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RESEARCH ARTICLE

Assessment of wide and specific adaptation of irrigated bread wheat elite genotypes for temperate agro-climatic zone of Iran: comparison of AMMI biplot and Pi index

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ABSTRACT

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Identifying bread wheat genotypes with high grain yield and yield stability is very important for breeding programs targeting diverse ecologies. This study was conducted to assess the adaptation and yield stability of elite bread wheat genotypes and included two experiments. In the first experiment, 18 promising irrigated bread wheat lines along with cv. Amin and cv. Farin as control, totally 20 genotypes, were evaluated using randomized complete block design with three replications. In the second experiment, 19 doubled haploid lines along with cv. Amin, cv. Farin, and cv. Radia, totally 22 genotypes, were evaluated. The trials were conducted over two cropping seasons (2020-21 and 2021-22) at five research field stations under optimal irrigation conditions, and three research field stations under terminal moisture stress conditions. Grain yield and bread making quality characteristics were recorded. Considering limitation of combined analysis of variance, adaptation of genotypes was studied only for the second experiment using the AMMI method, while for both experiments, non-parametric ranking (Rank) and the superiority index (Pi) were employed. Considering he results for grain yield, disease resistance and bread-making quality, M-99-15 and MDH-99-10 promising lines with average grain yield of 6.846 and 7.132 tha^{-1} respectively, were selected using AMMI and Pi index. These two genotypes have been commercially released as cv. Afrooz and cv. Mahlooji, respectively. The results showed that although the Pi index is a strong indicator of grain yield superiority and broad adaptability, its capacity to determine grain yield stability does not fully match the AMMI model, which provides more accurate view of genotypic responses to environments. The Pi index initially shows the grain yield superiority and could be considered as an indicator for grain yield stability.

Keywords: bread wheat, grain yield, broad adaptability, yield stability, bread making quality

INTRODUCTION

According to published statistics, wheat production in Iran during the 2022-2023 cropping season was 16.619 million tons. This level of production was achieved from an area of 7.511 million hectares (2.800 million hectares irrigated and 4.711 million hectares rainfed) (Annonymus, 2024). Of the total production, 6.142 million tons were harvested from rainfed wheat and 10.477 million tons from irrigated wheat (Anonymous, 2024). The temperate agro-climatic zone is one of the major wheat producing regions in Iran and include the central provinces of the country, which have favorable ecologies for wheat production, and account for more than 28 percent of the irrigated wheat growing areas in Iran. Given the high potential of these regions for wheat production, it is very important to select and introduce high-yielding cultivars with yield stability and good baking quality, which is being pursued through the national bread wheat breeding program for temperate agro-climatic zone.

In recent years, the production of irrigated wheat in Iran has achieved significant success, mainly due to the release of high-yielding cultivars that have led to considerable increases in grain yield. However, the variability of environmental factors and the disease pressure exerted by pathogen population, such as rusts, may break the resistance of the commercial cultivars at any time, making them susceptible to diseases or other biotic and abiotic threats. In this context, it is crucial for wheat breeding programs to continuously develop and release improved cultivars and maintain adequate level of genetic diversity in the fields to create barrier against the incidence of new pathogen races. Examining the performance and adaptability of different genotypes in regions with different ecologies, which is usually conducted in the final stages of breeding programs, is of special importance. Reducing the volume of materials and selecting genotypes with better adaptability to diverse environmental conditions are among the objectives of such breeding programs (Hein, 1987; Pullman, 1995; Jensen, 1988).

The bread wheat breeding scheme in Iran has provided the opportunity to evaluate and select germplasm with broader adaptability, thus forming the basis for selecting advanced lines for evaluation in regional adaptability trials with higher performance and grain yield stability across a larger number of environmental conditions. Suitable and adapted cultivars have been selected and commercially released using this scheme. For example, the cv. Pishtaz and cv. Shiraz were identified and released from the adaptability trials of 1996 under the temperate climate wheat breeding program, cv. Bahar from the adaptability trials of 2000, cv. Parsi and cv. Sivand from the adaptability trials of 2005, cv. Sirvan from the terminal drought adaptability trials of 2006, cv. Baharan from the terminal drought adaptability trials of 2010, cv. Rakhshan from the adaptability trials of 2011, cv. Talaei from the adaptability trials of 2012, cv. Torabi from the adaptability trials of 2013, and cv. Amin and cv. Farin from the adaptability trial of 2015, "Danesh" from the adaptability trial of 2017 and cv. Bamdad and cv. Sepehr from adaptability trials of 2018 have been selected and commercially released from this program.

Depending on the objectives and ecologies of the target regions, two entirely different concepts of yield stability, referred to as static stability and dynamic stability, have been defined (Becker and Lyon, 1988). Both concepts are valuable to breeders, depending on the trait of interest. In the static concept, a stable genotype exhibits consistent performance in variable environmental conditions, showing no deviation from the desired trait level. In other word, the variance of trait of interest in different environments is zero. In contrast, the dynamic concept observes a predictable reaction to the environment, where a stable genotype does not exhibit deviation from this reaction to the environment. This type of stability is termed agronomic stability and can be distinguished from the biological stability concept, which is equivalent to the static concept (Becker, 1981).

Numerous statistical methods have been used by researchers to assess phenotypic stability and analyze the genotype × environment (G × E) interaction effects. These methods include calculating the environmental variance (Romer, 1917), environmental coefficient of variation (Francis and Kannenberg, 1978), Wrick's ecovalence (1962), Shukla's stability variance (1972), Finley and Wilkinson's regression method (1963), Perkins and Jinks' method (1968), Eberhart and Russell's method (1966), Hanson's method (1970), Tai's method (1971), and Gauch's method (1992). Romagosa and Fox (1993) classified agronomic stability assessment methods into four categories: variance-based methods, regression methods, non-parametric methods, and multivariate methods.

Lin *et al.* (1986) categorized various methods for determining stability parameters into four distinct groups: Group 1 (Type I): based on this type, a stable genotype has the least environmental variance. Group 2 (Type II): the stability assessment methods in this group identify a genotype as stable when its reaction across various environments is equal to the average reaction of all genotypes. Group 3 (Type III): according to the methods in this group, stable genotypes exhibit the least mean squares of deviation from regression on the environmental index. Group 4 (Type IV): The methods in this group consider the existence of the least within-location variance over years as the basis for genotype stability.

The additive main effect and multiplicative interaction (AMMI) method proposed by Gauch (1992) was a significant advance in the analysis and interpretation of G × E interaction. This method has been thoroughly explained by Farshadfar, 1997 and used by others (Crossa *et al.*, 1990). With this method main effects (genotypes and environments) are first accounted for by a regular analysis of variance, and then the interaction (G × E) is analyzed by a principal component analysis which leads to identification of stable genotypes as well as genotypes with wide or specific adaptation in an easier manner. AMMI has been successfully used to estimate stability and its heritability, adaptation and G × E interaction in different crops.

Ortiz *et al.* (2001) used a complete diallel cross among eight bread wheat lines studied for several seasons in two locations, and estimated heritability of some stability parameters including interaction principal component axes (IPCA). Their result showed a considerable narrow sense heritability for IPCA1 of the AMMI method (h^2 = 0.461) followed to coefficient of phenotypic variation. AMMI analysis was used for root yield by Manrique and Hermann (2001) in sweet potato clones studied over four different locations. Their results showed that, none of the high-yielding clones had satisfactory stability for total root yield. The biplot for beta-carotene content in roots showed stability for five of the investigated clones.

Using AMMI and biplot method, if the first two components are significant, the biplot can be used to examine the status of genotypes alongside the test environments in two dimensions. In this case, the most stable genotypes will have values of the two components close to zero. Due to the practical information obtained from the AMMI method, it is employed in the yield stability analysis of adaptability trials of irrigated bread wheat program for temperate agro-climatic climates zones in Iran (Najafian *et al.*, 2010).

Lin and Binns (1988) introduced the Pi index, and showed it effectively identifies genotypes that combine high performance and stability across environments**.** Farias *et al.* (1997) found Pi index correlated well with regression-based stability methods, and is useful for evaluating cotton cultivar stability in multiple environments. Costa *et al.* (2022) used Pi index and found this index helped to rank soybean cultivars, highlighting those with consistent high seed yield and adaptability across environments. Cargnelutti Filho and Silva (2018) using this index demonstrated that sufficient number of environments is needed for reliable Pi index estimates, and confirmed its efficiency in stability and adaptability analyses**.** Pour-Aboughadareh (2022) reviewed and highlighted that Pi index is widely recognized as a simple and effective tool for assessing genotype stability and genotype-by-environment interactions. Carvalho *et al.* (2024) found that Pi index reliably identifies superior and stable cultivars, and emphasized its relevance in modern plant breeding programs for decision-making.

The aim of the present research was to select the superior advanced bread wheat breeding lines evaluated in 2020 ERWYT trial of irrigated bread wheat breeding program for the temperate agro-climatic zone of Iran, based on grain yield and yield stability and the adaptation to the environments using Ranking and Pi index methods in one data set and AMMI and Pi index in another data set. The efficiency of these methods have been also been compared.

MATERIALS AND METHODS

Plant materials

This study was carried-out in two separated experiments. In the first experiment (ERWYT-M-99), 20 bread wheat genotypes were evaluated, included 16 promising irrigated bread wheat lines selected from advanced regional bread wheat yield trials (ARWYT), along two control cultivars (cv. Amin and cv. Farin), and two promising lines M-95-10 and M-96-13. In the second experiment (ERWYT-MDH-99), 19 elite bread wheat doubled haploid lines were evaluated, along with three control cultivars: cv. Amin, cv. Farin, and the French bread wheat cv. Radia (a total of 22 genotypes). Both experiments were conducted over two consecutive growing seasons (2020-21 and 2021-22) in eight research field stations in temperate agro-climatic zone of Iran. In five research field stations (Karaj, Kermanshah, Zarghan, Broujerd, and Mashhad) trails were grown under optimal irrigation conditions, while in other three (Neishabour, Isfahan, and Varamin) terminal drought stress, from the heading stage on ward, was imposed. The name and parentage of of the evaluated lines are presented in Tables 1 and 2.

Table 1. Name and parentage of advance bread wheat lines evaluated in the ERWYT-M-99 adaptability trials under optimum and terminal drought conditions in 2020-2022 cropping seasons in eight research filed stations in the temperate agro-climatic zone

Genotype code	Name/Parentage
M-99-1	Amin
M-99-2	Farin
M-99-3	M-95-10 (WBLL1*2/VIVITSI//AKURI/3/WBLL1*2/BRAMBLING)
M-99-4	M-96-13 (SW89.5277/BORL95//SKAUZ/3/PRL/2*PASTOR/4/HEILO/5/WHEAR/SOKOLL)
M-99-5	CMH80-279/Pastor//Sivand/3/Parsi
M-99-6	SUNCO/2*PASTOR//Parsi/3/Niknejad
M-99-7	ATTILA/BABAX//PASTOR/3/Sivand/4/WS-85-10
M-99-8	ATTILA/BABAX//PASTOR/3/Sivand/4/WS-85-10
M-99-9	WAXWING*2/KIRITATI//NIKNEJAD
M-99-10	W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1/7/CNO79//PF70354/MUS/3/PASTOR/4/BAV92/5/FRET2/…
M-99-11	SERI.1B*2/3/KAUZ*2/BOW//KAUZ*2/4/MNCH/3*BCN
M-99-12	WBLL1*2/4/BABAX/LR42//BABAX/3/BABAX/LR42//BABAX*2/5/BOKOTA
M-99-13	WBLL1*2/BRAMBLING/4/BABAX/LR42//BABAX*2/3/SHAMA*2/5/MUU #1//PBW343*2/KUKUNA/3/MUU
M-99-14	THELIN/2*WBLL1/5/KAUZ//ALTAR 84/AOS/3/KAUZ/4/SW94.15464/6/QUELEA/7/QUELEA
M-99-15	SAUAL/YANAC//SAUAL/3/BECARD/QUAIU #1
M-99-16	ATTILA*2/PBW65*2//TNMU/5/SSERI1/CHIBIA/4/BAV92//IRENA/KAUZ/3/HUITES/6/ATTILA*2/PBW65*2//KACHU
M-99-17	PRL/2*PASTOR*2//FH6-1-7*2/3/KFA/2*KACHU
M-99-18	ONIX/KBIRD*2//KFA/2*KACHU
M-99-19	BABAX/LR42//BABAX*2/3/SHAMA/4/KINGBIRD #1/5/QUAIU/6/2*COPIO
M-99-20	PREMIO//PI 610750/PIFED*2/3/KSW/SAUAL//SAUAL

Table 2. Name and parentage of the irrigated bread wheat doubled haploid lines evaluated in the ERWYT-MDH-99 adaptability trials under optimum and terminal drought conditions in 2020-2022 cropping seasons in eight research filed stations in the temperate agro-climatic zone stations

Genotype code	Name/Parentage
IRMDH-99-1	Amin
IRMDH-99-2	Farin
IRMDH-99-3	Radia
IRMDH-99-4	SHARP/3/PRL/SARA//TSI/VEE#5/5/VEE/LIRA//BOW/3/BCN/4/KAUZ/6/Pishgam
IRMDH-99-5	SHARP/3/PRL/SARA//TSI/VEE#5/5/VEE/LIRA//BOW/3/BCN/4/KAUZ/6/Pishgam
IRMDH-99-6	SHARP/3/PRL/SARA//TSI/VEE#5/5/VEE/LIRA//BOW/3/BCN/4/KAUZ/6/Pishgam
IRMDH-99-7	SHARP/3/PRL/SARA//TSI/VEE#5/5/VEE/LIRA//BOW/3/BCN/4/KAUZ/6/Pishgam
IRMDH-99-8	SHARP/3/PRL/SARA//TSI/VEE#5/5/VEE/LIRA//BOW/3/BCN/4/KAUZ/6/Pishgam
IRMDH-99-9	Evwyt2/Azd//Rsh*2/10120/3/Azd//HD2172/V83035/4/Morvarid/5/Sirvan
IRMDH-99-10	Evwyt2/Azd//Rsh*2/10120/3/Azd//HD2172/V83035/4/Morvarid/5/Sirvan
IRMDH-99-11	Evwyt2/Azd//Rsh*2/10120/3/Azd//HD2172/V83035/4/Morvarid/5/Sirvan
IRMDH-99-12	Evwyt2/Azd//Rsh*2/10120/3/Azd//HD2172/V83035/4/Morvarid/5/Sirvan
IRMDH-99-13	Evwyt2/Azd//Rsh*2/10120/3/Azd//HD2172/V83035/4/Morvarid/5/Sirvan
IRMDH-99-14	Evwyt2/Azd//Rsh*2/10120/3/Azd//HD2172/V83035/4/Morvarid/5/Sirvan
IRMDH-99-15	Evwyt2/Azd//Rsh*2/10120/3/Azd//HD2172/V83035/4/Morvarid/5/Sirvan
IRMDH-99-16	BABAX/3/OASIS/SKAUZ//4*BCN/4/PASTOR/5/Pishtaz/6/Parsi
IRMDH-99-17	BABAX/3/OASIS/SKAUZ//4*BCN/4/PASTOR/5/Pishtaz/6/Parsi
IRMDH-99-18	BABAX/3/OASIS/SKAUZ//4*BCN/4/PASTOR/5/Pishtaz/6/Parsi
IRMDH-99-19	BABAX/3/OASIS/SKAUZ//4*BCN/4/PASTOR/5/Pishtaz/6/Parsi
IRMDH-99-20	CHEN/AE.SQ//2*OPATA/3/TILHI/4/ATTILA/2*PASTOR/5/Morvarid/6/Parsi
IRMDH-99-21	CHEN/AE.SQ//2*OPATA/3/TILHI/4/ATTILA/2*PASTOR/5/Morvarid/6/Parsi
IRMDH-99-22	CHEN/AE.SQ//2*OPATA/3/TILHI/4/ATTILA/2*PASTOR/5/Morvarid/6/Parsi

Planting and evaluation

In all research field stations, the experiments were planted in the first half of November. Plot dimensions differed between management regimes: under optimal irrigation conditions were 6 × 1.2 meters with harvested area of 6 m² (5 × 1.2 meter), while, under terminal drought stress conditions, the experimental plot dimensions were 4 ×1.2 meters with a harvested area of 3.6 m² (1.2 × 3 meters). In all research field stations, the experiments were conducted using randomized complete block design with three replications. Recommended agronomic practices were followed in all research field stations. At harvest, grain yield for each plot was weighed and recorded, and converted to tons hectare^{-1}.

Statistical analysis

Combined analysis of variance was performed for both experiments (16 environments) using SAS software version 9 (SAS Institute, 2013). Combined analysis of variance for data of optimal irrigation and terminal drought stress conditions was also performed separately. To identify high- grain yield potential lines, the mean grain yield of all lines across the stations was calculated. Grain yield stability analysis for the second experiment (ERWYT-MDH-99), where the three-way interactions and genotype effects were significant, was performed using the AMMI method.

For the first experiment (ERWYT-M-99), where the genotype × year and genotype × location interactions in ANOVA were not significant, the grain yield stability of the lines was assessed using the non-parametric rank method. The performance rank of each line in each region was determined, and the overall average rank, designated as R, was calculated across all research field stations. The standard deviation of the rank, designated as SDR, was also used to identify grain yield stable genotypes. Additionally, to simultaneously examine both performance and grain yield stability, the relative superiority index (Pi) was employed in both experiments. This index is calculated using the grain yield of each genotype in each environment according to Lin and Binns (1988).

RESULTS

A-Analysis of variance and grain yield performance

A-1. ERWYT-M-99 yield trials:

Combined analysis of variance was performed for data from eight research field stations in two growing seasons (2020-21 and 2021-22) based on mathematical expectations and revealed highly significant effects of genotype ($p \leq 0.01$) and location ($p \leq 0.01$) on grain yield (Table 3). While the genotype × year and genotype × location interaction effects on grain yield were not significant, the significant three-way genotype × year × location interaction ($p \leq 0.01$) indicated that performance of genotypes varied across locations between years.

Table 3. Combined analysis of variance for ERWYT-M-99 for grain yield in two cropping seasons (2020-21 and 2021-22 at eight research field stations.

S. O. V.	Df	SS	MS	F
Year (Y)	1	48.30	48.30	0.13
Location (L)	7	2606.28	372.32	22.78**
Y × L	7	114.40	16.34	2.95*
Rep.(Y × L)	32	177.36	5.54	9.12
Genotype (G)	19	78.32	4.12	2.86**
G × L	133	191.51	1.44	1.17
G × Y	19	16.13	0.85	0.69
G × Y × L	133	163.34	1.23	2.02**
Error	608	369.43	0.61	-
C.V. = 11.71%				

* and **: Significant at the 5% and 1% probability levels, respectively.

A separate combined analysis of variance was also performed for optimal irrigation conditions (five research field stations) and terminal drought stress conditions (three research field stations). In the analysis for optimal irrigation conditions, the location, genotype and genotype × year × location interaction effects on grain yield were significant. In the drought terminal stress conditions, only the effects of location, year × location, and genotype × year × location on grain yield were significant (results are not presented).

Total mean of grain yield of genotypes for all locations, as well as averages for optimal irrigation and terminal drought stress conditions are presented separately, in Table 4. There was significant yield differences among genotypes, with 970 kg ha^{-1} difference between the highest and lowest yielding entries. As can be seen, genotypes number 5, 11, 9, and 15 ranked second to fifth with grain yields of 7.160, 7.030, 7.005, and 6.846 tons ha^{-1}, respectively. The control cv. Amin and cv. Farin had grain yields of 7.180 and 6.635 tons ha^{-1} ranked first and eleventh, respectively. The grain yields of other genotypes ranged from 6.209 to 6.787 tons ha^{-1} (Table 4). The superior lines also had high grain yields under optimal irrigation conditions. Under terminal drought stress conditions, M-99-9 and M-99-11 were among the best and performed better than the other lines.

The mean grain yield in the research field stations showed that Broujerd, Zarghan and

Kermanshah had grain yield potentials of 10.352, 7.599, and 6.833 tons ha^{-1}, respectively. The Isfahan research field station (terminal drought stress conditions) had the lowest mean grain yield of 4.871 tons ha^{-1} among the stations, which was mainly due to the imposed terminal drought stress and also lack of winter rainfall (Table 5).

Table 4. Mean grain yield of bread wheat lines in ERWYT-M-99 under optimal irrigation (OI) and terminal drought stress (TDS) conditions in eight locations two-cropping season

Genotype code	Grand mean grain yield (tons ha^{-1})	Overall mean rank in all locations	Mean grain yield in OI conditions (tons ha^{-1})	Mean grain yield in TDS conditions (tons ha^{-1})
M-99-1 (Amin)	7.180	1	7.985	5.839
M-99-2 (Farin)	6.635	11	7.253	5.604
M-99-3 (M-95-10)	6.787	6	7.496	5.606
M-99-4 (M-96-13)	6.657	10	7.214	5.729
M-99-5	7.160	2	8.095	5.602
M-99-6	6.738	8	7.621	5.266
M-99-7	6.712	9	7.515	5.374
M-99-8	6.765	7	7.418	5.677
M-99-9	7.005	4	7.792	5.692
M-99-10	6.624	12	7.265	5.556
M-99-11	7.030	3	7.702	5.910
M-99-12	6.424	15	6.991	5.479
M-99-13	6.597	13	7.184	5.617
M-99-14	6.209	20	6.629	5.507
M-99-15	6.846	5	7.754	5.332
M-99-16	6.340	17	6.833	5.519
M-99-17	6.333	18	7.037	5.159
M-99-18	6.386	16	7.061	5.262
M-99-19	6.233	19	6.708	5.443
M-99-20	6.429	14	6.958	5.547
Mean	6.654	-	7.325	5.536
LSD5%	0.447	-	0.637	0.533

Table 5. Mean grain yield of eight test locations of ERWYT-M-99 using two-cropping season data

Field station name	Mean grain yield (tons ha^{-1})	Mean rank
Broujerd	10.352	1
Zarqhan	7.599	2
Kermanshah	6.833	3
Varamin	6.770	4
Mashhad	5.981	5
Karaj	5.862	6
Neishabour	4.967	7
Isfahan	4.871	8
LSD5%	1.234	-

A-2. ERWYT-MDH-99 yield trials:

Combined analysis of variance was performed using a mixed model approach, with year and location considered as random effects and genotype as a fixed effect. Combined analysis of variance showed that the effect of replication within (year × location) was significant, and therefore, the interaction effect of year × location was tested, which also confirmed the observed significance. Consequently, the effects of year and location, along with their interaction effect, were tested, which showed highly significant location effect ($p \leq 0.01$). Given the significance of the three-way interaction effect, the two-way interaction effects of genotype × year and genotype × location were also tested, where only the interaction effect of genotype × location was significant.

The effect of genotype was significant (Table 6), indicating that there is significant differences among genotypes for the grain yield. The significant genotype × location and genotype × year × location interactions demonstrated that genotypes performance was inconsistent across different locations and years. Therefore, separate combined analyses of variance for locations under optimal irrigation and terminal drought stress conditions showed that under optimal conditions (five locations), the effects of location, year × location, genotype × location, and genotype were significant, whereas under terminal drought stress conditions, only the effects of genotype and year × location were significant (results are not presented).

Table 6. Combined analysis of variance for grain yield of ERWYT-MDH-99 in two cropping seasons and eight research field stations.

S. O.V.	Df	SS	MS	F
Year (Y)	1	0.61	0.61	0.02
Location (L)	7	3354.20	479.17	13.07**
Y × L	7	256.57	36.65	22.51**
Rep.(Y × L)	32	52.11	1.62	4.08
G	21	56.62	2.70	1.77*
G × L	147	223.37	1.52	1.31*
G × Y	21	18.04	0.86	0.74^{ns}
G × Y× L	147	171.12	1.16	1.76**
Error	672	444.59	0.66	-
C.V. = 11.95%				

* and **: Significant at the 5% and 1% probability levels, respectively.

Grand mean grain yield of genotypes in two-cropping seasons for all locations in optimal irrigation and terminal drought stress conditions, is presented separately in Table 7. The mean grain yield across all locations showed an 820 kg ha^{-1} difference between the highest and lowest yielding genotypes. Genotypes; M-DH-99-5, M-DH-99-10, M-DH-99-9, M-DH-99-11, and M-DH-99-8 ranked from first to sixth with grain yields of 7.275, 7.132, 7.108, 7.069, and 6.942 t ha^{-1}, respectively. The control cultivars; cv. Amin and cv. Farin with grain yields of 7.246 and 6.630 t ha^{-1}, ranking second and seventeenth, respectively. Grain yields of other genotype ranged from 6.942 to 6.452 t ha^{-1}. Under optimal irrigation conditions, the superior lines demonstrated high grain yield potential, producing 7.700 to more than 8.000 t ha^{-1}. Under terminal drought stress conditions, these genotypes showed grain yields ≥5.600 t ha^{-1}. Doubled haploid lies; M-DH-99-9, M-DH-99-10, and M-DH-99-11 performed consistently superior in both optimal irrigation and terminal drought stress conditions, indicating their wider adaptation. Final cultivar selection should also consider additional agronomic traits as well as grain yield.

Table 7. Mean grain yield of bread wheat doubled haploid lines in ERWYT-M-99 under optimal irrigation (OI) and terminal drought stressed conditions in eight locations and two cropping seasons

Genotype code	Grand mean grain yield (tons ha^{-1})	Overall mean rank in all locations	Mean grain yield in OI conditions (tons ha^{-1})	Mean grain yield in TDS conditions (tons ha^{-1})
M-DH99-1 (Amin)	7.246	2	8.136	5.763
M-DH99-2 (Farin)	6.630	17	7.115	5.820
M-DH99-3 (Radia)	6.689	15	7.572	5.216
M-DH99-4	6.740	13	7.544	5.399
M-DH99-5	7.275	1	8.389	5.419
M-DH99-6	6.815	8	7.688	5.359
M-DH99-7	6.771	11	7.771	5.104
M-DH99-8	6.942	6	7.836	5.453
M-DH99-9	7.108	4	7.874	5.831
M-DH99-10	7.132	3	8.002	5.681
M-DH99-11	7.069	5	7.737	5.954
M-DH99-12	6.814	9	7.638	5.442
M-DH99-13	6.537	20	7.005	5.757
M-DH99-14	6.481	21	7.295	5.125
M-DH99-15	6.748	12	7.658	5.231
M-DH99-16	6.892	7	7.724	5.506
M-DH99-17	6.561	19	7.314	5.305
M-DH99-18	6.621	18	7.280	5.523
M-DH99-19	6.722	14	7.612	5.239
M-DH99-20	6.453	22	7.311	5.024
M-DH99-21	6.795	10	7.691	5.301
M-DH99-22	6.682	16	7.412	5.467
Mean	6.806	-	7.618	5.451
LSD5%	0.435	-	0.595	0.644

Significant variation in grain yield was observed among the test locations (Table 8). The highest-yielding locations were Broujerd (10.621 t ha^{-1}), Zarghan (7.992 t ha^{-1}), and Kermanshah (7.451 t ha^{-1}), respectively. In contrast, the Neishabour research field station recorded the lowest mean grain yield (4.718 t ha^{-1}), which is can be attributed to the combined effects of terminal drought stress and insufficient winter rainfall.

Table 8. Mean grain yield of eight test locations of ERWYT-M-DH99 using two cropping season data

Filed station name	Mean grain yield (tons ha^{-1})	Mean rank
Broujerd	10.621	1
Zarghan	7.992	2
Kermanshah	7.451	3
Varamin	6.672	4
Karaj	6.038	5
Mashhad	5.989	6
Isfahan	4.963	7
Neishabour	4.718	8
LSD5%	1.762	-

B- Grain yield stability analysis

B-1. ERWYT-M-99:

Grain yield stability and adaptability of the ERWYT-M-99 lines were assessed using the rank analysis and the Pi index. The results showed that the genotype e× environment interaction effect on grain yield using AMMI method was not significant (results are not presented), therefore, this method was not used. The results of rank analysis using the mean grain yield of genotypes are presented in Table 9. The results showed that bread wheat doubled haploid lines; M-DH-99-5, M-DH-99-9, M-DH-99-11, M-DH-99-15 and control cv. Amin was identified as the superior genotypes for grain yield, since had higher mean grain yields than mean of all genotypes. These genotypes had moderate to high standard deviation ranks and had the lowest Pi index values (Table 9).

The low value of the Pi index indicated the grain yield stability and relative wide adaptability of these genotypes. Lin and Binns (1988) and Costa *et al.* (2022) have considered the low values of the Pi index as an indicator of grain yield superiority and, to some extents, grain yield stability of genotypes. It should be noted that in selection of superior genotypes, in addition to grain yield, agronomic characteristics, disease resistance and baking quality of the genotypes were also considered (results are not presented). This information can help to simultaneously improve grain yield and quality under different environmental conditions.

Table 9. Mean grain yield and yield stability parameters of bread wheat genotypes evaluated in ERWYT-M-99 in eight locations and two cropping seasons (16 environments)

Genotype code	MEAN_M	STD_M	CV_M	MEAN_R	STD_R	CV_R	SUM_R	YIR %	Pi
M-99-1 (Amin)	7.180	1.899	26.443	5.81	5.14	88.45	93	108	0.20
M-99-2 (Farin)	6.635	1.831	27.603	10.44	6.39	61.19	167	100	0.69
M-99-3 (M-95-10)	6.787	2.106	31.026	9.56	5.68	59.40	153	102	0.54
M-99-4 (M-96-13)	6.657	2.085	31.319	10.19	5.26	51.60	163	100	0.77
M-99-5	7.160	2.026	28.290	6.94	6.06	87.36	111	108	0.18
M-99-6	6.738	2.256	33.479	10.81	5.83	53.95	173	101	0.50
M-99-7	6.712	1.927	28.706	11.50	4.95	43.07	184	101	0.59
M-99-8	6.765	1.859	27.479	9.13	3.63	39.79	146	102	0.47
M-99-9	7.005	1.892	27.018	8.50	6.85	80.60	136	105	0.27
M-99-10	6.624	1.850	27.934	11.06	4.96	44.83	177	100	0.69
M-99-11	7.030	1.909	27.150	6.94	5.70	82.13	111	106	0.34
M-99-12	6.424	1.787	27.815	12.75	4.45	34.90	204	97	0.91
M-99-13	6.596	1.795	27.217	10.31	5.58	54.13	165	99	0.74
M-99-14	6.209	1.768	28.472	13.06	6.44	49.33	209	93	1.45
M-99-15	6.846	2.221	32.439	9.94	4.89	49.23	159	103	0.37
M-99-16	6.340	1.547	24.404	12.31	6.00	48.71	197	95	1.07
M-99-17	6.333	1.736	27.417	12.50	6.15	49.23	200	95	1.00
M-99-18	6.387	1.624	25.429	12.94	4.74	36.63	207	96	0.88
M-99-19	6.233	1.542	24.740	13.69	4.50	32.86	219	94	1.18
M-99-20	6.429	1.460	22.718	11.81	6.09	51.56	189	97	1.02

MEAN_M: Mean grain yield (tons ha^{-1}, STD_M: Standard deviation of the mean, CV_M: Coefficient of variation of the mean, MEAN_R: Mean rank, STD_R: Standard deviation of the rank, CV_R: Coefficient of variation of the rank, SUM_R: Total rank; YIR: Percentage of mean grain yield compared to the mean grain yield of genotypes; Pi: Productivity and stability index.

B-2. ERWYT-MDH-99:

Considering the significance of the genotype × location interaction in the combined analysisof variance using the AMMI method, the grain stability and adaptability of the genotypes were estimated. Results of the AMMI analysis showed that the effects of environment and genotype were significant, and the genotype × environment interaction sum of squares accounted for 64.25% of the first two interaction principal components (IPC1 and IPC2) axes (Table 10). Since mean grain yield of two cropping seasons were used for the AMMI analysis, the genotype × environment interaction was not significant. However, given the significance of the first two interaction principal components, a biplot of the first two AMMI components was depicted to examine the wide and specific adaptation of the genotypes (Fig. 1). Two IPCs used in construction of biplot showed contribution of each genotype and location to interaction effect. Therefore, genotypes and locations near to zero point of each IPCs showed lower contribution in G × E, hence more adaptability and grain yield stability.

Table 10. Results of AMMI analysis of variance for evaluated bread wheat doubled haploid lines in ERWYT-MDH-99 in two cropping seasons and eight research field stations

S.O.V.	Df	AMMI SS	AMMI MS	F	Probability	Percent	Ac. percent
Environment (E)	7	1677.09**	239.6	362.1	0.000	–	–
Genotype (G)	21	28.31**	1.35	2.04	0.004	–	–
G × E	147	111.68	0.76	1.15	0.13	–	–
IPC1	27	39.32**	1.46	2.20	0.000	35.21	35.21
IPC2	25	32.43**	1.30	1.96	0.003	29.04	64.25
IPC3	23	16.94	0.74	1.10	0.32	15.16	79.41
IPC4	21	8.70	0.42	0.63	0.90	7.88	87.29
IPC5	19	7.40	0.39	0.59	0.91	6.70	93.99

**: significant at the 1% probability level.

Considering the biplot diagram, bread wheat doubled haploid line; M-DH-99-8, M-DH-99-9, M-Dh-99-10, M-Dh-99-14, M-Dh-99-17 and to some extents M-Dh-99-18 showed the highest wide adaptation, respectively, as their location in the biplot is near to center point and zero cross point of two IPC's Ffig. 1). This implies that they did not contribute to interaction effect. In addition, genotypes M-DH-99-2, M-DH-99-12, M-DH-99-11, M-DH-99-22 showed greater adaptability to terminal drought stress conditions, while genotypes M-DH-99-5, M-DH-99-7, M-DH-99-19, M-DH-99-21, M-DH-99-20 showed the highest adaptability, respectively, to optimum irrigation conditions (Zarghan and Broujerd). The superior lines for grain yield (genotypes 5, 8, 9, 10, and 11, respectively), particularly genotypes MHD-99-9 and M-DH-99-10, demonstrated reasonable wide adaptation (Fig. 1). This type of interpretation has been well documented by Gauch (1992), Crossa *et al.* (1990) and Najafian *et al.* (2010).

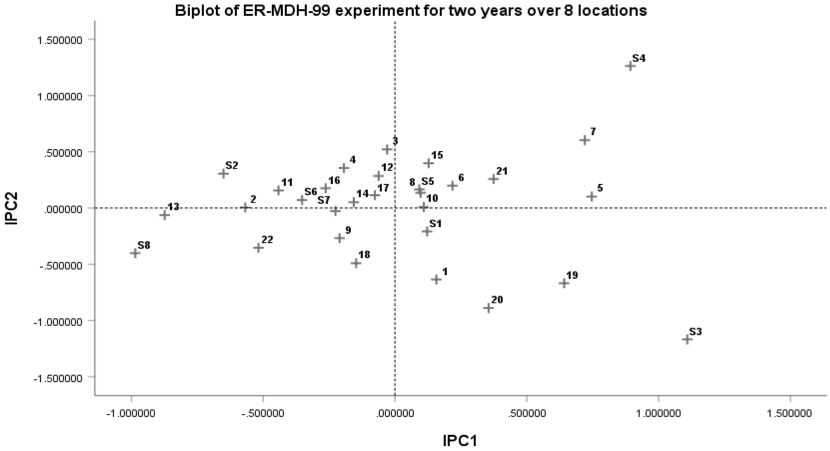

Fig. 1. Biplot diagram of AMMI analysis for the ERWYT-MDH-99 trial in two cropping seasons and eight research field stations**.** S1: Karaj, S2: Kermanshah, S3: Zarghan, S4: Broujerd, S5: Mashhad, S6: Neishabour, S7: Isfahan, S8: Varamin

To evaluate the grain yield stability of the doubled haploid lines, the rank method and Pi index were also used. The results of rank analysis for the evaluated genotypes using two cropping seasons and eight filed stations experimental data are presented in Table 11. Complementary analysis using the Pi index confirmed that high-yielding genotypes M-DH-99-5, M-DH-99-8, M-DH-99-9, M-DH-99-10, and M-DH-99-11 had the lowest Pi values (0.20-0.40) as well as the lowest STD-R (except M-DH-99-5). Therefore, these genotypes had higher grain yield stability (Table 9).

Table 11. Mean grain yield and yield stability parameters of bread wheat genotypes evaluated in ERWYT-MDH-99 in eight locations and two cropping seasons (16 environments)

Genotype	MEAN_M	STD_M	CV_M	MEAN_R	STD_R	CV_R	SUM_R	YIR %	Pi
M-DH99-1 (Amin)	7.246	1.862	25.702	6.81	5.53	81.15	109	106	0.26
M-DH99-2 (Farin)	6.629	1.913	28.861	12.56	6.54	52.07	201	97	0.87
M-DH99-3 (Radia)	6.689	2.278	34.058	14.50	5.90	40.68	232	98	0.62
M-DH99-4	6.740	2.029	30.113	12.94	6.40	49.49	207	99	0.62
M-DH99-5	7.275	2.607	35.831	7.75	7.36	94.99	124	107	0.20
M-DH99-6	6.815	2.145	31.471	12.50	5.81	46.46	200	100	0.43
M-DH99-7	6.771	2.315	34.190	11.88	5.60	47.13	190	99	0.59
M-DH99-8	6.942	2.205	31.762	9.88	5.82	58.92	158	102	0.35
M-DH99-9	7.108	1.950	27.435	8.25	5.62	68.07	132	104	0.32
M-DH99-10	7.132	1.967	27.577	7.63	4.33	56.84	122	105	0.21
M-DH99-11	7.068	1.823	25.797	8.13	5.51	67.84	130	104	0.40
M-DH99-12	6.815	1.936	28.412	11.25	5.71	50.75	180	100	0.55
M-DH99-13	6.537	1.865	28.530	13.06	7.66	58.67	209	96	1.18
M-DH99-14	6.481	1.787	27.579	14.75	6.79	46.02	236	95	0.95
M-DH99-15	6.748	2.083	30.867	12.88	5.52	42.91	206	99	0.55
M-DH99-16	6.892	1.774	25.747	10.25	5.39	52.54	164	101	0.56
M-DH99-17	6.561	1.852	28.229	13.56	5.48	40.38	217	96	0.81
M-DH99-18	6.621	1.815	27.420	12.75	5.54	43.48	204	97	0.80
M-DH99-19	6.722	2.271	33.791	12.63	7.22	57.18	202	99	0.62
M-DH99-20	6.453	2.058	31.892	16.13	6.37	39.47	258	95	0.98
M-DH99-21	6.795	1.956	28.787	11.25	6.29	55.89	180	100	0.57
M-DH99-22	6.683	1.586	23.731	12.00	5.38	44.82	192	98	0.86

MEAN_M: Mean grain yield (tons ha^{-1}, STD_M: Standard deviation of the mean, CV_M: Coefficient of variation of the mean, MEAN_R: Mean rank, STD_R: Standard deviation of the rank, CV_R: Coefficient of variation of the rank, SUM_R: Total rank; YIR: Percentage of mean grain yield compared to the mean grain yield of genotypes; Pi: Productivity and stability index.

Discussion

Understanding of genotype × environment interaction effect in plant breeding is very important, particularly for breeding programs targeting diverse agro-ecological zones. The temperate agro-climatic zones of Iran is characterized by significant environmental variation due to environmental factors such as terminal drought stress, salinity, soil degradation, etc. Bread wheat cultivar development and recommendation for these regions requires comprehensive evaluation of the grain yield and yield stability as well as wide and specific adaptation for evaluated advanced lines in the breeding scheme.

AMMI method has been successfully used to estimate grain yiled stability and its heritability, adaptation and G × E interaction in various crops (Ortiz *et al.*, 2001; Manrique and Hermann, 2001; Najafian *et al.*, 2010). In the present study, we evaluated the elite bread wheat lines using both the AMMI model and the superiority index (Pi), which provides a joint assessment of performance and yield stability (Lin and Binns, 1988). The Pi index is widely used in crop breeding programs to assess yield stability of test genotype and their adaptability across multiple environments (Lin and Binns, 1986; Farias *et al.*, 1997; Costa *et al.*, 2022, Cargnelutti Filho and Silva, 2018).

In the first experiment (ERWYT-M-99), where the genotype × location × year interaction effect was not-significant, grain yield stability was assessed using non-parametric rank statistics and the Pi index. The results showed that genotypes M-99-5, M-99-9, M-99-11, and M-99-15 hadlower value of Pi index which implied their grain yield superiority and grain yield stability and wide adaptation. Interestingly, these genotypes did not show the lowest rank standard deviation (SDR), highlighting a key distinction between different yield stability concepts. The most yield stable genotype based on rank standard deviation was M-99-8. Pi index for this genotype was not the lowest.. Because of it's relatively lower grain yield and reasonable Pi value, this genotype was identified as less suitable for selection. The Pi index shows wide adaptation but not high grain yield stability. STD-R also shows grain yield stability while it is not a perfect indicator for wide adaptation. For this study, which focused on breeding high-yielding and environmentally friendly bread wheat cultivars, the Pi index is considered more practical parameter and led to the selection of genotypes with optimal combination of grain yield and yield stability as well as disease resistance and acceptable baking quality.

In the second experiment (ERWYT-MDH-99), the superior lines M-DH-99-5, M-DH-99-8, M-DH-99-9, M-DH-99-10, and M-DH-99-11, had low Pi values, confirming their grain yield superiority and wide adaptation. Due to significance genotype×location effect in ANOVA, AMMI method was used to evaluate adaptation and yield stability of the genotypes. Above mentioned genotypes showed relatively high wide adaptation. We observed partial concordance between the AMMI biplot and Pi index results, however, some genotypes (e.g., M-DH-99-14 and M-DH-17) identified as stable yield genotypes by AMMI showed higher Pi values, indicating that the Pi index is more strongly correlated with grain yield than with yield stability. It seems that the Pi index may be more useful when large number of experimental sites (Cargnelutti Filho and Silva, 2018). The genotype MDH-99-10 showed wide adaptation and yield stability based on all three methods (AMMI, Rank and Pi). The best genotype identified by Pi index was MDH-99-5 while its STD-R was high and its location in the AMMI biplot was also showed specific adaptation toward high yield potential locations.

Finally, M-99-15 and M-DH-99-10 lines were selected and released as new commercial cultivars (cv. Afrooz and cv. Mahlooji) based on integrated assessment of grain yield, yield stability (Pi and AMMI) as well as agronomic characteristics including baking quality properties. Our findings demonstrated that the Pi can be used as a reliable index for determination of grain yield superiority and wide adaptation, though its suitability for assessment of static yield stability is limited. Future research is required to compare the Pi index efficiency eith other established yield stability parameters (e.g. Eberhart and Russell, 1966; Wricke, 1962) across larger sets of test environments in bread wheat breeding programs. However, using AMMI and GGE biplot along with Pi index is still beneficial for bread wheat breeders for selection of superior advanced line with high grain yield and yield stability as well as wid.

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CONFLICT OF INTEREST

Authors declare that there is no conflict of interest among them.

ARTIFICIAL INTELLIGENCE TOOLS USE STATEMENT

Authors declare that ChatGPT was used for translation from Persian to English and refining and editing the text of the manuscript.

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