV, DR, CD, Tai, IR LR and Class-C (down-right) including SM, RS, HM as well as grain yield (GY). It seems that PC1 axis could divide stability methods according to yield and stability while the PC2 axis distinguishes most of the regression models from the Type I stability concept. It is interesting that the rarely used stability methods such as HM or H statistic of Martynov (1990), and RS or relative superiority of Kamidi (2001) as well as the frequently used method i.e. SM or superiority measure of Lin and Binns (1988) grouped with yield performance, thus, it can be recommend for stability analysis in future breeding programs.

The observed significance of GE interaction of barley genotypes indicated that the genotypes have both crossover and non-crossover types of GE interaction and this complexity of GE interaction could be involved with the nature of the barley in rainfed environmental

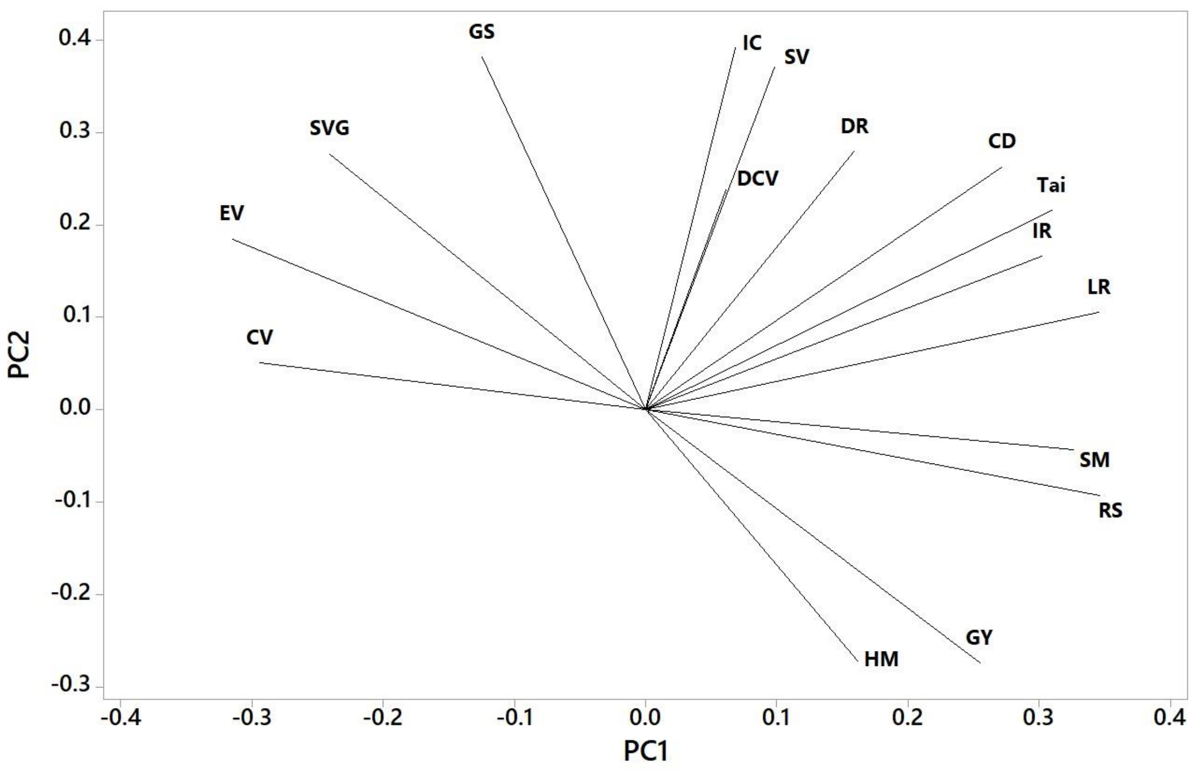

Figure 1. Plot of the two first PCs of ranks of 15 stability methods plus grain yield, estimated by 21 statistics using data from 18 barley genotypes grown in 15 test environments.

GY: Grain yield, EV: Environmental variance (Romer, 1917; Becker, 1981), LR: Linear regression (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966), GS: Genotypic stability (Hanson, 1970), IR: Independent regression (Freeman and Perkins, 1971), Tai: Stability method of Tai (1971), SV: Stability variance (Shukla, 1972), CV: Coefficient of variation (Francis and Kannenberg, 1978), SVG: Selection value of genotype of Kilchevskii (1985), SM: Superiority measure (Lin and Binns,1988), HM: Statistic of Martynov (1990), IC: Imperfect correlation (Muir *et al.*,1992), DCV: Dynamic coefficient of variation (Lidansky *et al.,* 1997), DR: Dynamic regression (Lidansky *et al.,* 1998), and RS: Relative superiority of Kamidi (2001).

Table 7. Ranks of the 18 barley genotypes for yield and 18 different stability methods with 26 univariate statistics.

Code	GY	EV	θ_i	$\theta_{(i)}$	W^2	LR	GS	IR	Tai	SV	CD	CV	SVG	SM	HM	IC	DCV	DR	RS
G1	5	16	4	4	4	1	11	1	1	4	1	15.5	14	4.5	8.5	5	15	9	2
G2	1	18	16	16	16	2	18	5.5	3.5	16	4	18	18	1	2	11	3	4	1
G3	14	4	1	1	1	8	2	5.5	5	1	4	7	5	7.5	15.5	2	1	1	13
G4	11	8	9	9	9	12	9	12.5	13	9	13	10	8	12	8.5	10	13.5	16	11
G5	4	17	15	15	15	5	17	8	8.5	15	12	17	15	3	8.5	15	12	5	3
G6	17	1	8	8	8	13	1	12.5	12	8	9	1	2	15.5	8.5	1	13.5	14	18
G7	8	12	14	14	14	14	15	11	15	14	16	12	10	14	8.5	16	18	18	10
G8	15	11	6	6	6	6	6	3	6	6	7	13.5	4	11	15.5	7	6	2.5	8
G9	6	15	13	13	13	7	14	7	10	13	10	15.5	12	4.5	8.5	14	16	15	4
G10	18	2	12	12	12	16	4	17	15	12	14.5	3	1	18	18	9	8	7	17
G11	16	9	7	7	7	9	8	10	8.5	7	8	13.5	3	13	15.5	8	5	9	9
G12	9	10	2	2	2	3.5	5	2	2	2	2	11	9	7.5	8.5	4	10	6	7
G13	2	14	11	11	11	10.5	12	14.5	11	11	11	6	17	2	2	13	4	12	6
G14	7	7	18	18	18	17	16	14.5	17.5	18	17	4.5	13	17	8.5	18	17	13	15
G15	13	5	3	3	3	10.5	3	9	7	3	6	8	6	9.5	15.5	3	2	2.5	12
G16	10	6	10	10	10	15	7	16	15	10	14.5	4.5	11	9.5	8.5	12	7	11	14
G17	12	3	17	17	17	18	13	18	17.5	17	18	2	7	15.5	8.5	17	11	17	16
G18	3	13	5	5	5	3.5	10	4	3.5	5	4	9	16	6	2	6	9	9	5

GY: Grain yield, EV: Environmental variance (Romer, 1917; Becker, 1981), θ_i: Mean variance component (Plaisted and Peterson, 1959), $\theta_{(i)}$: GE variance component (Plaisted, 1960), W^2: Ecovalance (Wricke, 1962), LR: Linear regression (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966), GS: Genotypic stability (Hanson, 1970), IR: Independent regression (Freeman and Perkins, 1971), Tai: Stability method of Tai (1971), SV: Stability variance (Shukla, 1972), CV: Coefficient of variation (Francis and Kannenberg, 1978), SVG: Selection value of genotype of Kilchevskii (1985), SM: Superiority measure (Lin and Binns,1988), HM: Statistic of Martynov (1990), IC: Imperfect correlation (Muir *et al.,* 1992), DCV: Dynamic coefficient of variation (Lidansky *et al.,* 1997), DR: Dynamic regression (Lidansky *et al.,* 1998), and RS: Relative superiority of Kamidi (2001).

conditions or diverse genetic background of genotypes (Janmohammadi *et al*., 2014). The barley grain yield is the result of G, E and GE interaction and complex GE result in various physiological processes which occur during development and such finding is similar to those found in other researches (Mohammadi *et al*., 2013; Faramoushi *et al*., 2018). However, if ignoring this GE interaction and necessary trials in all target environments, it would be very challenging to find an indirect response to identify the most favorable barley genotypes through a selection in a limited number of target environments. Environmental issues play a significant role in the performance of plant materials as well as edaphic issues, thus the GE interaction is one of the main problems facing breeders in genetic improvement programs (Karimizadeh *et al*., 2012; Pour-Aboughadareh *et al.,* 2022). Increasing grain yield has been the main objective of barley breeders and stability analysis can improve this objective by developing more adaptable genotypes (Sabaghnia *et al*., 2013).

CONCLUSION

Yield is a complex trait highly influenced by the environment. Hence, plant breeders test newly developed lines across the environments before commercialization or release as a variety. Regarding, the mean values of yield for each location across three years as well as stability methods which is applied in the present work, genotypes G13 for Moghan and Gachsaran, G18 for Gonbad and G05 for Kuhdasht were the most favorable genotypes and therefore could be recommended for cultivation to farmers. Also, H statistic of MARTYNOV (1990), and RS of KAMIDI (2001) and superiority measure of LIN and BINNS (1988) can be recommend for stability analysis in future breeding programs of barley in order to simultaneous selection of yield and stability.

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