Genotype by environment interaction analysis of barley grain yield in the rain-fed regions of Algeria using AMMI model

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Multi-environment trials were conducted in two locations (Algiers and Setif) during two crop seasons in order to assess the responses of 17 genotype of barley (*Hordeum vulgare* L.) by evaluation of genotype-by-environment interactions (GEI) on grain yield and determine the stable genotypes. Results showed significant ($p < 0.001$) effects of environment and genotypes and their interaction on grain yield. The genotypes had different behavior conducting to yield variation in the tested locations. So, selection could consider a specific adaptation of the genotypes and their yield stability. The Additive main effects and multiplicative interaction analysis is a useful tool allowing to explore important information on the obtained results; it revealed that 'Plaisant/charan01' is the most stable genotype followed by 'Barberousse' and 'Barberousse/Chorokhod', while 'Begonia' and 'Plaisant' were unstable with specific adaptation to Setif location during 2018/19. the cultivar 'Express' presented a high productivity.

1   Introduction

Barley (*Hordeum vulgare* L.) is one of the principal cultivated cereal crops in Algeria after wheat. It's grown mainly in rain-fed areas and is mostly subject to rainfall variation bringing fluctuation in yield. Developing new varieties adapted to a wide range of environments (Abdipur & Vaezi, 2014) with stability of performance are important in crop breeding programs (Chalak et al., 2015). In presence of genotype environment interaction (GEI), the selection of superior genotypes becomes more difficult and lead to complicate breeding programs. The use of Multi-environment trials for testing genotype adaptation becomes a necessary tool (Rodrigues et al., 2016).

The means of yeilds of genotypes across environments hide important information to compare tested genotypes in each environment. But this method is not enough sufficient for exploiting all information contained in the dataset (Halimatus & Alfian, 2016). Additive main effects and multiplicative interaction (AMMI) is a powerful model to analyze the GEI (Alfian & Halimatus, 2016). It is combines analysis of variance technics (an additive model) to study the main effects of genotypes and environments with principal component analysis (PCA) to study the interaction of genotype by environment (Zobel et al., 1988).

However, some genotypes show stable values in an axis, but they are not stabling for the second axis because they contribute differently in the two axis of Interaction

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Principal Component Analysis (IPCA) (Temesgen et al., 2015). Therefore, we need a weighted value and Additive Main effects and Multiplicative Interaction stability value (ASV) to quantify and rank genotypes according to their yield stability (Purchase et al., 2000).

The present study aimed to evaluate the magnitude of genotype by environment interaction on grain yield of 17 genotypes and cultivars tested across two different locations and to identify barley genotypes that have high performance and yield stability. The results of the study could be used to determine suitable genotypes as parents in the future breeding programs for each location.

2 Material and methods

2.1 Plant materials and growth conditions

Field experiments were carried out during two growing seasons(2017/2018 and 2018/2019) and in two locations each year; each combination of location × growing season was treated as an environment, making a total of four environments. Trials were carried out at the high national school of agronomy in the district of Algiers and in the Field Crop Institute (Institut technique des grandes cultures ITGC) in the district of Setif.

The design of experiments in each year-location trials were randomized complete block with four replications. The annual rainfall and annual monthly average of experimental areas and years were presented in Table 1. Algiers (altitude 50 m, 36° 43' N, longitude 3° 08' E) is characterized by mild and wet winter with dry and hot

spring and clay loam soil. Setif (altitude 1,023 m, 36° 12' N, longitude 5° 24' E) is a semi-arid area with cold winter and hot and dry spring, the soil is silt loam (Bouzerzour & Dekhili, 1995).

The study used 15 spring barley genotypes and cultivars comprising Tichedrett and Saida, six row type Algerian cultivars and genotypes. Rihane03, Barberousse/Chorokhod and Plaisant/Charan01 six row type and Soufara'S', Rahma and Tissa, two row type varieties and advances breeding lines from the Icarda breeding program. Acsad176 and El Fouara, six row type Syrian released cultivars. El Bahia, selected six row cultivar by ITGC of Setif; Barberousse, Jaidor and Express, six row type French varieties; and Tina, six row type Spanish cultivars. Moreover, Plaisant and Begonia were used as French and Spanish six row type winter varieties respectively.

The genotypes were sown in the beginning of December in Algiers and in the end of November in Setif for the two growing season. The plot received 52 kg ha^{-1} of phosphor applied before sowing and 58 kg ha^{-1} of Nitrogen was applied at the onset of tillering and jointing growth stage (GS 21 and 31, Zadoks et al., 1974). Weed control was carried out chemically.

2.2 Variables recorded and statistical analysis

After harvest, grain yield was determined for each plot and the data was subjected to a combined analysis of variance (ANOVA) using the agricolae package version 1.2-8 (De Mendiburu, 2017) of R 3.5.3 statistical software. Each combination of location × growing season was treated as an environment and the AMMI analysis was

Table 1 Climatic characteristics of testing environments.

Location	Algiers				Setif			
Season	2017/2018 T° (C°)	2017/2018 P (mm)	2018/2019 T° (C°)	2018/2019 P (mm)	2017/2018 T° (C°)	2017/2018 P (mm)	2018/2019 T° (C°)	2018/2019 P (mm)
September	23.60	35.00	24.70	27.00	20.90	41.00	21.60	25.00
October	19.00	17.00	19.90	64.00	15.94	10.70	14.10	64.00
November	13.90	128.00	16.00	105.00	9.20	55.70	9.80	26.00
December	11.10	133.00	12.00	31.00	5.28	33.50	9.30	11.00
January	11.60	30.00	10.00	117.00	6.43	13.90	3.40	77.00
February	10.30	64.00	10.80	19.00	5.10	23.90	5.30	15.00
March	14.10	118.00	13.30	38.00	8.83	90.40	8.80	27.00
April	16.10	104.00	15.50	46.00	11.21	81.30	11.80	44.00
May	17.60	55.00	18.50	19.00	15.40	51.90	14.40	59.00
June	22.00	31.00	23.10	8.00	20.78	39.80	28.60	0.00
Total	/	715.00	/	474.00	/	442.10	/	348.00
Mean	15.93	71.5	16.38	47.40	11.91	44.21	12.71	34.80

T° – temperature, P – precipitation

performed according to the model suggested by (Gauch, 1988) using the following formula:

$$Yge = \mu + ag + \beta e + \sum_{n=1}^{N} \lambda n \Upsilon gn \, \eta en + \theta ge$$

where:

Yge – the yield of genotype *g* in environment e, μ – the overall mean, *ag* – the genotype mean deviation, β*e* – the environment mean deviation, λ*n* – the eigen value of the *n*th principal component (PCA) axis, Y*gn* and η*en* are the genotype and environmental PCA scores for the *n*th PCA axis, θ*ge* – the residual

The AMMI Stability Value (ASV) is known as the distance from the coordinate point to the origin in a two-dimensional scatter graph of IPCA1 scores against IPCA2 scores in the AMMI model. ASV was calculated as described by Purchase et al. (2000) as follows:

$$ASV = \sqrt{(SSIPCA1 / SSIPCA2)(IPCA1)^2 + (IPCA2)^2}$$

where:

SSIPCA1/SSIPCA2 – the weight given to the IPCA1 value by dividing the IPCA1 sum of square by the IPCA2 sum of square

Yield stability index is calculated as follows:

$$YSI = RASV + RY$$

RASV ranks genotypes based on grain yield across environments with considering the rank of AMMI stability value. This index is the rank of ASV and yield (Farshadfar et al., 2011).

3 Results and discussion

Growing season 2017/2018 was characterized by high precipitation in the two locations, Algiers and Setif, compared to 2018/2019; whereas Algiers received in 2018/2019 season 102 mm less than 2017/2018 season during December. Moreover, Setif received in 2018/2019: 22.5 mm and 63.4 mm in December and March respectively, less than 2017/20018 season.

As shown in Table 1, the mean temperatures of months during 2017/2018 season was low compared to those of 2018/2019 season in both locations; therefore, cold weather that characterized 2017/2018 season compared to the climate of each region conducted to differences in plant growth. 2017/2018 was an exceptional season which received high precipitation and low temperature compared to the habitual climatic conditions of sites, which make differences in growth and on grain yield.

Analysis of variance of the AMMI model indicated a significant effect (p <0.001) on grain yield of barley of all three factors, the genotype, environment and GEI (Table 2). The high variation of climatic conditions between environments and the presence of genetic variation is the results of different behaviour observed. It's results high variation across seasons and locations for precipitation and temperatures. Genotypes responded differently in each season, this led to a change in yield grain yield in genotypes. The results indicated that 28.45% of total sum of squares (TSS) was accounted by the environmental effect. Genotypic effect accounted 39.28% of grain yield variation While 32.27% of total sum of squares (TSS) was attributed to the GEI effect on grain yield variation.

The barley grain yield variation depends on genotype and environmental factors and their interaction. Based on the table 2, three possible interaction principal

Table 2 Combined analysis of variance and AMMI analysis for grain yield of barley genotypes.

Source of variation	DF	SS	MS	F	Pr	%SS (G+E+GE)
Treatments	67	249,325,996	3,721,284	13.800	0.0000***	
Env	3	70,930,062	23,643,354	23.628	2.528e-05 ***	28. 449
Blocs/Env	12	12,007,911	1,000,659	3.710	4.798e-05 ***	
Gen	16	97,938,949	6,121,184	22.693	<2.2e-16 ***	39. 282
Env : Gen	48	80,456,986	1,676,187	6.214	<2.2e-16 ***	32. 270
PC1	18	62,994,542	3,499,696.8	12.970	0.0000 ***	
PC2	16	15,000,951	937,559.4	3.480	0.0000***	
PC3	14	2,461,493	175,820.9	0.650	0.8203 Ns	
Residuals	192	51,789,855	269,739			
Total	271	313,123,763	32,441,384			

CV = 10.823, mean = 4,798.852, DF – degree free, SS – sum square, MS – mean square, Pr – probability, Gen and G – genotype, Env and E – environment, PC – principal component, Ns and *** – non-significant and significant at the 0.001 probability level respectively

component axis (IPCA) resulted from the partition of the GEI component of variation. Whereas, the IPC1 captured 78.3% of the interaction sum of squares and the IPC2 captured 18.6% of the interaction sum of square for grain yield; this first two IPCA showed very highly significant (P <0.001) difference and explained 96.9% of the total interaction variance. The result is with agreement of Vishnu et al. (2016). Many researchers (Mirosavljevic et al., 2014) reported for barley that the first two IPCA score explained significant and greater percentage of GEI.

3.1 AMMI 1

The IPC1 bi-plot represents the genotype and environment main effect in × axis and the interaction effects in y axis (IPC1 scores versus mean yield). When the IPC1 score is close to zero that means the genotype shows general adaptation of that trait to the tested environments (Dogan et al., 2016). Accordingly, Tissa, and Plaisant/Charan01 presented 0.497 and -2.215 IPC1 scores respectively (Table 3). These two genotypes are near the origin, which means they presented a mean grain yield near to overall average with an IPC1 score close to zero, in other word, they are insensitive to environmental interactions. These genotypes are considered as the most stable genotypes and they could be recommended for most test environments. Moreover, Barberousse and

Barberousse/Chorokhod with -3.840 and 4.181 IPC1 scores respectively, showedhigh adaptation to the tested environments and were stable genotypes (Figure 1). Begonia presented the highest positive IPC1 score with 38.957 and low mean grain yield with 3,628.534 kg ha^{-1} after Tina. The last one recorded the lowest mean grain yield with 3,479.794 kg ha^{-1} and 16.793 of positive IPC1 score. Plaisant recorded 3,949.156 kg ha^{-1} of mean grain yield and the second highest positive IPC1 score with 26.696. These genotypes can be considered as the most sensitive genotypes to the interaction. Elbahia, Jaidor and Saida presented the lowest negative IPC1 score and acceptable mean grain yield with specific adaptability for Algiers17/18 and Algiers18/19 environments and they were sensitive to the interaction. Moreover, 'Saida' recorded 4,774.317 kg ha^{-1} of mean grain yield with nearly value to the overall mean.

'Soufara's' and 'Acsad176' showed a moderate interaction with 6.855 and -8.743 IPC1 scores respectively. Moreover, these two genotypes showed a mean grain yield with nearly value to the overall mean. While 'Tichedrett' showed a negligible interaction IPC1 = 0 with grain yield less than the general mean. This one is considered as a stable Algerian cultivar with acceptable grain yield under semi-arid conditions, where rainfall changes from year to another.

Table 3 AMMI stability values of grain yield and ranking of the 17 barley genotypes.

Genotypes	Means (kg ha^{-1})	IPCA 1	IPCA 2	ASV	rASV	YSI	rYSI
Tichedrett	4,248.410	-0.067	-11.208	11.209	2	16	14
Tina	3,479.794	16.793	-16.606	38.210	14	31	17
Soufara's	4,761.469	6.855	-5.329	15.025	5	18	13
Acsad176	4,871.814	-8.743	10.964	21.004	8	18	10
Barberousse	5,090.660	-3.840	11.161	13.656	4	10	6
Rihane03	5,405.737	-8.882	7.215	19.580	7	9	2
Rahma	5,395.905	10.077	-14.983	25.512	11	14	3
Begonia	3,628.534	38.957	11.125	80.603	17	33	16
Plaisant	3,949.156	26.696	14.596	56.619	16	31	15
Jaidor	5,025.882	-15.477	11.125	31.766	12	20	8
Express	5,586.289	-11.371	-2.461	23.431	10	11	1
Tissa	4,954.568	0.497	-21.508	21.532	9	18	9
Saida	4,774.317	-17.197	8.772	36.317	13	25	12
Elfouara	5,290.357	-8.250	-2.051	17.386	6	10	4
Elbahia	5,203.617	-19.477	-1.562	39.943	15	20	5
Barberousse/Chorokhod	4,861.785	-4.181	9.648	12.903	3	14	11
Plaisant/Charan01	5,052.188	-2.215	0.460	4.562	1	8	7

IPCA – interaction principal component analysis, ASV – AMMI stability value, rASV – ranking AMMI stability value, YSI – yield stability index, rYSI – ranking yield stability
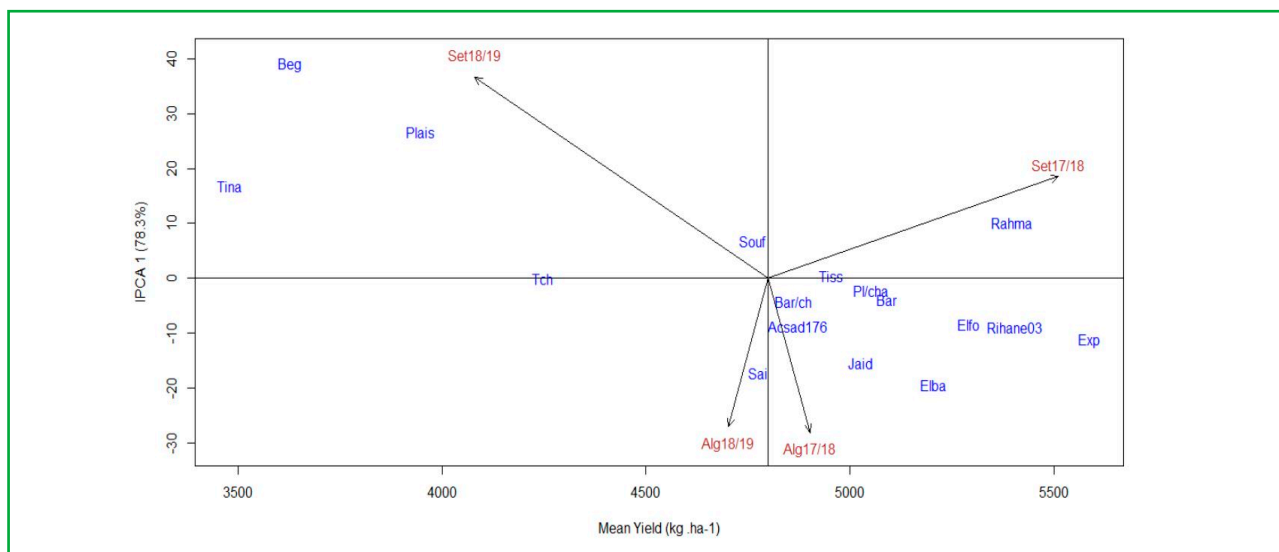
Figure 1 AMMI 1 biplot for grain yield showing the plotting of mean yield and IPCA 1 of genotypes
Alg17/18 – Algiers 2017/2018, Set 2017/2018 – Setif 2017/2018, Alg 2018/2019 – Algiers 2018/2019, Set 2018/2019 – Setif 2018/2019; tch – Tichedrett, tina – Tina, souf – Soufara's, acsad – Acsad176, bar – Barberouss, rihane – Rihane, rahma – Rahma, beg – Begonia, plai – Plaisant, jaid – Jaidor, exp – Express, tiss – Tissa, sai – Saida, elfo – Elfoura, elb – Elbahia, bar/ch – Barberousse/Chorokhod, pl/cha – Plaisant/Charan01

3.2 AMMI 2

AMMI2 biplot (IPC2 versus IPC1 scores) provides a good explanation of the data pattern to interpret genotypic behaviours across locations and seasons; it was constructed using genotypic and environmental scores of the first two IPCA axes. When looking at the Figure 2, clear divisions of genotypes appear along IPC1 and IPC2 axes. Regarding IPC1 and IPC2 scores, 'Plaisant/Charan01' has the lowest IPC scores with relatively moderate mean yield and is project static concept of yield stability, which mean it is broadly adapted to tested environments. This genotype was the most stable one among the tested genotypes followed by 'Barberousse' and 'Barberousse/Chorokhod' that showed a relative stability on the AMMI2.

Genotype Elfouara recorded a negative IPC score and showed a relative stability on the AMMI2. Express and Elbahia with -2.461 and -1.562 IPC2 score, respectively, showed a specific adaptation to Algiers18/19 environment; on the contrary they presented negative correlation to Setif17/18 and Setif18/19 environements. Rihane Acsad176 Saida and Jaidor, with a positive IPC2 score, were better adapted to Algiers17/18 environment and they seem to be not adapted to Setif17/18 in reason of the negative correlations. On the right of AMMI2 biplot, we can see genotypes Begonia and Plaisant with positive IPC2 scores were specifically adapted to Setif18/19 environment and they showed negative correlations to Algiers18/19. Tina and Rahma marked negative scores on the IPCA2, showing a specific adaptation to Setif17/18 environment and negative correlations to Algiers17/18, while Soufara's presented relative association to

Setif17/18. As shown on AMMI2 biplot, genotypes Tichedrett and Tissa recorded IPC1 scores close to zero and they don't show association to any environments.

On the base of the previous results, genotypic effect contributed to the major part of grain yield variation followed by GEI and environmental factors. Therefore, choosing potential genotype or variety constitutes an important key for the higher yielding and productivity, but of course with considering specific adaptation of the genotype. However, Peyman et al. (2017) reported that the major part of the total sum of squares of grain yield variation with 41% is explained by GEI effects followed by genotypic effects with 30%; while only 29% of the total sum of squares was attributable to environmental effects. Farshadfar et al. (2012), Showed that the environmental effect was accounted for 21.7% of total sum of squares and the GEI was accounted for 55.3% of TSS.

Genotype Plaisant/Charan01 showed high and broad adaptation to the tested environments; it can be recommended for farmers in both locations and for the similar environments. Moreover, this genotype presents an important genetic material that could be integrated in the future breeding programs for semi-arid area. Other genotypes as BarberousseBarberousse/Chorokhod and Tissa seem to be highly adapted with yield stability and could be recommended for both locations. Romagosa and Fox (1993), described the origins of genotype adaptation to an environment to the presence of adaptation genes, that control the characters playing a role in adaptation, and the buffering capacity linked to the genetic structure of some genotypes.
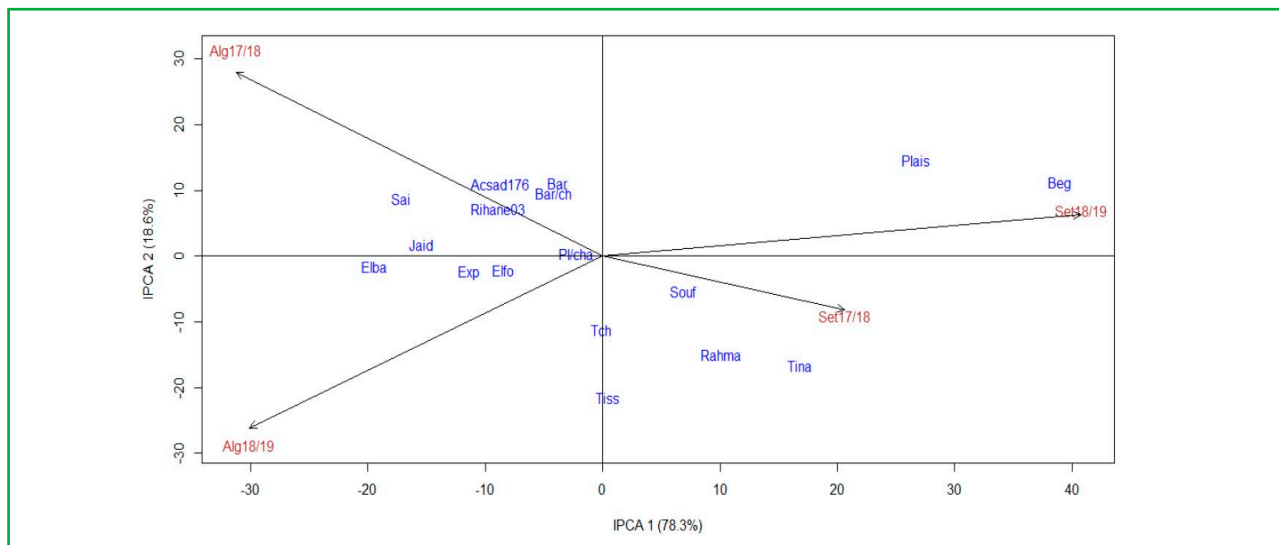
Figure 2 AMMI 2 biplot for grain yield showing the plotting of IPCA1 and IPCA2 of genotypes
Alg17/18 – Algiers 2017/2018, Set 2017/2018 – Setif 2017/2018, Alg 2018/2019 – Algiers 2018/2019, Set 2018/2019 – Setif 2018/2019; tch – Tichedrett, tina – Tina, souf – Soufara's, acsad – Acsad176, bar – Barberouss, rihane – Rihane, rahma – Rahma, beg – Begonia, plai – Plaisant, jaid – Jaidor, exp – Express, tiss – Tissa, sai – Saida, elfo – Elfoura, elb – Elbahia, bar/ch – Barberousse/Chorokhod, pl/cha – Plaisant/Charan01

According to Yan et al. (2007), successful genotypes of barley must be highly adapted to a broad range of environmental conditions to ensure their yield stability.

Express was the most productive followed by RahmaRihane and Elfouara. However, Rahma seem to be more associated with Setif17/18 environment. These genotypes could be recommended for farmers and can be introduced in the national catalogue of varieties to start their seed production.

As it is known, most of the farmers across the country prefer six rows barley genotypes than two rows genotypes. However, Rahma as two rows barley genotype was more productive with high stability of grain yield and can be suggested for semi-arid regions where rainfall is variable and unpredictable. Therefore, this genotype must be recommended for farmers to increase national production.

Genotypes Begonia and Plaisant were specifically adapted to Setif; it can be explained by their vernalization requirement; therefore, they are highly inadvisable for Algiers location. These genotypes can be suggested for farmers where location is characterized by low temperature during winter, but also for the future breeding programs for such environments.

Multi-environment trials are an important step in plant breeding and selection, whereas new genotypes should be tested across different locations for many seasons in order to select them according to their adaptation for each environment. Then, they can be commercialized to farmers. Therefore, good interpretation of the results

is a critical point where the AMMI biplots presented excellent tools for data analysis visualization and for its interpretative option (Gauch et al., 2008).

The range from IPC1 = -05 to IPC1 = 05 on the IPC1 axis and from IPC2 = -12 to IPC = 12 on the IPC2 axis presents favourable response to the interaction. Accordingly, the present range indicates a favourable genotype by environment interaction response and includes genotypes with a suitable response to the tested environments indicating high yield stability.

However, the range from IPC1 = -20 to IPC1 = 20 on the IPC1 axis and from IPC2 = -15 to IPC2 = 15 includes genotypes with unfavourable interaction response and more sensitivity to environmental stresses; where genotypes present special adaptation regarding to the tested environments and with low yield stability.

According to Purchase et al. (2000), AMMI stability value (ASV) serves to quantify and ranks genotypes according to their yield stability. Based on the table 3, the lowest ASV was observed for Plaisant/Charan01 followed by Tichedrett' Barberousse/Chorokhod and Barberousse respectively indicating high stability for these genotypes. While the genotype Begonia was observed as the most unstable genotype followed by Plaisant and Tina.

4 Conclusion

The present study indicated a very highly significant effect of genotype and environment and their interaction on grain yield of barley. Genotypes showed a differential response in various environments, whereas GEI had

a remarkable effect on their performance. AMMI analysis supplied more useful information about genotypes performance and yield stability. Moreover, the AMMI stability value should be taken into account for selection genotypes. Express, Rihane and Rahma were the most productive genotypes across environments with low stability; accordingly, they can be recommended for high performing environments. While Begonia', Tina and Plaisant were specifically adapted to Setif17/18 and Setif18/19 environments with sensitivity to environmental changes. Tichedrett was stable in the tested environments indicating its adaptation to semi-arid conditions, but tended to be low yielding genotype, it can be recommended for harsh environments. Plaisant/Charan01 can be suggested as the most stable genotype with relative high yield and would be recommended for the future breeding programs.

Acknowledgments

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