NARDI FUNDULEA, ROMANIA ROMANIAN AGRICULTURAL RESEARCH, NO. 40, 2023
www.incda-fundulea.ro; doi.org/10.59665/rar4017 Print ISSN 1222-4227; Online ISSN 2067-5720

GGE BIPLOT ELUCIDATION OF SPRING BARLEY YIELD PERFORMANCE UNDER MULTIFARIOUS CONDITIONS OF UKRAINE

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ABSTRACT

The present study aims to elucidate the peculiarities of yield performance and stability of spring barley cultivars in the multi-environment trial. Thirty six spring barley cultivars widespread in production conditions of Ukraine were tested in three different natural zones in three years. The strong cross-over genotype by environment interaction was revealed not only through different natural zones, but also in individual ecological niches in different years. The cultivars with high yield and stability have been identified. The most adapted to the conditions of Forest-Steppe were the cultivars MIP Bohun, MIP Myrnyi, MIP Saliut, MIP Azart; of Polissia - Avhur, MIP Myrnyi, Mirazh, Skarb, Alehro; of Steppe - Skarb and Sviatomykhailivskyi, Alehro, Krok, Statok. The cultivars MIP Myrnyi, Skarb, Avhur, MIP Saliut, and MIP Bohun could be highlighted as genotypes with relatively wide adaptability. Thus, the combination of these cultivars in production conditions can be considered as the most optimal for all natural zones of Ukraine. Our results also contribute to the further understanding the yield performance of spring barley in the genotype by environment interaction depend on different environmental and weather conditions. The cultivars distinguished in this study have a high value in plant breeding as genetic sources for developing new spring barley strains with increased adaptive potential for conditions of Ukraine and some other East European countries.

Keywords: *Hordeum vulgare* L., adaptability, genotype by environment interaction, GGE biplot.

INTRODUCTION

Barley (*Hordeum vulgare* L.) is one of the most ancient and widespread crops in agriculture. Ukraine is one of the largest producers and exporters of barley grain in the world (FAOstat, 2022). However, the bioclimatic potential of barley grain yield in Ukraine is far not completely achieved. The geographical territory of Ukraine is quite large and characterized with significant differences in the environmental resources among a number of natural zones. In recent years, the diversity of growing conditions has been exacerbated by global climate change, which lead to significant fluctuations in weather conditions during spring barley growing season (Moore and Lobell, 2015; Goncharova et al., 2021).

Taking into account the mentioned aspects, an increase in barley grain production is possible due to the development of new cultivars and applying effective technologies for their cultivation (Macholdt and Honermeier, 2016; Laidig et al., 2017; Vasilescu et al., 2020). At the same time, the role of a cultivar is fundamental. In this regard, it is necessary to develop new

Received 29 November 2022; accepted 1 February 2023. First Online: February, 2023. DII 2067-5720 RAR 2023-105

cultivars with a combination of increased yield potential and adaptability (Reynolds et al., 2021; Zhou et al., 2022). It should be distinguished wide and specific adaptability. The genotype providing stable phenotypic manifestation of the trait in various environmental conditions is characterized as one with wide adaptation. If the genotype predominates only in one environment, it is specifically adapted.

The latter is largely related to the phenomenon which is called genotype by environment interaction (Malosetti et al., 2013; van Eeuwijk et al., 2016; Saltz et al., 2018). As a result, the selection of a genotype in one environment may not ensure its advantages in another environment. Most researchers consider that plant breeding should be carried out purposefully for certain environmental conditions (Ceccarelli, 1996; Pswarayi et al., 2008).

That is, based on the determination of the most critical abiotic and biotic natural factors in the environment, combine the appropriate traits and alleles in the genotype (von Korff et al., 2008; Cammarano et al., 2021). Along with that, the possibility of creating varieties with a relatively wide adaptability should not be completely denied. However, such genotypes can "function effectively" also only in a certain set of environmental conditions. This set of conditions is defined as the target population of environments (Bustos-Korts et al., 2019).

The effectiveness of multi-environment trials for evaluation the genotype by environment interaction and identification of genotypes with specific or/and wide adaptation to the different target population of environments have been shown in a number of studies (Kendal et al., 2019; Akbarzai et al., 2022; Shibeshi and Mekiso, 2022).

Thus, the main aim of our study was to elucidate the peculiarities of yield performance and stability in a set of spring barley cultivars depending on different natural zones of Ukraine and years of trial, as well as to characterize test-environments in terms of discriminating power and representativeness.

MATERIAL AND METHODS

Multi-environment trial was carried out in 2016-2018 at three plant breeding institutions of the National Academy of Agrarian Sciences of Ukraine (NAAS) which located in different natural zones of Ukraine:

1) The V.M. Remeslo Myronivka Institute of Wheat of NAAS (MIW) (Forest-Steppe). Soils are deep, slightly leached chernozem. Humus content is 3.8%, nitrogen (N) - 59.0 mg/kg, phosphorous (P_2O_5) - 220.1 mg/kg, potassium (K_2O) - 96.0 mg/kg, pH - 5.8;

2) Nosivka Plant Breeding and Experimental Station of the V.M. Remeslo MIW of NAAS (NPBES) (Polissia). Soils are leached chernozem. Humus - 2.6%, N - 85.0 mg/kg, P_2O_5 - 122.0 mg/kg, K_2O - 75.0 mg/kg, pH - 4.6;

3) Institute of Agriculture of Steppe of NAAS (IAS) (Steppe). Soils are deep, clayic loamic chernozem. Humus - 4.6%, N - 120.0 mg/kg, P_2O_5 - 116.0 mg/kg, K_2O - 118.0 mg/kg, pH - 5.4. Meteorological conditions during spring barley growing season were significantly different in various ecological niches and years of trial, as well as relative to the long-term data in each site (Table 1).

The trial was laid out with randomized complete blocks in three replications in each natural zone. The size of elementary plot was 10 m^2. Thirty six spring barley cultivars widespread in production of Ukraine were tested. Thirty three cultivars were developed at major Ukrainian plant breeding institutions. These are Virazh (G1), Talisman Myronivskyi (G2), MIP Myrnyi (G3), MIP Saliut (G4), MIP Sotnyk (G5), MIP Azart (G6), and MIP Bohun (G7) (MIW); Imidzh (G8), Mirazh (G9), and Kozatskyi (G10) (NPBES); Statok (G11), Krok (G12), and Sviatomykhailivskyi (G13) (IAS); Voievoda (G14), Vsesvit (G15), Halaktyk (G16), Hetman (G17), Sviatohor (G18), Luka (G19), Vakula (G20), and Helios (G21) (Plant Breeding and Genetics Institute - National Center of Seed and Cultivar Investigation of NAAS); Dokaz (G22), Inkliuzyv (G23), Vzirets (G24), Vitrazh (G25), Veles (G26), Skarb (G27), Perl (G28), Alehro (G29), Avhur (G30), and Modern (G31) (Plant Production Institute nd. a. V.Ya. Yuriev of NAAS), Skif (G32), and

Svaroh (G33) (Institute of Feed Research and Agriculture of Podillia of NAAS). In addition, in the trial there were included three cultivars developed in foreign countries. These are Shakira (G34), KWS Bambina (G35) (both from Germany), and Brusefield (G36) (Canada).

Table 1. Meteorological conditions during spring barley growing season in different test-environments

Year	Code of the test-environment	Monthly air temperature (°C)				Monthly precipitation (mm)			
		April	May	June	July	April	May	June	July
MIW									
2018	M18	13.3	18.4	20.2	20.9	21.1	33.3	95.0	74.8
2017	M17	10.4	15.4	20.6	21.0	42.7	23.6	20.1	101.8
2016	M16	12.4	15.2	20.1	22.2	55.4	91.7	68.6	19.1
Long-term data		8.8	15.0	18.0	19.7	42.1	51.2	85.2	86.5
NPBES									
2018	N18	11.4	17.5	19.2	20.3	2.0	31.0	64.0	81.0
2017	N17	9.5	13.9	18.6	19.1	35.4	44.3	33.0	109.3
2016	N16	11.7	15.3	20.0	21.8	58.4	122.9	36.5	51.3
Long-term data		7.9	15.0	18.4	20.2	35.6	45.1	64.5	73.0
IAS									
2018	K18	15.0	20.8	22.9	23.7	10.0	25.5	29.2	141.0
2017	K17	10.9	17.6	23.1	23.2	23.5	10.7	22.2	66.0
2016	K16	13.9	17.3	22.2	24.3	52.3	153.2	107.5	15.5
Long-term data		8.9	15.3	18.6	20.0	36.0	45.0	66.0	72.0

The genotype main effects plus genotype by environment interaction (GGE) biplot model was applied for elucidation of the genotype by environment interaction, characterizing test-environments, differentiating genotypes and selection ones with an optimal combination of yield performance and its stability (Yan and Tinker, 2006; Yan et al., 2007). A graphical analysis was performed with non-commercial software GEA-R, version 4.1 (CIMMYT, Mexico).

RESULTS AND DISCUSSION

Yield performance of spring barley cultivars in different ecological niches and years of trial is shown in the Table 2. Obtained results indicate that there was a very high variation in the grain yield of spring barley cultivars depend on both different natural zones and different years of trial in certain ecological niches. For instance, in the environment M16 the maximal (max) yield (7.41 t ha^{-1}) was in the cultivar MIP Myrnyi (G3), and the minimal (min) yield (4.31 t ha^{-1}) was in the cultivar Modern (G31). Accordingly, limits of yield variation in other test-environments were as follows: in the M17 max (5.45 t ha^{-1}) in the cultivar MIP Bohun (G7), min (3.47 t ha^{-1}) in the cultivar Kozatskyi (G10); in the M18 max (3.77 t ha^{-1}) in the cultivar MIP Myrnyi (G3), min (1.44 t ha^{-1}) in the cultivar Brusefield (G36); in the N16 max (6.99 t ha^{-1}) in the cultivar MIP Myrnyi (G3), min (4.80 t ha^{-1}) in the cultivar Vitrazh (G25); in the N17 max (7.09 t ha^{-1}) in the cultivar Skarb (G27), min (5.46 t ha^{-1}) in the cultivar Vitrazh (G25); in the N18 max (6.55 t ha^{-1}) in the cultivar Skarb (G27), min (3.36 t ha^{-1}) in the cultivar Vitrazh (G25); in the K16 max (6.47 t ha^{-1}) in the cultivar Vakula (G20), min (4.09 t ha^{-1}) in the cultivar Kozatskyi (G10); in the K17 max (5.11 t ha^{-1}) in the cultivar Svaroh (G33), min (3.22 t ha^{-1}) in the cultivar Kozatskyi (G10); in the K18 max (4.35 t ha^{-1}) in the cultivar Halaktyk (G16), min (2.08 t ha^{-1}) in the cultivar Helios (G21). In the trial in general (three sites and three years) maximal yield was produced in the cultivars MIP Myrnyi (G3) (5.53 t ha^{-1}), Skarb (G27) (5.38 t ha^{-1}), and MIP Bohun (G7) (5.28 t ha^{-1}). The poorest yield performance was in the cultivar Kozatskyi (G10) (3.82 t ha^{-1}).

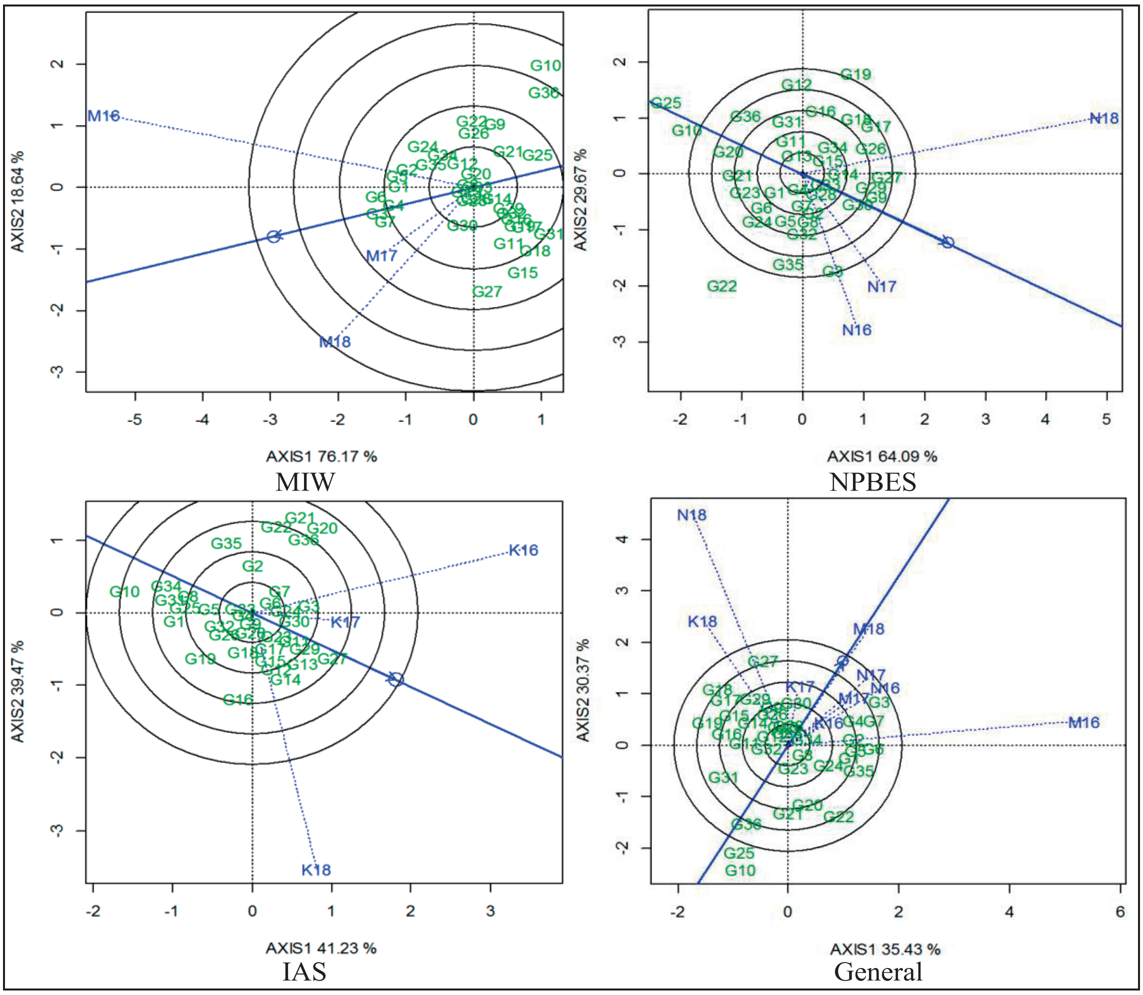
Furthermore, as we can see, there was a strong cross-over genotype by environment interaction in most of studied cultivars. This mean a significant change in yield ranks of the same genotype from one test-environment to another. For example, in a number of cultivars [Helios (G21), Shakira (G34), KWS Bambina (G35), Brusefield (G36), etc.] this interaction were high not only among different ecological niches but even in one niche in different year.

Table 2. Grain yield of spring barley cultivars in the multi-environment trial, t ha^{-1}

Code	Cultivar	Test-environment									Grand mean
		M16	M17	M18	N16	N17	N18	K16	K17	K18	
G1	Virazh	7.13	5.08	3.34	5.56	7.01	4.66	4.45	3.81	2.99	4.89
G2	Talisman	7.05	4.97	2.65	6.08	7.02	5.22	5.50	4.34	2.57	5.04
G3	MIP Myrnyi	7.41	5.23	3.77	6.99	7.08	5.38	5.81	4.89	3.22	5.53
G4	MIP Saliut	7.16	5.01	3.63	5.82	6.89	5.21	5.16	4.50	3.17	5.17
G5	MIP Sotnyk	7.22	4.83	2.87	6.44	6.49	4.82	5.06	3.46	3.10	4.92
G6	MIP Azart	7.38	5.19	3.64	5.85	6.82	4.43	5.65	4.15	3.17	5.14
G7	MIP Bohun	7.21	5.45	3.67	6.18	6.66	5.10	5.68	4.63	2.97	5.28
G8	Imidzh	5.92	4.53	2.99	6.27	6.90	5.13	4.77	3.63	2.85	4.78
G9	Mirazh	5.75	4.21	2.31	6.15	7.01	6.28	5.15	4.79	3.28	4.99
G10	Kozatskyi	5.06	3.47	1.51	5.23	5.60	3.60	4.09	3.22	2.62	3.82
G11	Statok	4.79	4.22	3.35	5.46	6.30	5.15	5.87	4.14	3.74	4.78
G12	Krok	6.12	4.37	2.96	5.03	5.83	5.44	5.46	4.67	3.98	4.87
G13	Sviatomyk-hailivskyi	5.95	4.06	3.31	6.08	5.91	5.32	5.77	4.53	4.03	5.00
G14	Voievoda	5.32	4.83	2.75	6.28	6.34	5.80	5.80	3.50	4.16	4.98
G15	Vsesvit	4.55	4.59	3.43	6.05	6.20	5.69	5.38	4.38	3.95	4.91
G16	Halaktyk	4.89	4.42	2.98	5.19	6.32	5.69	5.03	3.87	4.35	4.75
G17	Hetman	4.66	4.61	2.88	5.46	6.70	6.49	5.43	4.61	3.66	4.94
G18	Sviatohor	4.47	4.53	3.08	5.85	6.13	6.45	5.12	4.79	3.68	4.90
G19	Luka	4.76	5.08	2.72	5.10	6.00	6.39	4.46	4.53	3.61	4.74
G20	Vakula	5.81	4.55	2.79	5.39	6.11	4.15	6.47	4.75	2.10	4.68
G21	Helios	5.31	4.63	2.23	5.72	6.19	4.21	6.29	4.33	2.08	4.55
G22	Dokaz	6.08	4.64	2.28	6.73	6.84	3.60	5.97	4.23	2.13	4.72
G23	Inkliuzyv	5.71	4.50	3.08	5.82	6.43	4.25	5.43	4.83	3.54	4.84
G24	Vzirets	6.88	4.66	2.91	6.01	6.61	4.53	5.73	4.53	3.25	5.01
G25	Vitrazh	4.78	4.35	2.14	4.80	5.46	3.36	4.57	4.17	2.98	4.07
G26	Veles	6.03	4.29	2.50	5.95	6.43	6.39	4.91	4.34	3.39	4.91
G27	Skarb	5.08	4.99	3.74	6.11	7.09	6.55	6.13	4.72	4.02	5.38
G28	Perl	5.76	4.85	2.98	5.95	6.72	5.41	5.13	5.01	3.44	5.03
G29	Alehro	5.08	4.63	2.84	6.11	6.95	6.22	5.89	4.32	3.77	5.09
G30	Avhur	5.85	4.54	2.46	6.27	6.95	5.96	5.89	4.04	3.37	5.04
G31	Modern	4.31	4.64	2.72	5.23	6.20	5.14	4.31	4.34	2.76	4.41
G32	Skif	5.01	4.43	2.96	6.24	7.00	5.11	5.05	3.74	3.33	4.76
G33	Svaroh	5.72	4.76	2.82	6.01	6.67	5.54	4.94	5.11	3.00	4.95
G34	Shakira	6.52	4.21	2.53	5.33	7.07	5.71	4.31	4.55	2.64	4.76
G35	KWS Bambina	6.66	4.73	2.50	6.70	7.00	4.69	5.22	4.36	2.17	4.89
G36	Brusefield	4.92	4.29	1.44	5.10	5.95	4.54	6.37	3.97	2.42	4.33
Mean in the environment		5.79	4.62	2.94	5.85	6.52	5.21	5.34	4.33	3.21	4.87
Max in the environment		7.41	5.45	3.77	6.99	7.09	6.55	6.47	5.11	4.35	5.53
Min in the environment		4.31	3.47	1.44	4.80	5.46	3.36	4.09	3.22	2.08	3.82
R (Max-Min)		3.11	1.99	2.33	2.19	1.62	3.19	2.38	1.89	2.28	1.71
LSD_{05}		0.35	0.29	0.21	0.46	0.29	0.46	0.19	0.37	0.17	0.31

Note: test-environment code according to the Table 1.

The GGE biplot model has been widely used in recent years to interpret the genotype by environment data from multi-environment trials (Dyulgerova and Dyulgerov, 2019; Öztürk, 2020; Kozachenko et al., 2022). In our study for in-depth evaluation of multi-environment experimental data we provided GGE biplot analysis both seperatly for each ecological niche and for the trial in general. Figure 1 shows the GGE biplot representativeness and discriminating power of the test-environments. The first two principal components labeled as AXIS 1 and AXIS 2, respectively. There were found differences among ecological niches in the percentage of the genotype by environment interaction captured by principal components of the GGE biplot. At the MIW it was 94.81%, at the NPBES it was 93.76%, at the IAS it was 80.71%, and it the trial in general it was only 65.80%. There were even more significant differences among them in the ratio of the values of the first and the second principal components. The thick line that intersects the origin of the biplot is the average environment axis (AEA). The mathemtically calculated average environment for the trial in general is pointed on the AEA as encircled arrow. The dashed lines represent the vectors of each test-environments. The angle between the vector and the AEA denote its representativeness. The smallest angle means the highest representativeness. The length of the vector shows discriminating power of certain environment. The longest vector corresponds to the highest discriminating power and *vice versa*. An angle between vectors shows their similarieties or differenses. At the MIW, the most distant one from another were vectors of the test-environments M16 and M18. So they were the most different. The M16 had the highest discriminating power. More representative that others was the test-environment M17. At the NPBES, the highest discriminating power was found in the N18. The test-environments N16 and N17 were relatively similar. At the IAS, the high discriminating power was noted in the test-environments K16 and K18. At the same time, they were the most remote one from another. In the trial in general, the test-environment M18 was the most representative. The test-environments K18 and M16 were the least representative and the most remote one from another. The test-environments M17, N16, N17, and K16 were relatively similar, since they had acute angles between their vectors. The test-environments M16 and N18 were characterized by the highest discriminating power. The smallest discriminating power was found in the K16 and K17. As we also can see, at the MIW, the conditions in two of three years (the test-environments M16 and M18) had high discriminating power, and in two years (the test-environments M16 and M17) had high representativeness. At the NPBES, a high discriminating power was in one year (the test-environment N18) and higher than average in two other years (the test-environment N16 and N17). In addition, in two years (the test-environments N16 and N17) the conditions at the NPBES were quite representative. At the same time, conditions of IAS in two years (the test-environments K16 and K17) were characterized with the lowest discriminating power. Thus, obtuse angles between some test-environments both in each ecological niche and it the trial in general clearly pointed on the presence a strong cross-over genotype by environment interaction.



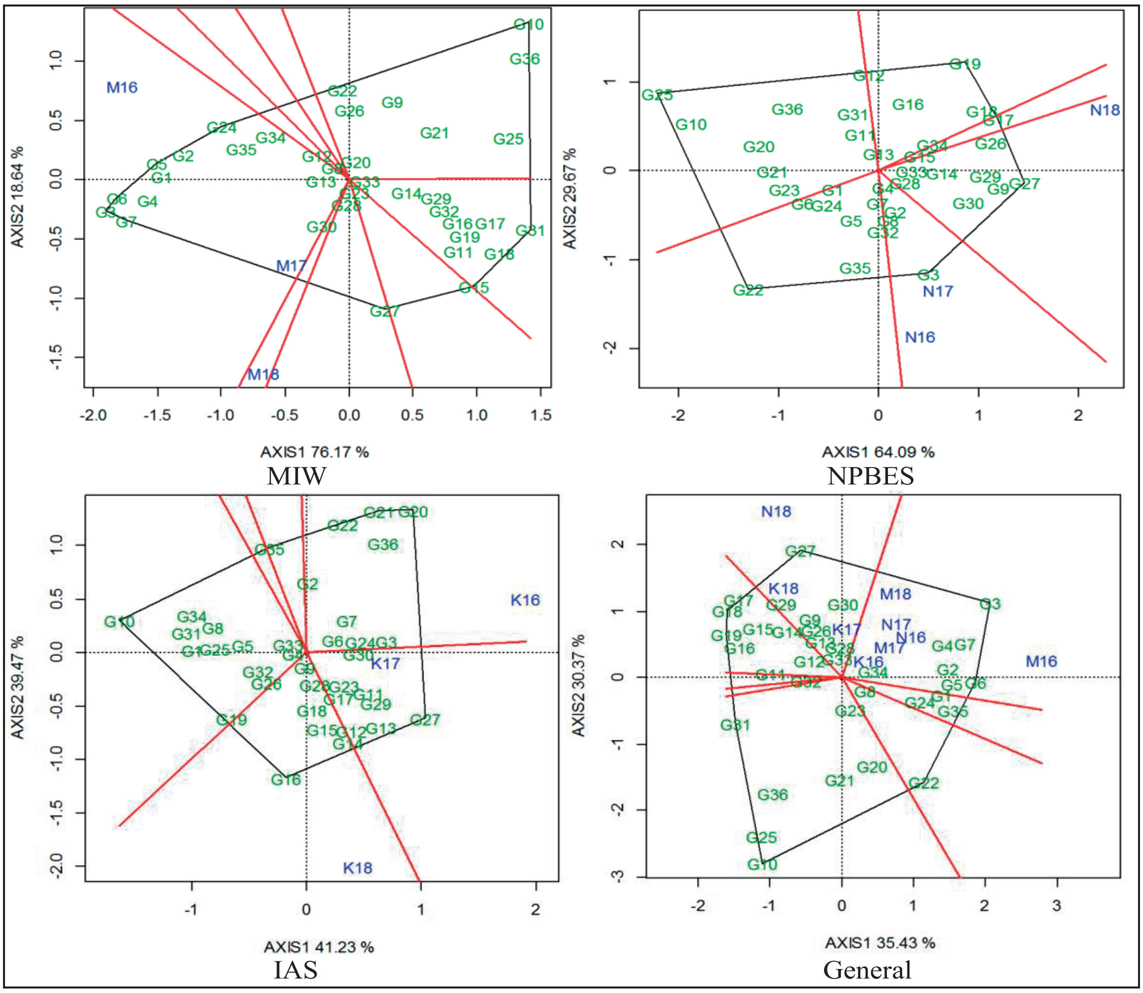
Note: Test-environment code according to the Table 1, cultivar code according to the Table 2.

Figure 1. The GGE biplot of discriminating power and representativeness of test-environments

The GGE biplot "which-won-where" polygon view is very useful for visualizing interaction patterns between genotypes, environments, and mega-environments designation (Figure 2). The polygon figure is formed by connecting the genotypes that are the farthest from the origin of GGE biplot. A set of perpendicular to each side of the polygon lines split the space of the biplot into different sectors. In some sectors at the tops of the polygon are placed cultivars that have an advantage in a particular environment or in a group of the environments (mega-environment). Environments which fell in the same sector create a mega-environment. When all environments fell into the different sectors, it means that different cultivars won in them. At the MIW, two test-environments (M16 and M17) fell into one sector. The winner in this sector was the cultivar MIP Myrnyi (G3). However, the group of cultivars [MIP Azart (G6), MIP Bohun (G7), MIP Saliut (G4), etc.] were close to it. Some of them [MIP Azart (G6), MIP Bohun (G7), MIP Sotnyk (G5), Talisman (G2), Vzirets (G24)] were placed on the polygon line. The test-environment M18 was in the narrow sector with no cultivars. At the NPBES, two test-environments (N16 and N17) were in the same sector. The winner in it was the cultivar MIP Myrnyi (G3). In the sector with the test-environment N18 the superior over others was the cultivar Skarb (G27). At the IAS, all three test-environment fell into different sectors. In the sector with the K16 winner was the cultivar Vakula (G20). The cultivars Helios (G21), Dokaz (G22), and Brusefield (G36) were also close to the top of the polygon. In the sector with the test-environment K17 the best was the cultivar Skarb (G27), and in the sector with the K18 superior over other was the cultivar Halaktyk

(G16). That is, in this ecological niche in different years the winners were different cultivars.

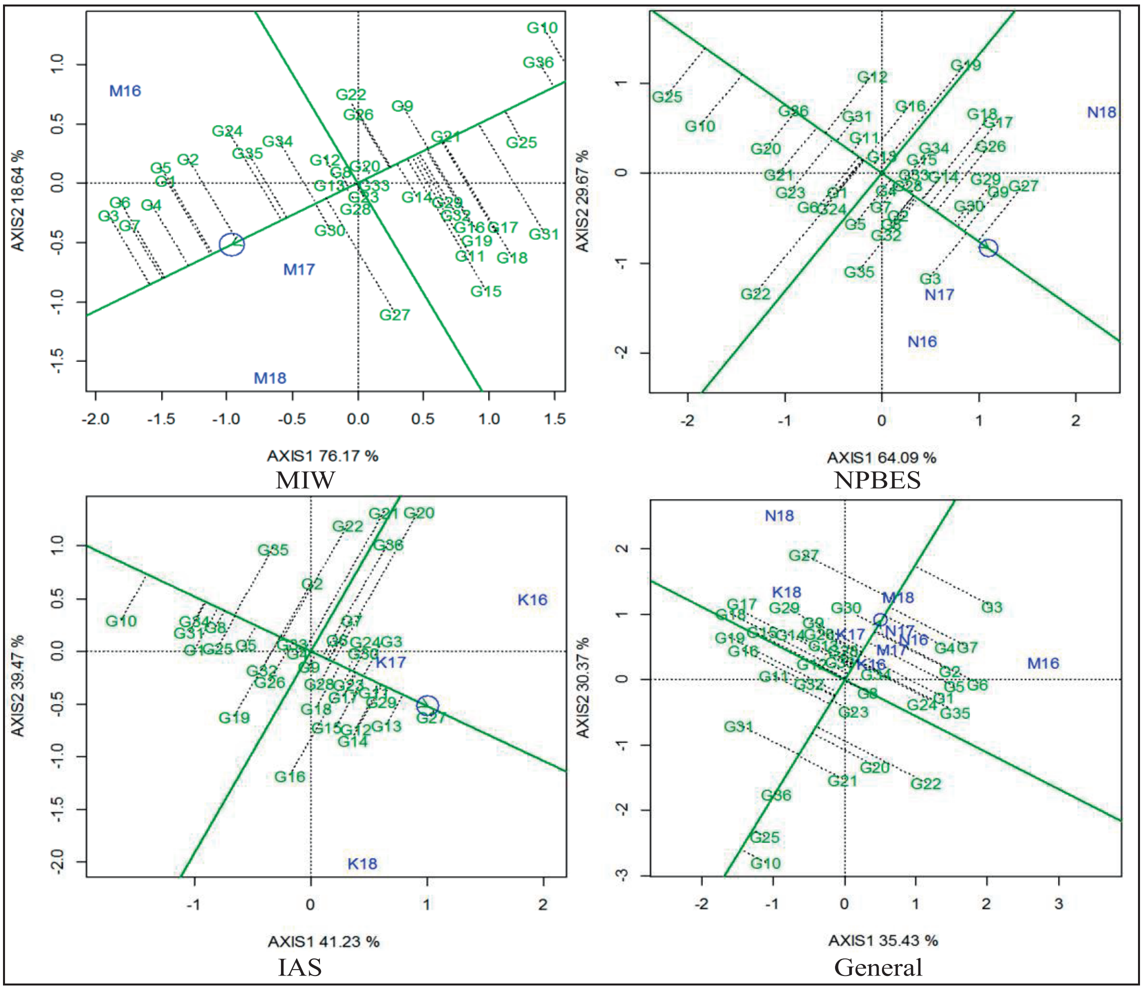
In the trial in general, the first mega-environment is formed by three test-environments K17, K18 and N18. The second mega-environment included six test-environments M16, M17, M18, N16, N17, and K16. The winner in the first mega-environment was the cultivar Skarb (G27). The cultivars Alehro (G29), Mirazh (G9), Veles (G26), Sviatomykhailivskyi (G13), Perl (G28), Svaroh (G33), and Avhur (G30) also fell in this sector. The cultivar MIP Myrnyi (G3) was the best in the second mega-environment. This mega-environment also included cultivars Talisman (G2), MIP Saliut (G4), MIP Sotnyk (G5), MIP Bohun (G7), and Shakira (G34). It should be noted that the cultivar MIP Azart (G6), which belonged to this mega-environment, had high reaction to the test-environment M16. All other cultivars fell into the sectors which contained no environments. It is indicating that these genotypes had poorer performance in the mentioned mega-environments. It also can be seen that the two mega-environments mentioned above included different years in different ecological niches. This confirms that not only contrasting environmental conditions of natural zones significantly influenced on the yield of the genotypes, but also the specific meteorological conditions in the years of trial. Thus, even in individual natural zones cross-over the genotype by environment (the genotype by year) interaction has been detected. On the whole, the GGE biplot "which-won-where" confirmed and complemented the peculiarities discussed above when analyzing discriminating power and representativeness of the test-environments.



Note: Test-environment code according to the Table 1, cultivar code according to the Table 2.

Figure 2. The GGE biplot "which-won-where" polygon view for spring barley cultivars and test-environments

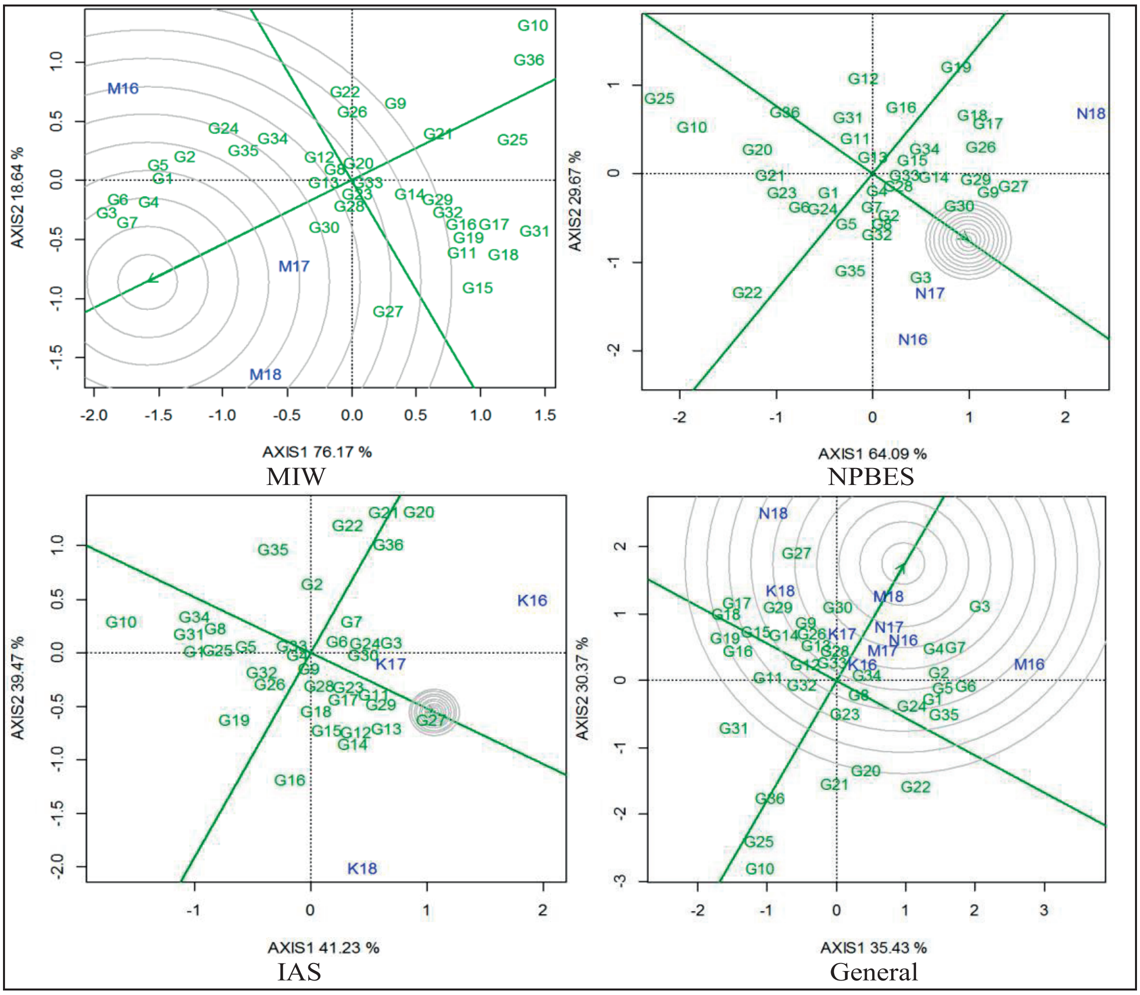
Figure 3 shows the average environment coordination of cultivars in terms of mean yield performance and stability. In the direction marked with encircled arrow on the AEA, the cultivars are ranked according to mean performance (in the values of principal components). Perpendicularly to the AEA the origin of the GGE biplot is crossed by the average ordinate. The intersection point of the AEA (abscissa) and the ordinate represents the grand mean performance for all environments. The displacement of cultivars along the ordinate axis from the AEA, marked with dashed lines, characterizes their variability with respect to the expected performance. In the other words, it shows the deviation in the cultivar performance from general (average) trend of all cultivars in the trial. At the MIW, the highest performance was in the cultivar MIP Myrnyi (G3), and the poorest one was in the cultivar Kozatskyi (G10). However we should mentioned that MIP Myrnyi (G3) and the group of other cultivars [MIP Bohun (G7), MIP Azart (G6), MIP Saliut (G4), Virazh (G1), MIP Sotnyk (G5), Talisman (G2), Vzirets (G24), KWS Bambina (G35), and Shakira (G34)], that exceeded the grand mean, were clearly shifted towards the test-environment M16. That is, they in this test-environment were much better than it could be expected. The cultivar Skarb (G27), on the contrary to them, was displaced towards the conditions of M18. At the NPBES, the highest performance was in the cultivar Skarb (G27), and the lowest one was in the cultivar Vitrazh (G25). It should be noted that group of cultivars with high yield [Skarb (G27), MIP Myrnyi (G3), Mirazh (G9), Alehro (G29), and Avhur (G30)] were shifted in different directions. For instance, the cultivars Skarb (G27), Mirazh (G9), and Alehro (G29) were shifted towards the N18, and the cultivar MIP Myrnyi (G3) towards the N17 and N16. Thus, in the production conditions they will complement each other in reaction to the conditions of different years in this ecological niche. Compared to them, the cultivar Avhur (G30) had better stability, as it was only slightly shifted towards the N18. At the IAS, the cultivar Skarb (G27) combined the highest yield and the stability. Thus, it was the best for these conditions. The poorest performance was found in the cultivar Kozatskyi (G10). The highest variability was in the cultivars Vakula (G20), Helios (G21), Brusefield (G36), and Dokaz (G22). In the trial in general, it is clearly visible that the highest yield performance was produced in the cultivar MIP Myrnyi (G3) and the poorest one was in the cultivar Kozatskyi (G10). There were a number of cultivars [MIP Myrnyi (G3), Skarb (G27), MIP Bohun (G7), MIP Saliut (G4), Avhur (G30), Talisman (G2), and MIP Azart (G6)] with relatively high mean performance, but they were shifted in different directions. Accordingly, the cultivars MIP Myrnyi (G3), MIP Bohun (G7), MIP Saliut (G4), Talisman (G2), and MIP Azart (G6) could be complimented with the cultivars Skarb (G27) and Avhur (G30) in the production conditions for more stable barley grain production in different natural zones of Ukraine.



Note: Test-environment code according to the Table 1, cultivar code according to the Table 2.

Figure 3. The GGE biplot average environment coordination view of spring barley cultivars for mean yield against stability

Figure 4 shows ranking the cultivars relative to a hypothetical “ideal genotype” that is indicated on the AEA with an arrow in the center of centric circles. An “ideal genotype” should optimally combine a high mean yield performance and its stability in different environments. Thus, the cultivars which located closer than others to the “ideal genotype” are more desirable in terms of adaptability (a combination of yield level and its stability). At the MIW, the cultivars MIP Bohun (G7), MIP Myrnyi (G3), MIP Saliut (G4), and MIP Azart (G6) were much closer to the “ideal genotype” than others, and accordingly, they were the best for these conditions. The other cultivars that exceeded the grand mean yield had more specific reaction to the conditions of one or more test-environments, or had lower mean yield. However, given that into the trial were involved modern commercial cultivars widespread in production conditions, the ones of them which were on the side of the biplot with the arrow on the AEA have also practical value, but lesser that highlighted above ones. These (in descending order) were Virazh (G1), MIP Sotnyk (G5), Talisman (G2), Vzirets (G24), KWS Bambina (G35), Shakira (G34), Avhur (G30), Skarb (G27), Perl (G28), Sviatomykhailivskyi (G13), Krok (G12), and Imidzh (G8). The cultivars which were on “the other side” of the biplot, and accordingly had lower performance that grand mean have little value for growing. At the NPBES, only the cultivar Avhur (G30) was placed within the set of the centric circles. Thus, it should be considered as the best for this ecological niche. All other cultivars were out of circles. This is due to the fact that they had high variability in yield performance depending on conditions of the year of trial. On the "right side" of the biplot (in descending order) there were also placed cultivars MIP Myrnyi (G3), Mirazh (G9), Skarb (G27), Alehro (G29), Voievoda (G14), Perl (G28), MIP Saliut (G4), MIP Bohun (G7), Svaroh (G33), Skif (G32), Imidzh (G8), Talisman (G2), Veles (G26), Vsesvit (G15), Shakira (G34), KWS Bambina (G35), Hetman (G17), Sviatohor (G18), and MIP Sotnyk (G5).



Note: Test-environment code according to the Table 1, cultivar code according to the Table 2.

Figure 4. The GGE biplot ranking spring barley cultivars relative to an "ideal genotype"

At the IAS, also, as it was at the NPBES, the only one cultivar was within the set of centric circles. It was the cultivar Skarb (G27). Other cultivars that had performance better than grand mean in descending order were Sviatomykhailivskyi (G13), Alehro (G29), Krok (G12), Statok (G11), Voievoda (G14), Inkliuzyv (G23), Hetman (G17), Avhur (G30), MIP Myrnyi (G3), Vzirets (G24), Perl (G28), MIP Azart (G6), MIP Bohun (G7), Mirazh (G9), Halaktyk (G16), Brusefield (G36), and Vakula (G20). In the trial in general, nearer than others to the "ideal genotype" there were cultivars MIP Myrnyi (G3), Avhur (G30), Skarb (G27), MIP Saliut (G4), and MIP Bohun (G7). Thus, they had relatively better wide adaptability. The cultivars that also exceeded grand mean value were Talisman (G2), MIP Sotnyk (G5), MIP Azart (G6), Shakira (G34), Svaroh (G33), Perl (G28), Sviatomykhailivskyi (G13), Veles (G26), Mirazh (G9), Alehro (G29), Voievoda (G14), Virazh (G1), Vzirets (G24), KWS Bambina (G35), Vsesvit (G15), Sviatohor (G18), and Hetman (G17).

In addition to the practical selection of the best adapted cultivars for certain conditions, our result also contribute to the further understanding the yield manifestation of spring barley in the genotype by environment interaction depending on different environmental and weather conditions. The cultivars highlighted in this study have a high value in plant breeding as genetic sources for developing new spring barley strains with increased adaptive potential. Taking into consideration multifarious conditions of Ukraine in which the cultivars were differentiated, they also could have practical value as collection accessions for involvement in breeding programs in some other East European counties.

CONCLUSIONS

As a result of our study, the strong cross-over genotype by environment interaction was revealed not only through different natural zones of Ukraine, but also in individual ecological niches through different years. Significant variability in yield of spring barley cultivars in both spatial and temporal gradients indicates that to ensure the high and stable grain production it is necessary to combine several complementary genotypes in terms of yield potential and stability. In the studied panel of genotypes the cultivars MIP Bohun, MIP Myrnyi, MIP Saliut, and MIP Azart should be highlighted as the best ones under the conditions of Forest-Steppe. In the conditions of Polissia the optimal will be combination of the cultivars Avhur, MIP Myrnyi, Mirazh, Skarb, and Alehro. The most adapted to the conditions of Steppe is the cultivar Skarb. The cultivars Sviatomykhailivskyi, Alehro, Krok, Statok were slightly inferior to it, but better than others. The cultivars MIP Myrnyi and Skarb were characterized with the highest relatively wide adaptation. In some environments, these varieties had the maximum potential of productivity and at the same time had the relative ecological stability through the most environments. However, they were winners in two different mega-environments. In addition to cultivars MIP Myrnyi and Skarb, the genotypes Avhur, MIP Saliut, and MIP Bohun were also closer than others to the “ideal genotype” according to the GGE biplot model. Thus, the combination of cultivars MIP Myrnyi, Skarb, Avhur, MIP Saliut, and MIP Bohun in production conditions could be considered as the most optimal for all natural zones of Ukraine. Our results also contribute to the further understanding the yield manifestation of spring barley in the genotype by environment interaction depending on different ecological and weather conditions. The cultivars highlighted in this study have a high value in plant breeding as genetic sources for developing new spring barley strains with increased adaptive potential for conditions of Ukraine, as well as for other East European countries.

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